Chapter 9

Zero-Voltage or Zero-Current Switchings

Chapter 9 Resonant Converters: Zero-Voltage and/or Zero-Current Switchings 249

- converters for soft switching

One Inverter Leg

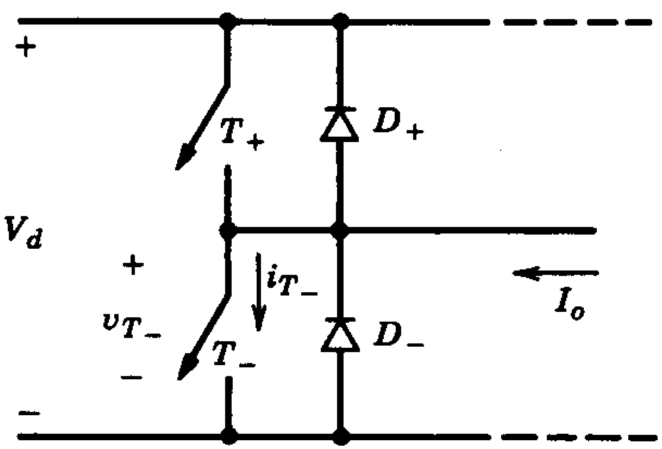


Figure 9-1 One inverter leg.

- The output current can be positive or negative

Hard Switching Waveforms

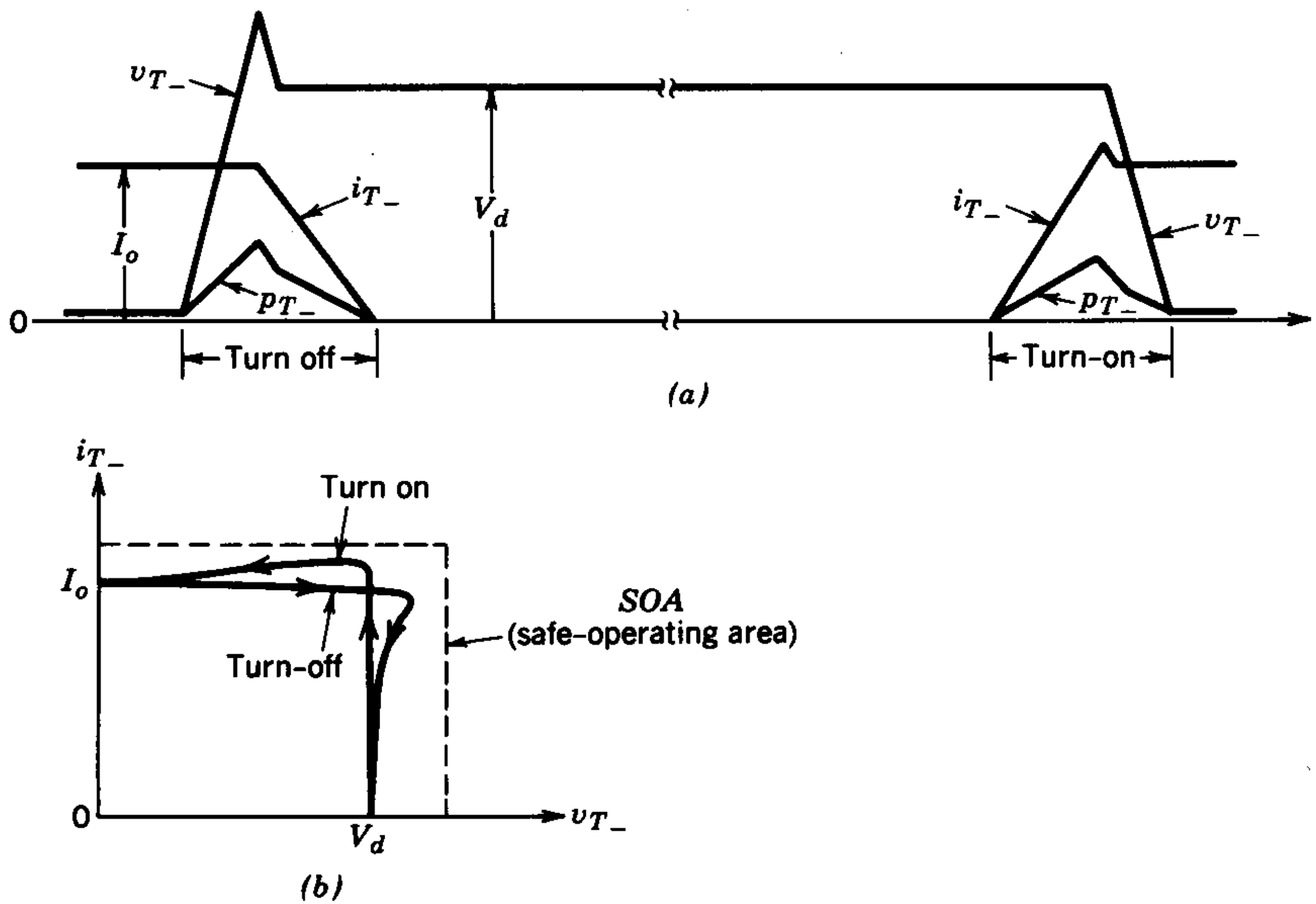


Figure 9-2 Switch-mode inductive current switchings.

- The output current can be positive or negative

Turn-on and Turn-off Snubbers

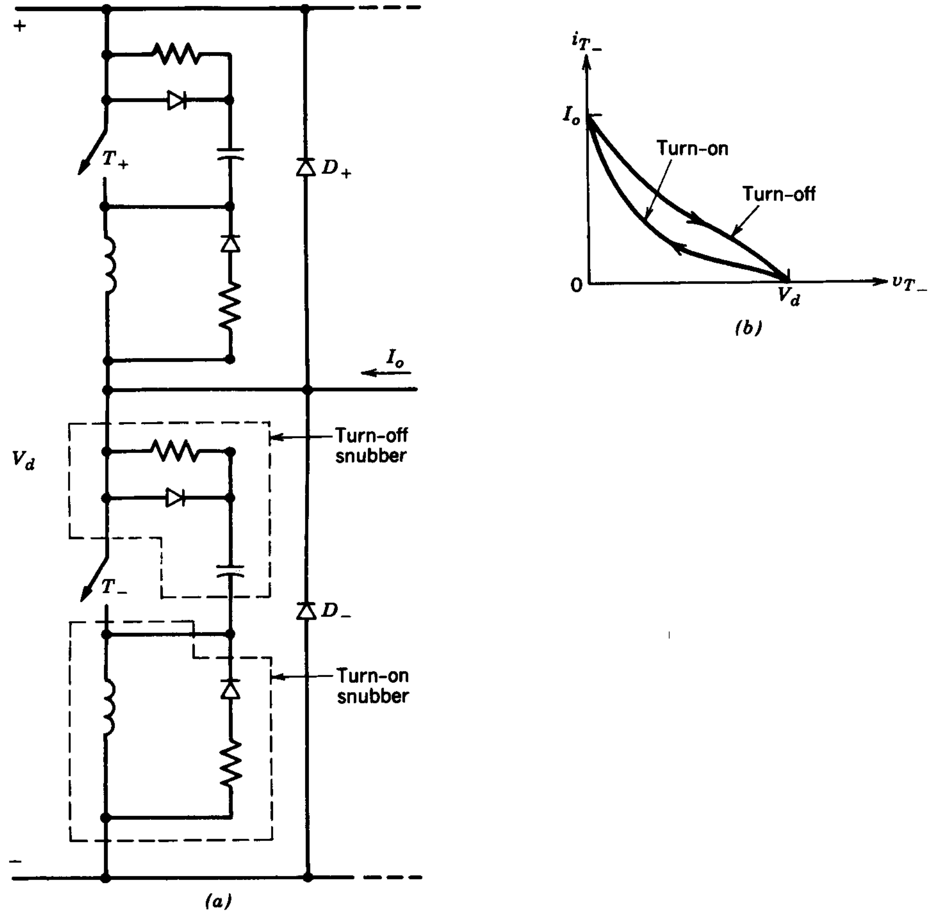


Figure 9-3 Dissipative snubbers: (*a*) snubber circuits; (*b*) switching loci with snubbers.

- Turn-off snubbers are used

Switching Trajectories

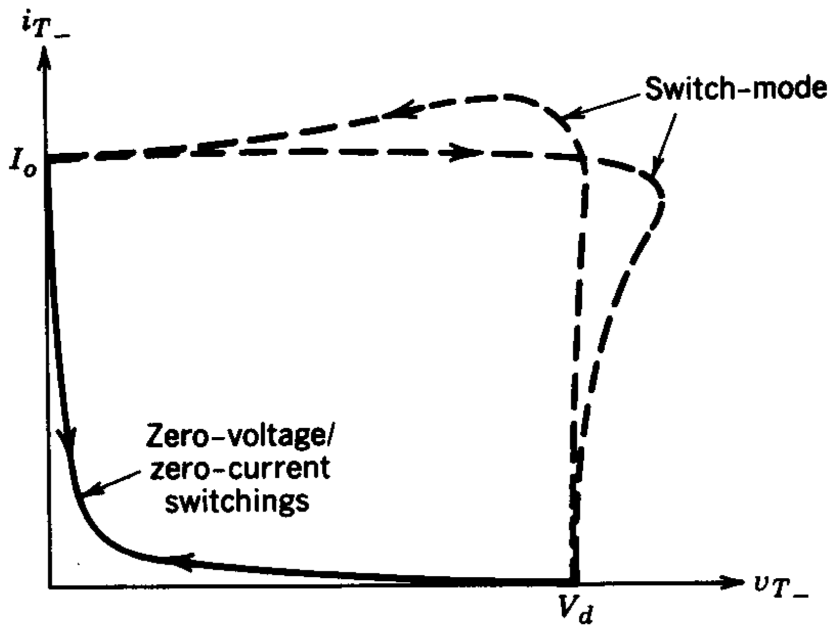


Figure 9-4 Zero-voltage-/zero-current-switching loci.

- Comparison of Hard versus soft switching

Undamped Series-Resonant Circuit

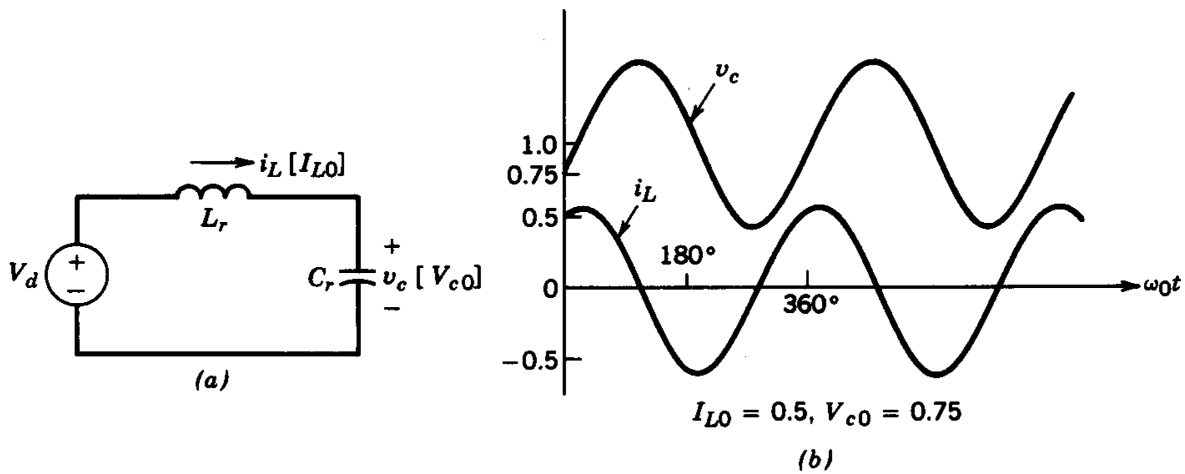


Figure 9-5 Undamped series-resonant circuit; i_L and v_c are normalized: (*a*) circuit; (*b*) waveforms with $I_{L0} = 0.5$, $V_{c0} = 0.75$.

- The waveforms shown include initial conditions

Series-Resonant Circuit with Capacitor-Parallel Load

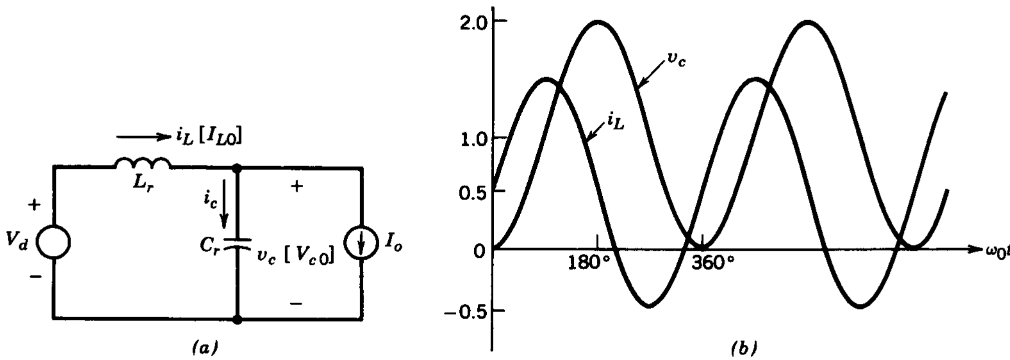


Figure 9-6 Series-resonant circuit with capacitor-parallel load (i_L and v_c are normalized): (*a*) circuit; (*b*) $\mathbf{V}_{c0} = 0$, $I_{L0} = I_o = 0.5$.

- The waveforms shown include initial conditions

Impedance of a Series-Resonant Circuit

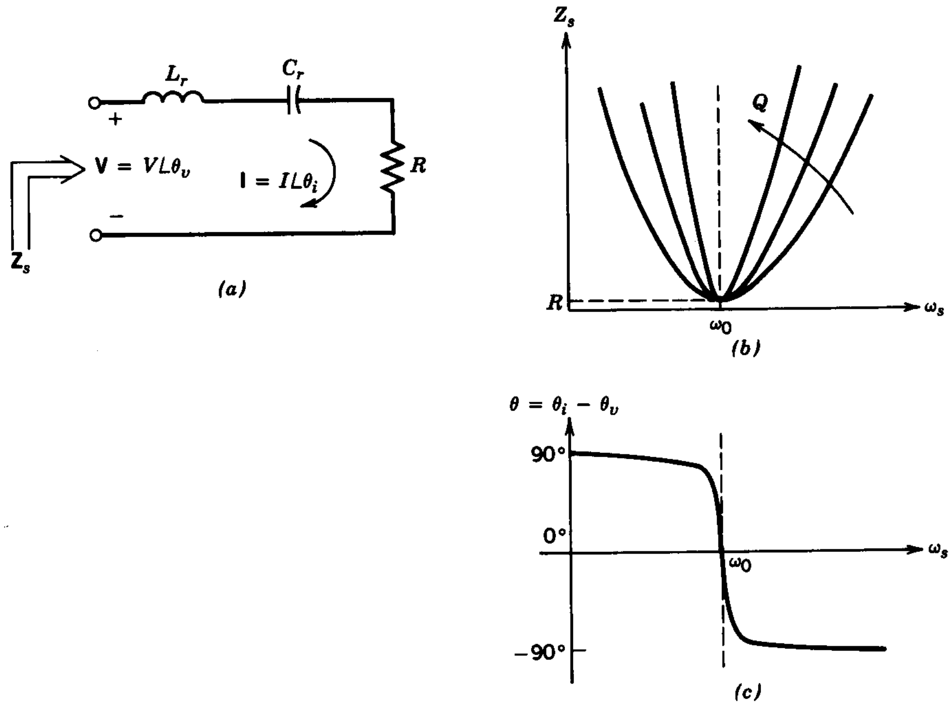


Figure 9-7 Frequency characteristics of a series-resonant circuit.

- The impedance is capacitive below the resonance frequency

Undamped Parallel-Resonant Circuit

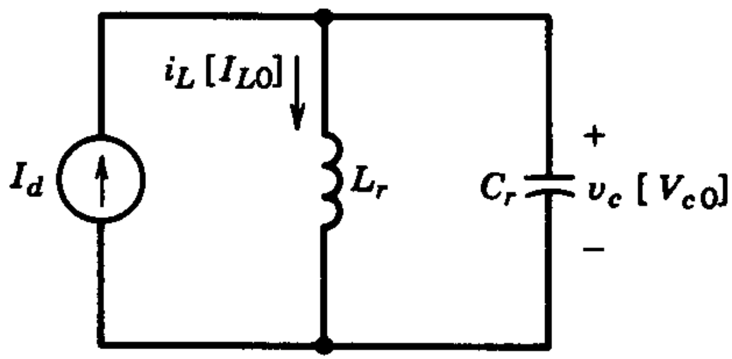


Figure 9-8 Undamped parallel-resonant circuit.

- Excited by a current source

Impedance of a Parallel-Resonant Circuit

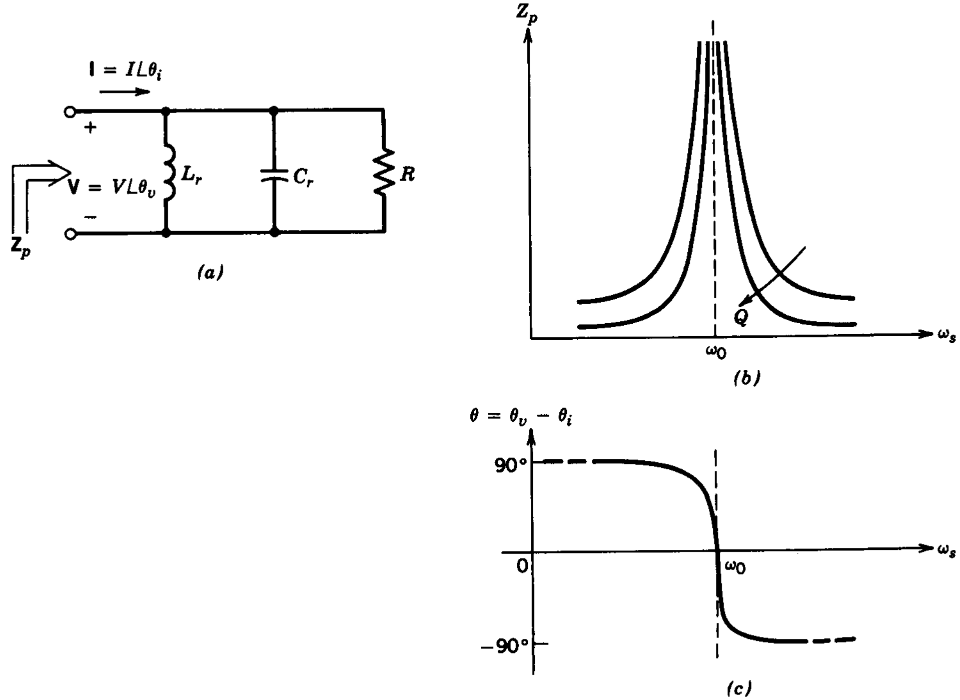


Figure 9-9 Frequency characteristics of a parallel-resonant circuit.

- The impedance is inductive at below the resonant frequency

Series Load Resonant (SLR) Converter

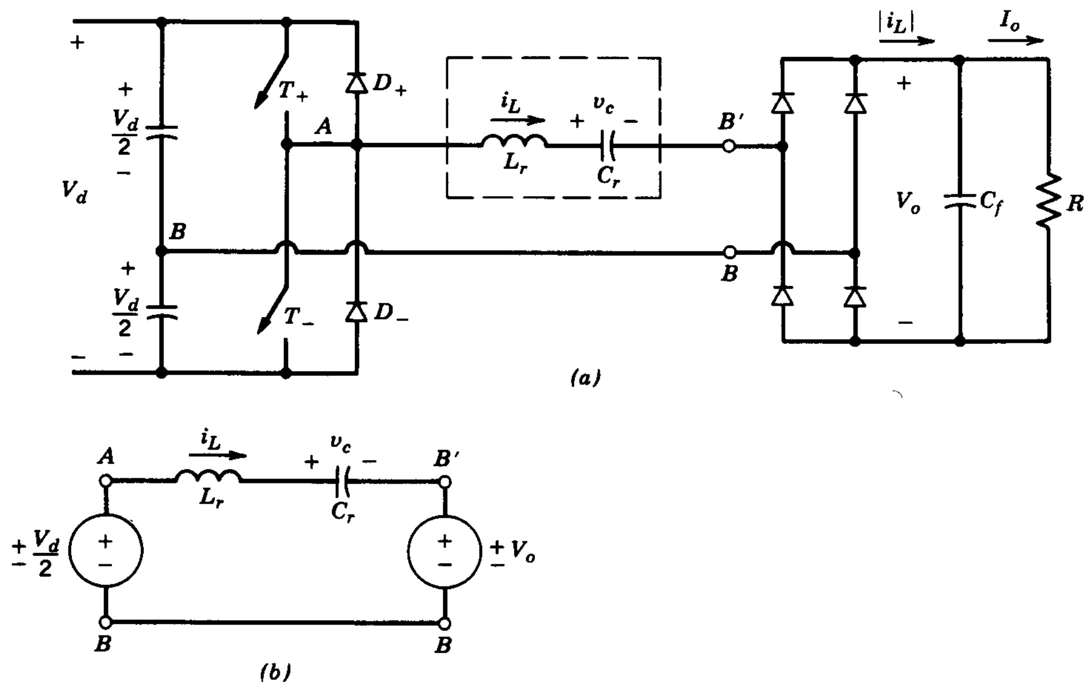


Figure 9-10 SLR dc–dc converter: (*a*) half-bridge; (*b*) equivalent circuit.

- The transformer is ignored in this equivalent circuit

SLR Converter Waveforms

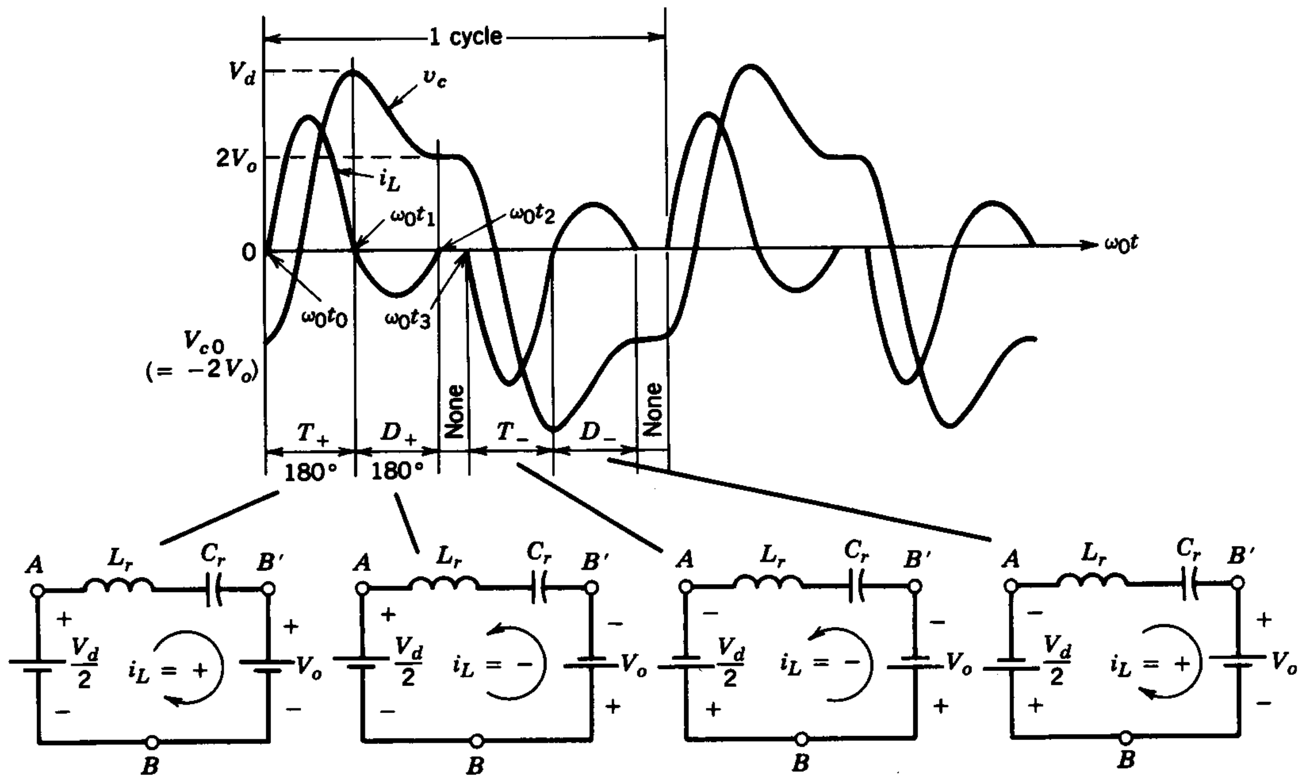


Figure 9-11 SLR dc–dc converter; discontinuous-conduction mode with $\omega_s < \frac{1}{2}\omega_0$.

- The operating frequency is below one-half the resonance frequency

SLR Converter Waveforms

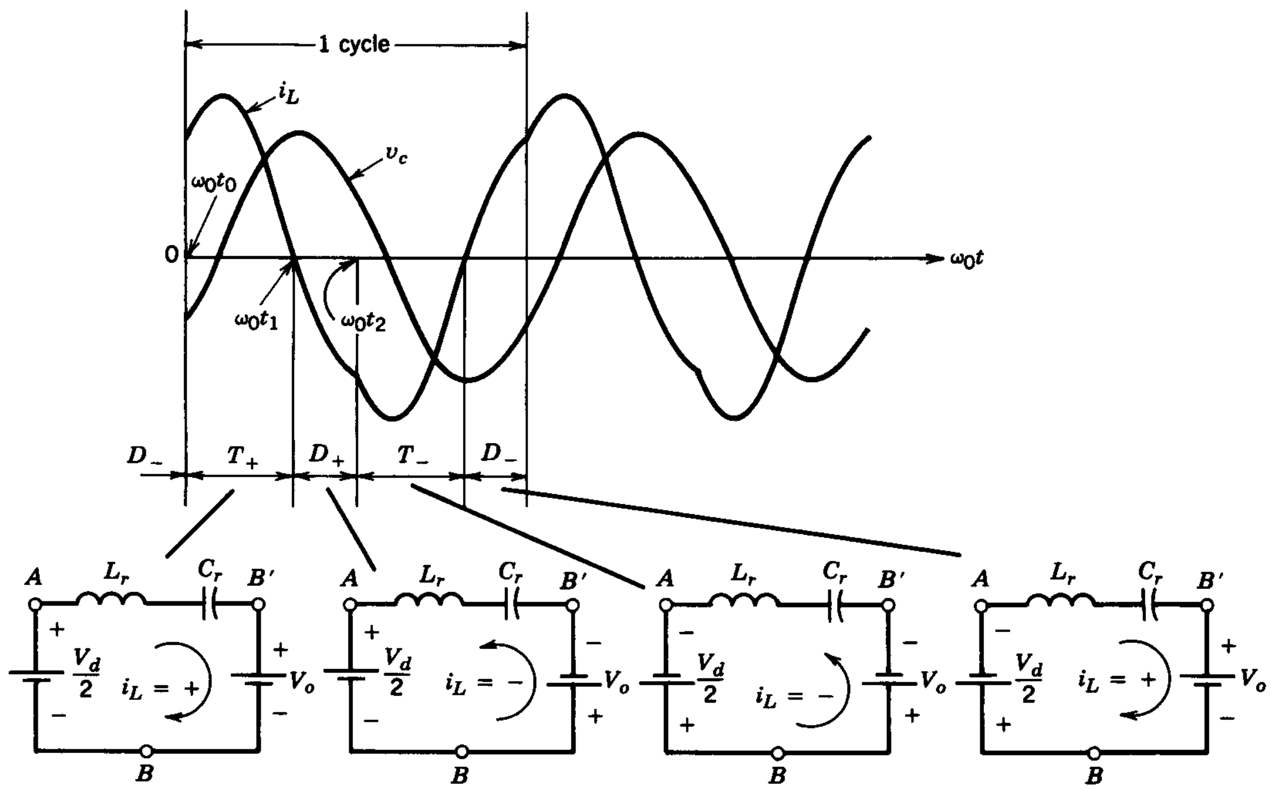


Figure 9-12 SLR dc–dc converter; continuous-conduction mode with $\frac{1}{2}\omega_0 < \omega_s < \omega_0$.

• The operating frequency is in between one-half the resonance frequency and the resonance frequency

SLR Converter Waveforms

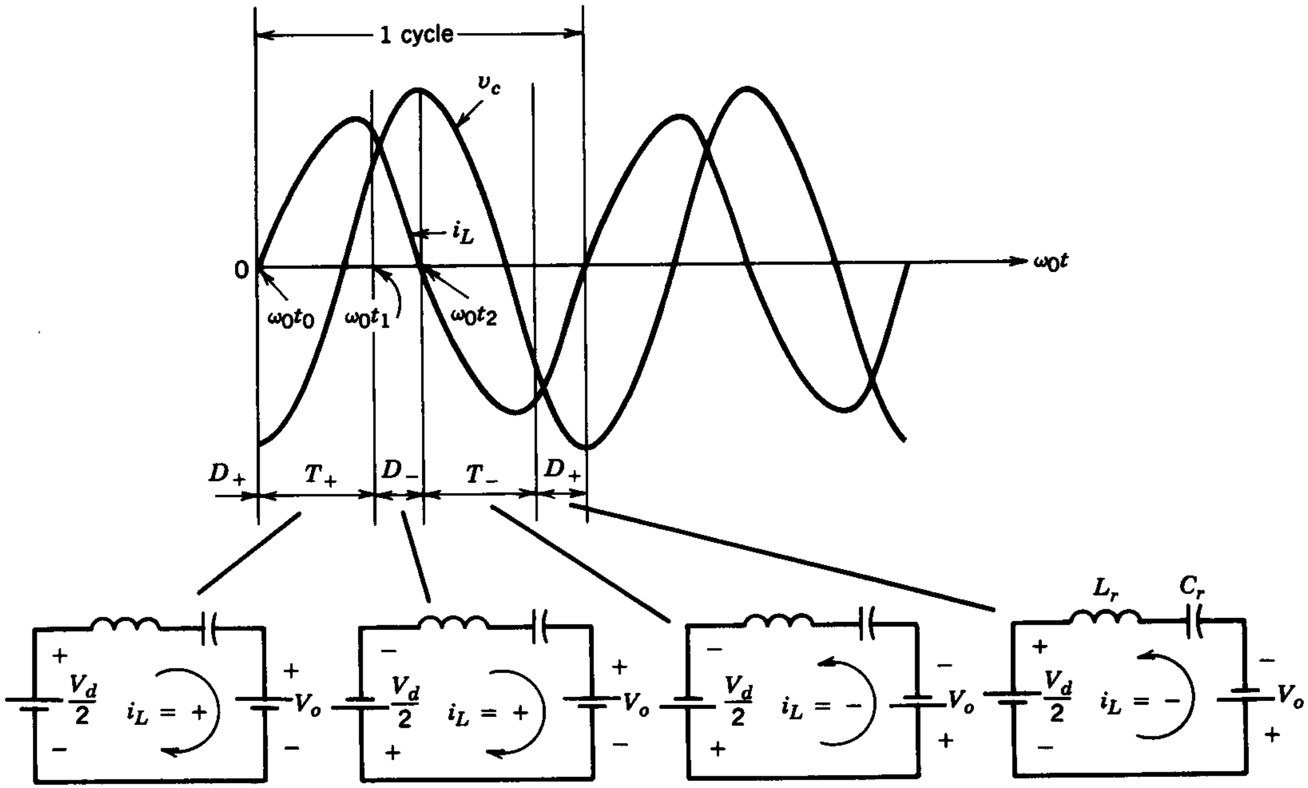


Figure 9-13 SLR dc–dc converter; continuous-conduction mode with $\omega_s > \omega_0$.

• The operating frequency is above the resonance frequency

Lossless Snubbers in SLR Converters

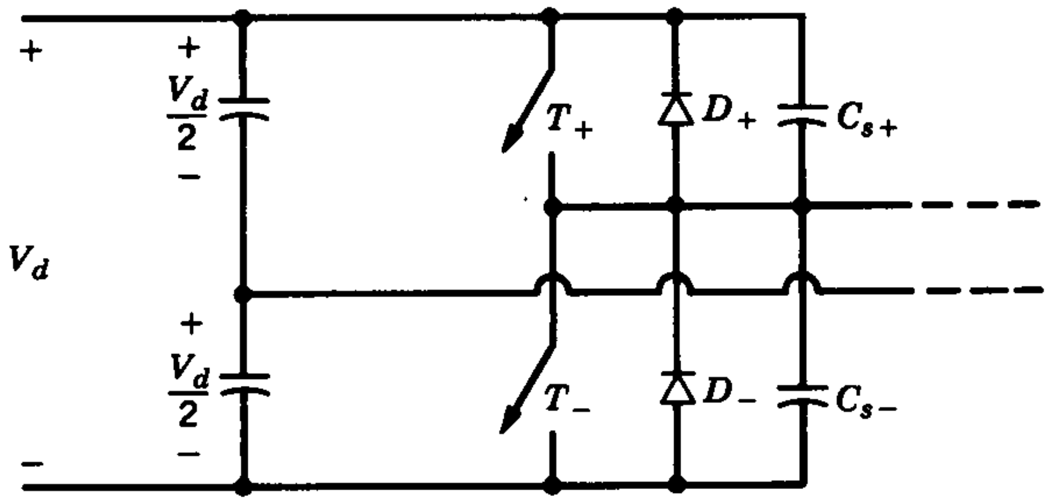


Figure 9-14 Lossless snubbers in an SLR converter at $\omega_s > \omega_0$.

- The operating frequency is above the resonance frequency

SLR Converter Characteristics

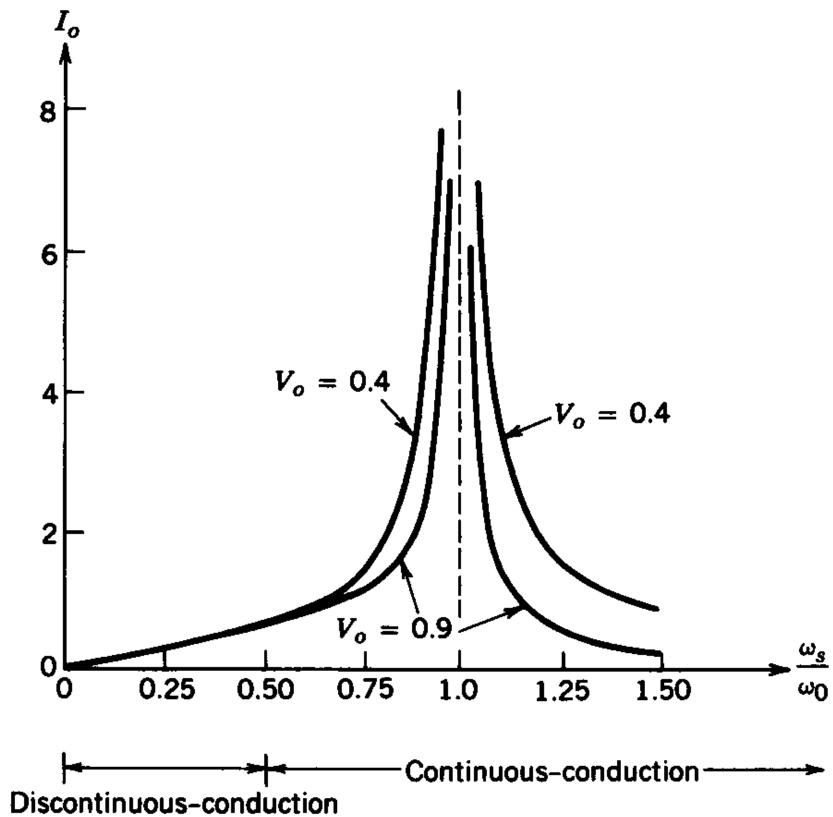


Figure 9-15 Steady-state characteristics of an SLR dc–dc converter; all parameters are normalized.

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

SLR Converter Control

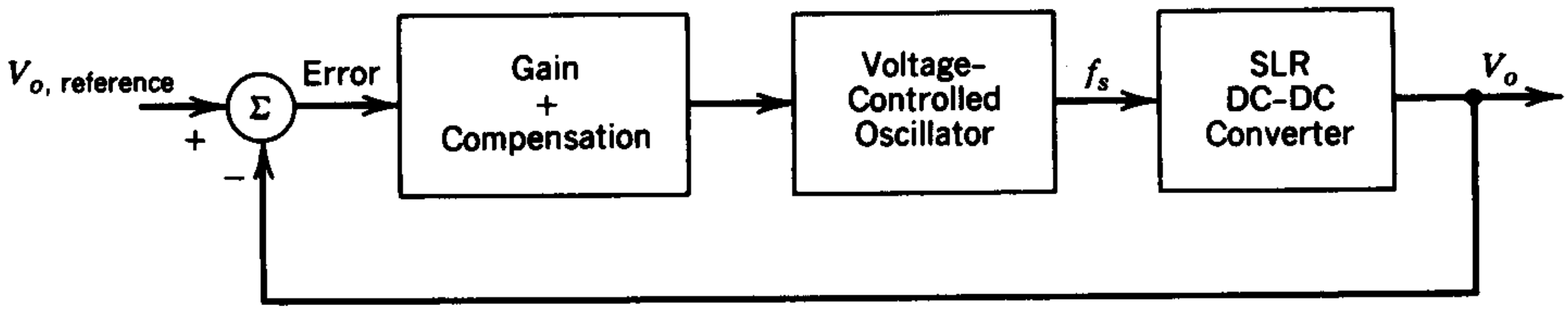


Figure 9-16 Control of SLR dc–dc converter.

- The operating frequency is varied to regulate the output voltage

Parallel Load Resonant (PLR) Converter

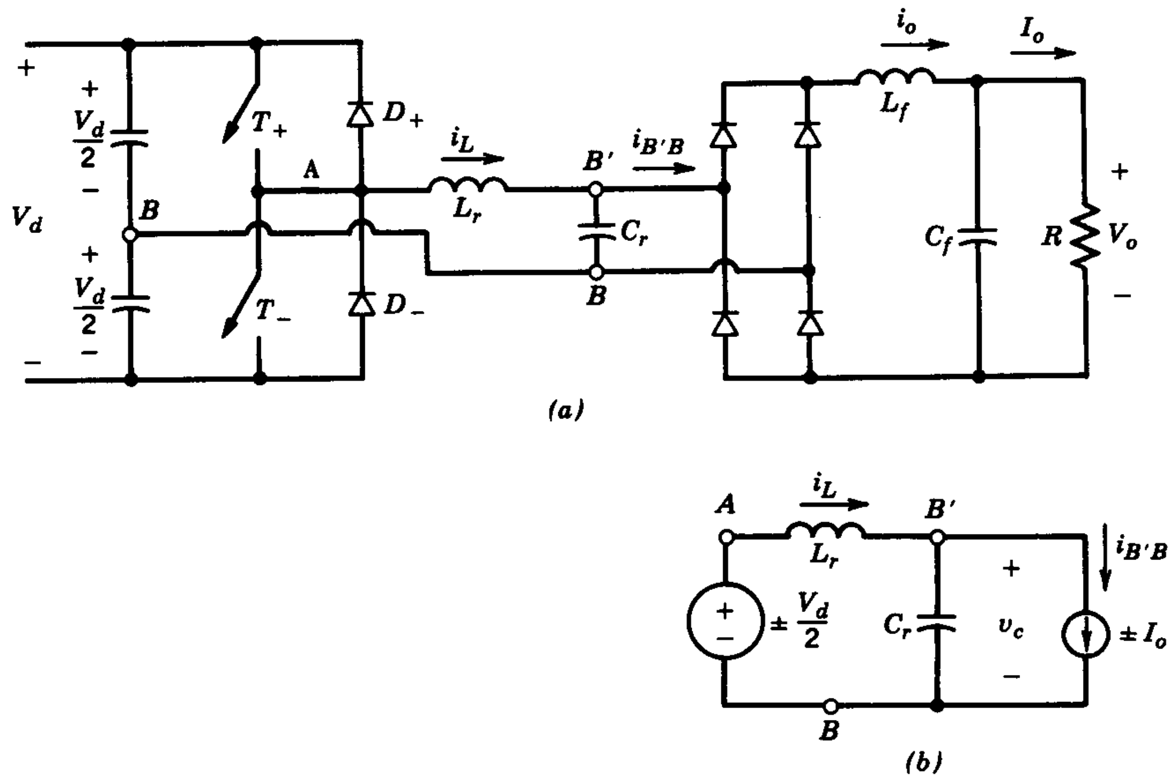


Figure 9-17 PLR dc–dc converter: (*a*) half-bridge; (*b*) equivalent circuit.

- The transformer is ignored in this equivalent circuit

PLR Converter Waveforms

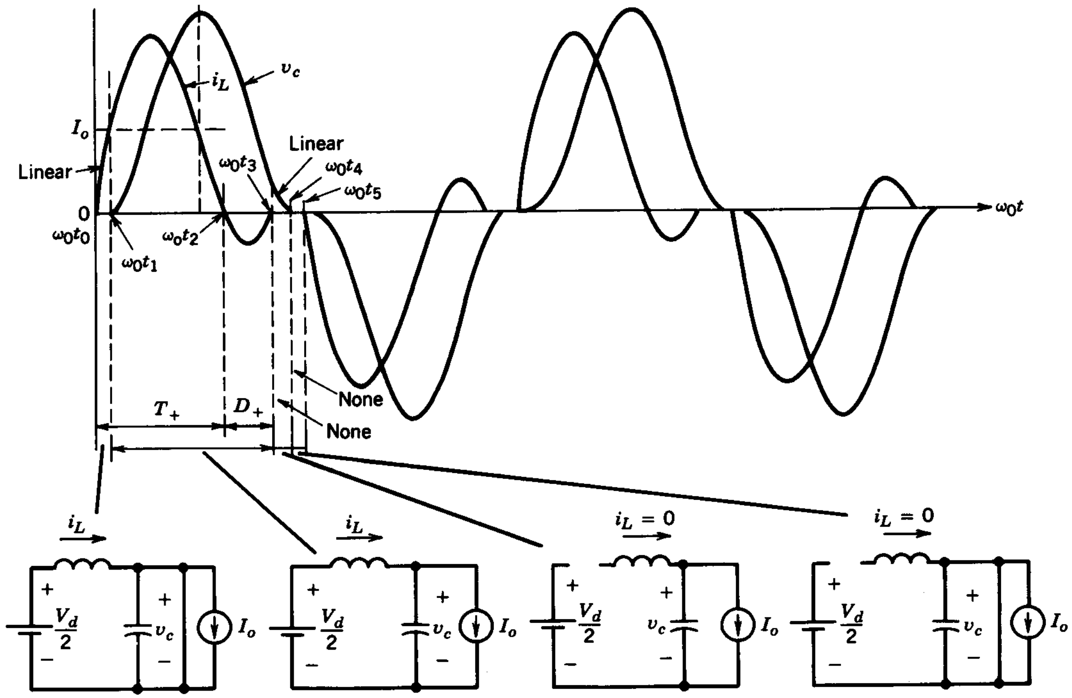


Figure 9-18 PLR dc–dc converter in a discontinuous mode.

• The current is in a discontinuous conduction mode

PLR Converter Waveforms

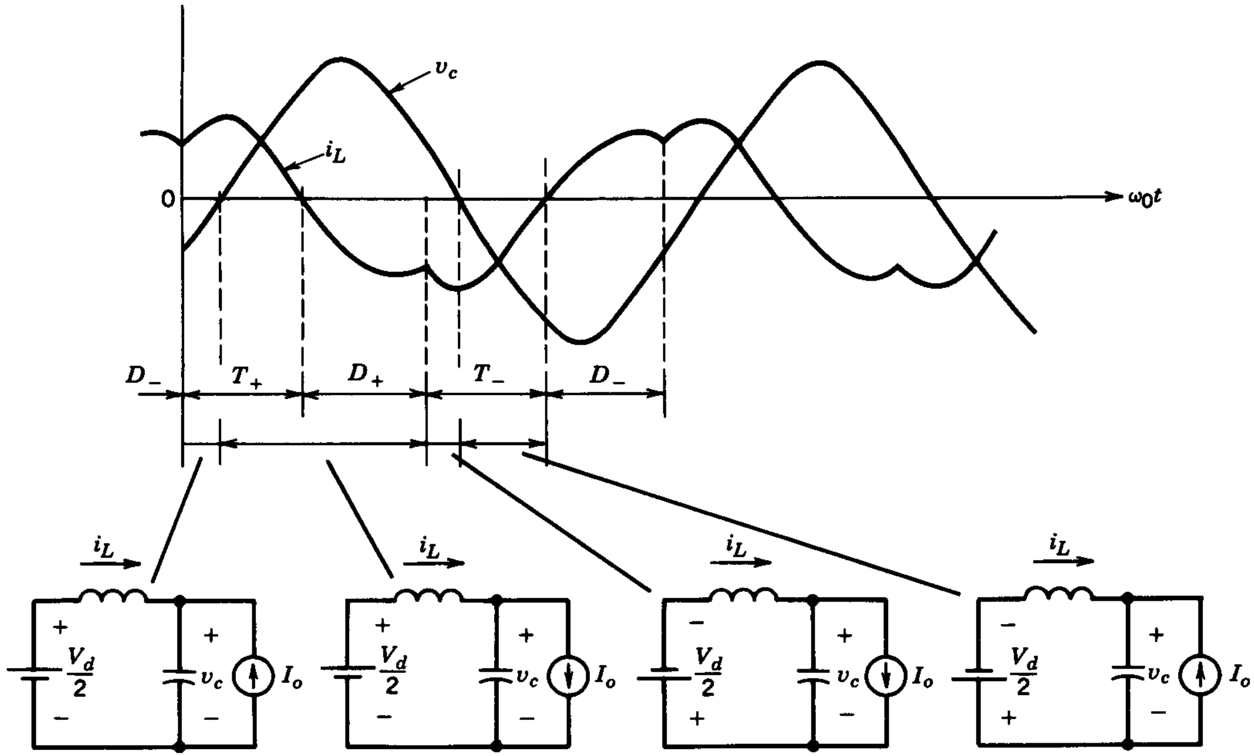


Figure 9-19 PLR dc−dc converter in a continuous mode with $\omega_s < \omega_0$.

- The operating frequency is below the resonance frequency

PLR Converter Waveforms

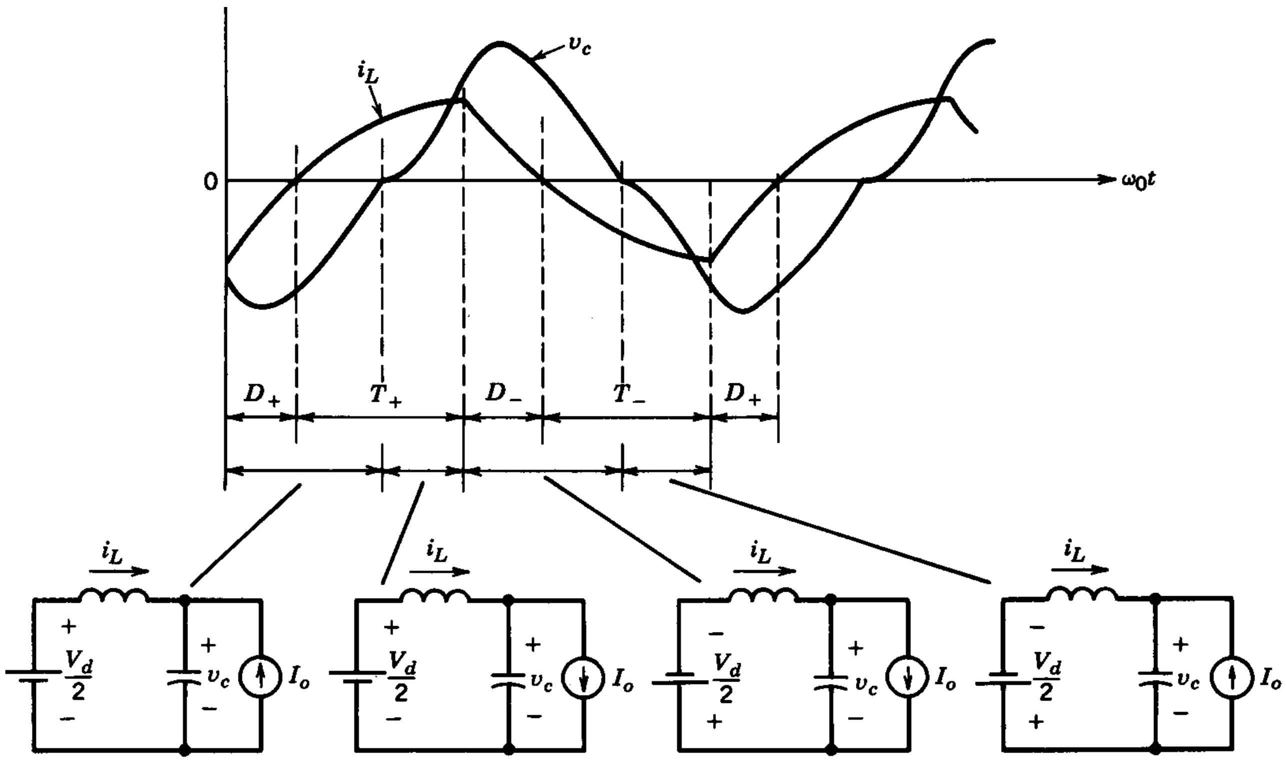


Figure 9-20 PLR dc–dc converter in a continuous mode with $\omega_s > \omega_0$.

• The operating frequency is above the resonance frequency

PLR Converter Characteristics

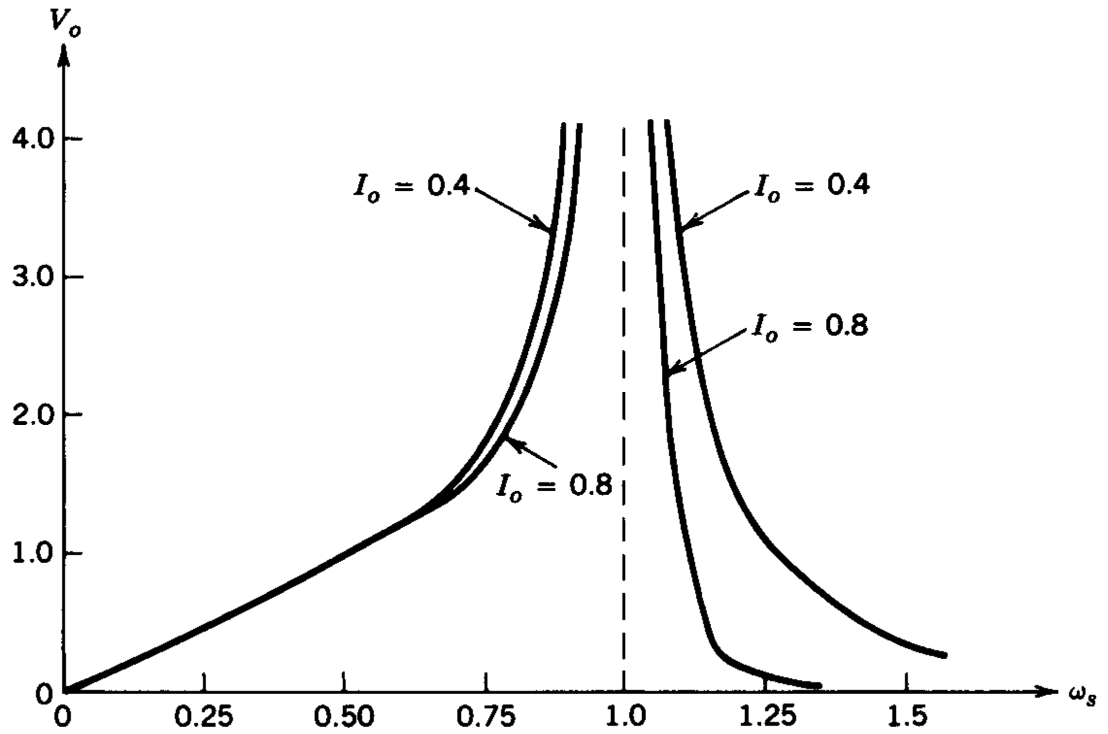


Figure 9-21 Steady-state characteristics of a PLR dc−dc converter. All quantities are normalized.

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

Hybrid-Resonant DC-DC Converter

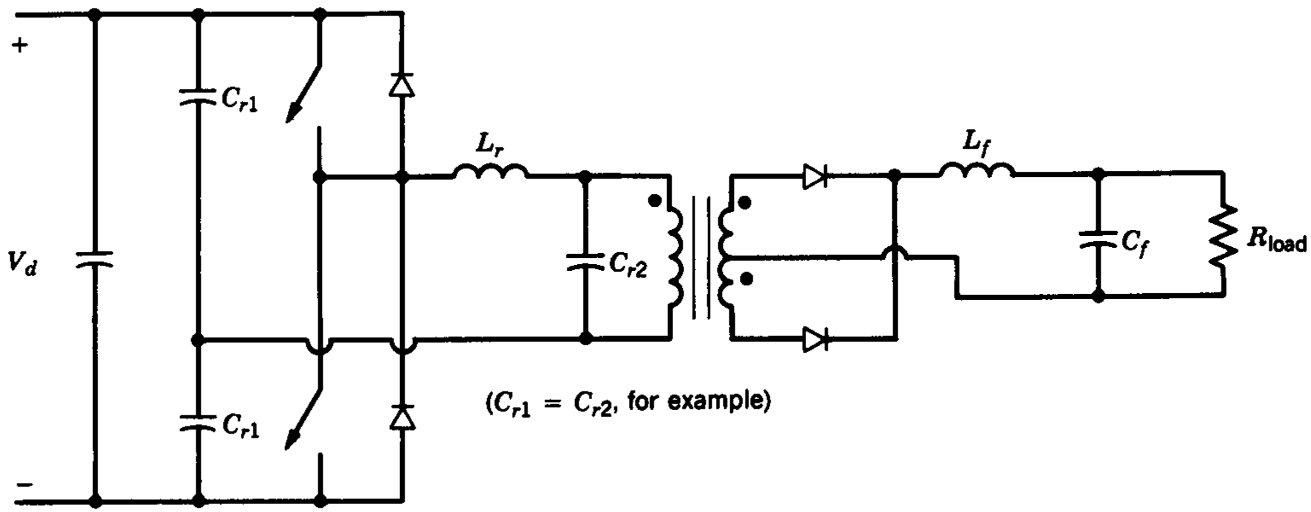


Figure 9-22 Hybrid-resonant dc–dc converter.

- Combination of series and parallel resonance

Parallel-Resonant Current-Source Converter

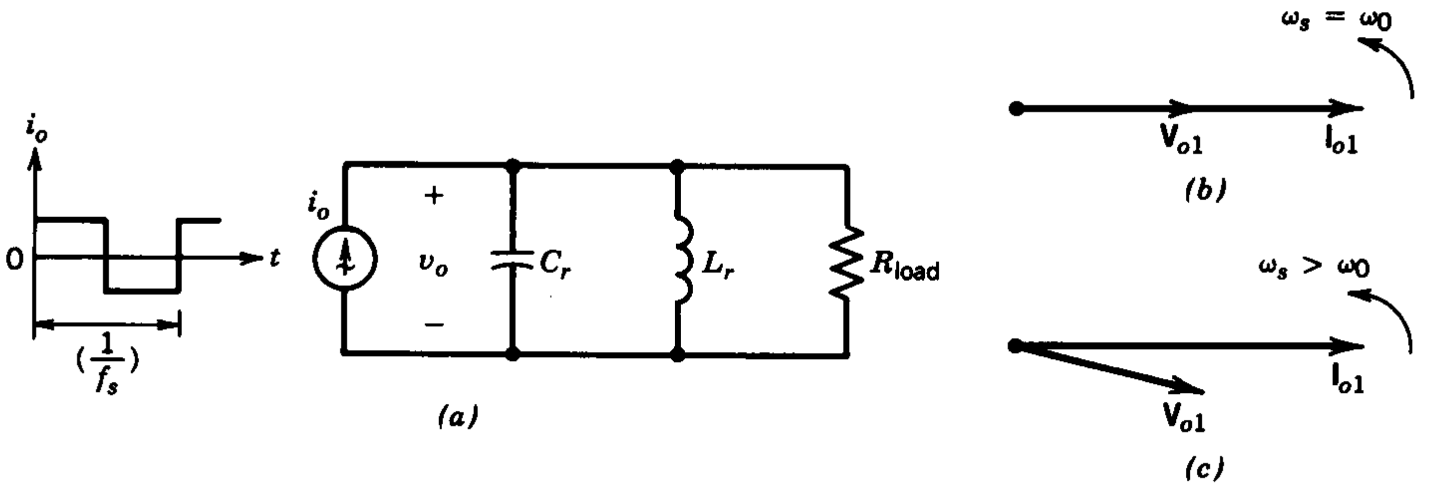


Figure 9-23 Basic circuit for current-source, parallel-resonant converter for induction heating: (*a*) basic circuit; (*b*) phasor diagram at $\omega_s = \omega_0$; (*c*) phasor diagram at $\omega_s > \omega_0$.

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

Parallel-Resonant Current-Source Converter

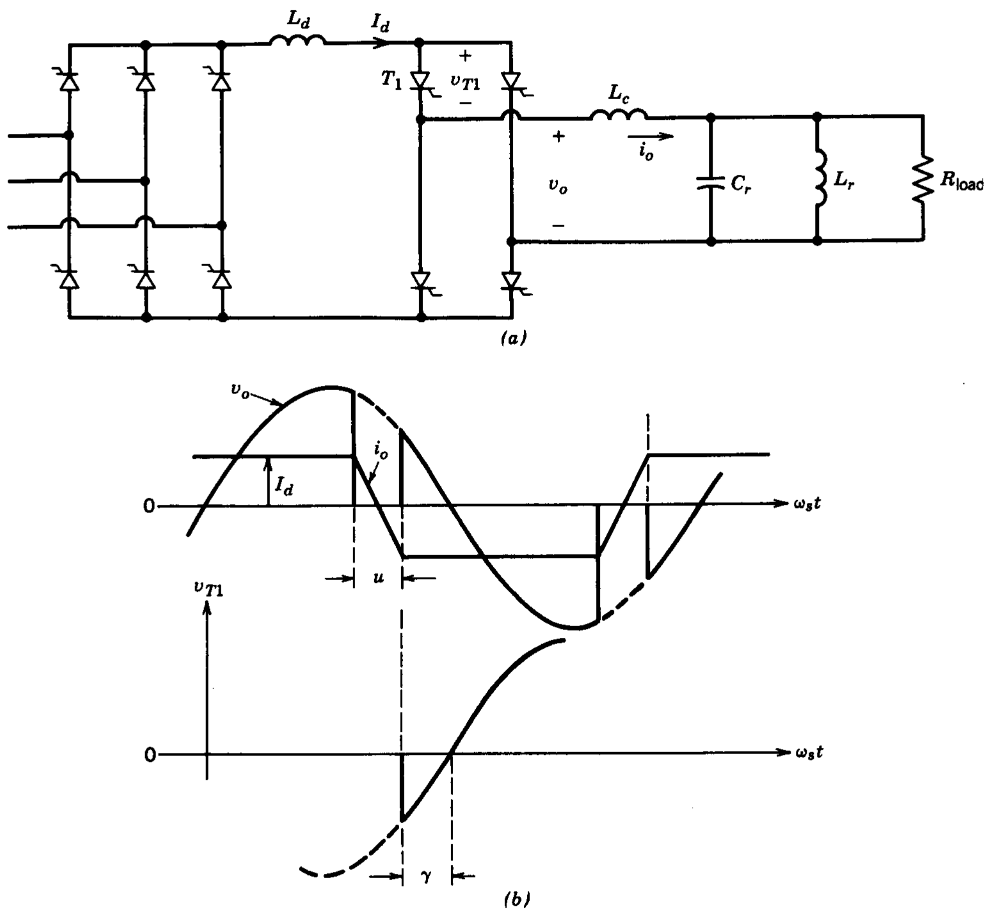


Figure 9-24 Current-source, parallel-resonant inverter for induction heating: (*a*) circuit; (*b*) waveforms.

- Using thyristors; for induction heating

Class-E Converters

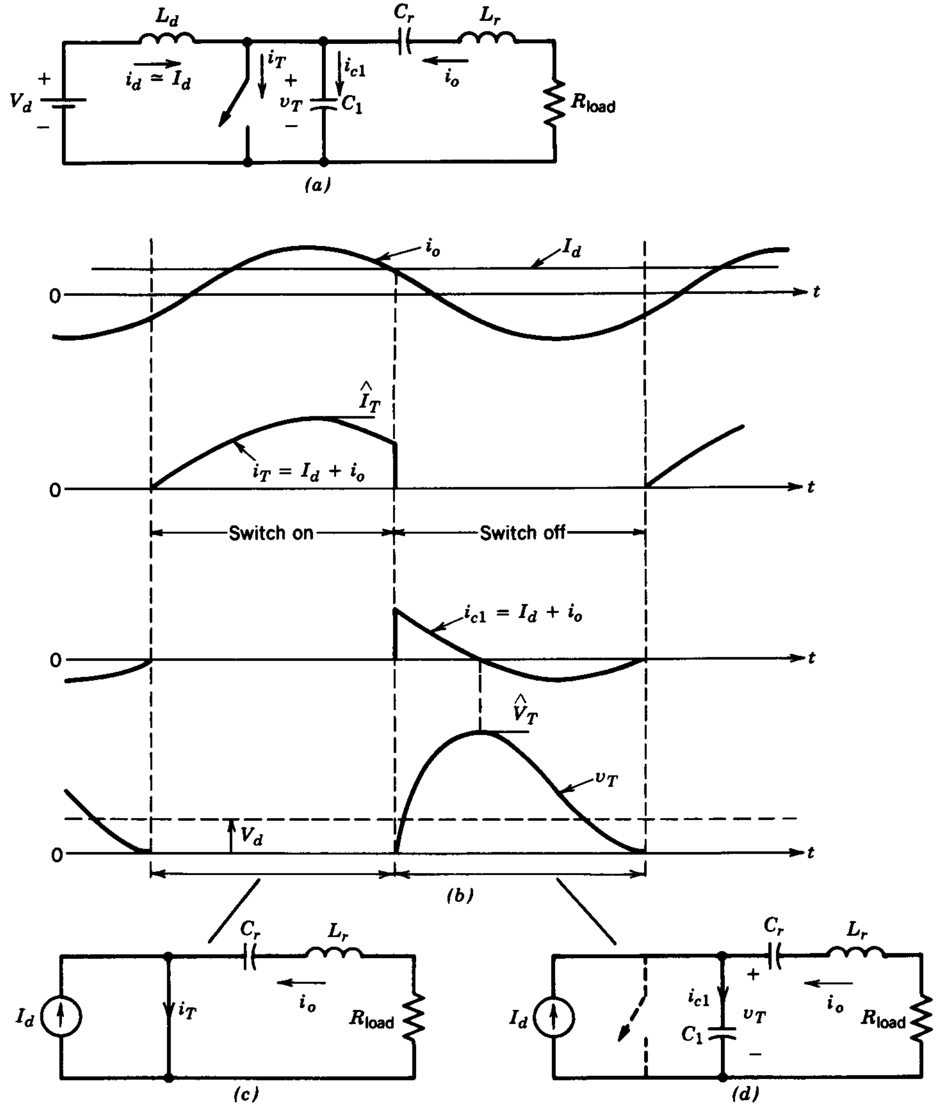


Figure 9-25 Class E converter (optimum mode, $D = 0.5$).

Optimum mode

Class-E Converters

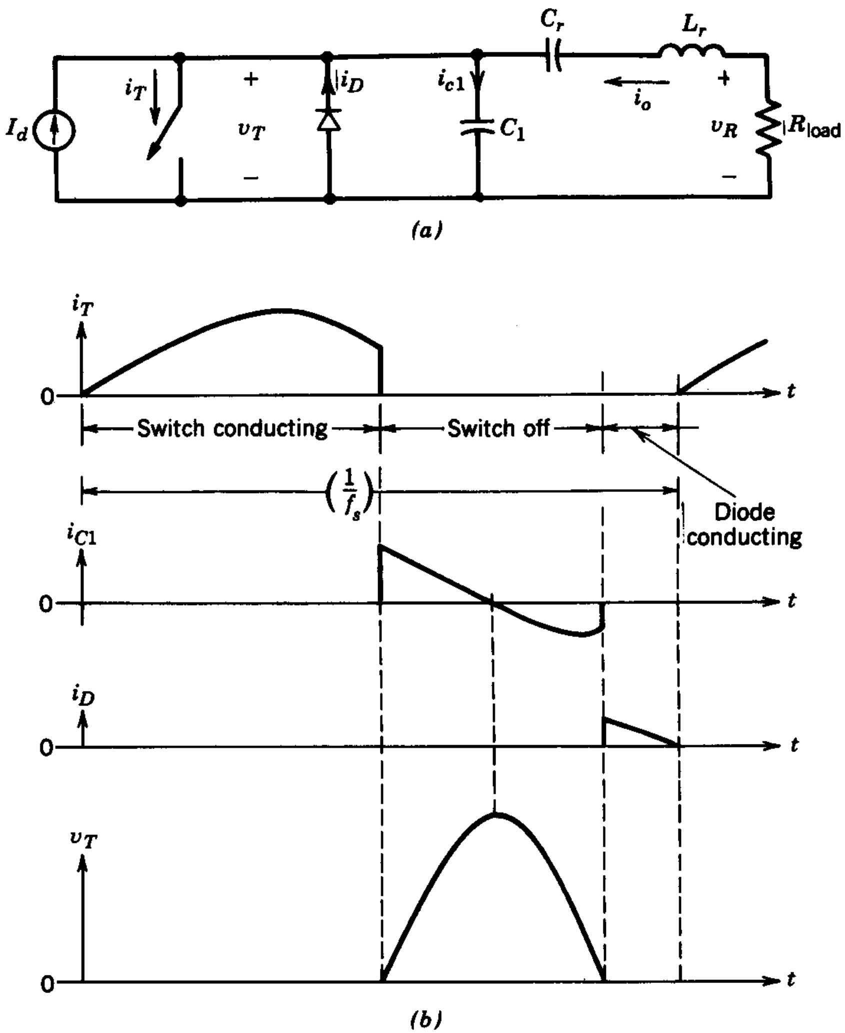
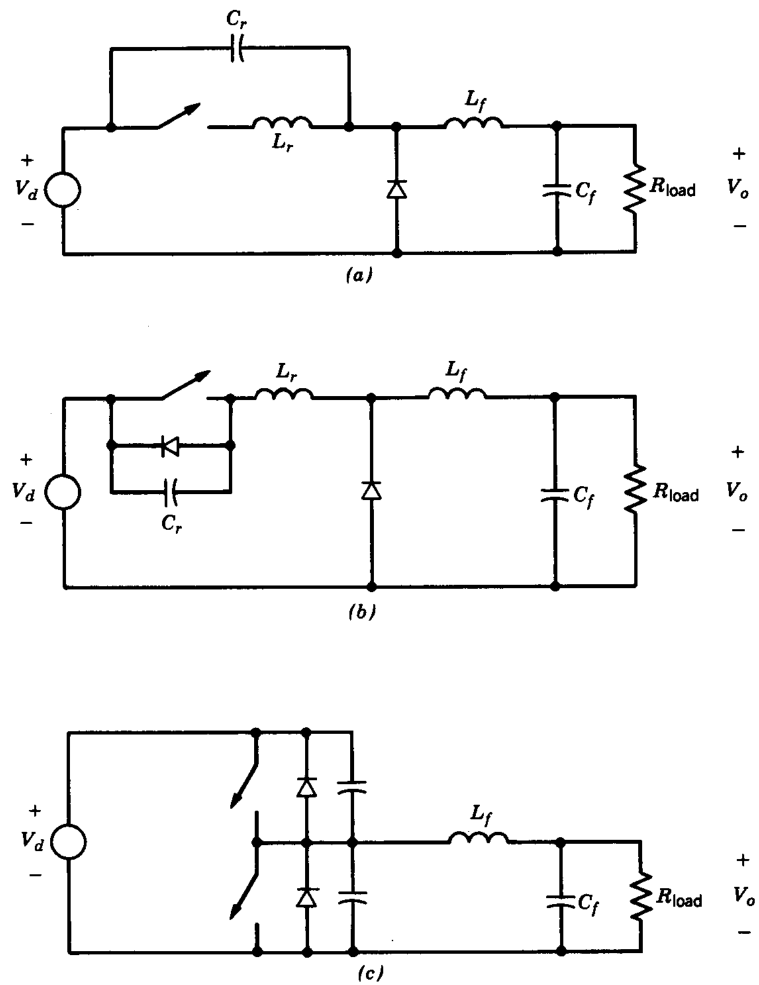


Figure 9-26 Class E converter (nonoptimum mode).

Non-Optimum mode

Resonant Switch Converters



Classifications

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).

ZCS Resonant-Switch Converter

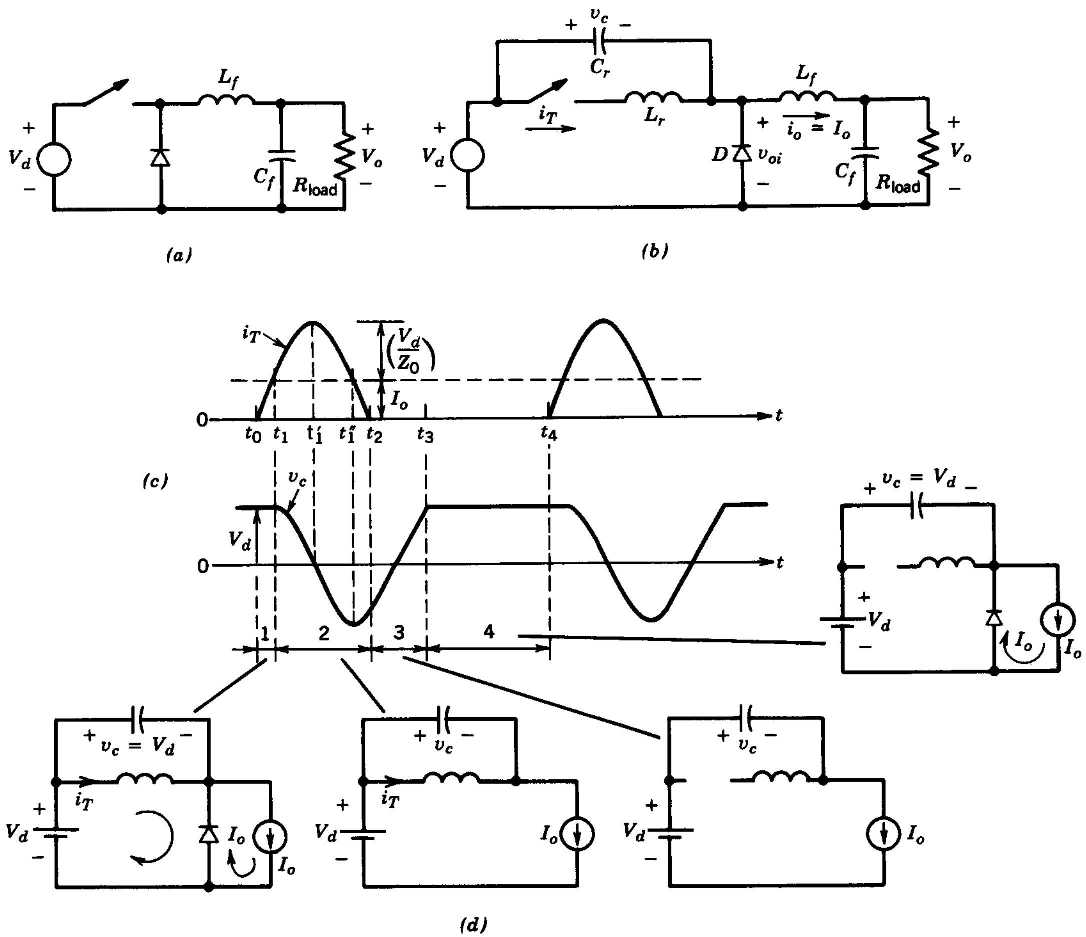


Figure 9-28 ZCS resonant-switch dc–dc converter.

- One possible implementation

ZCS Resonant-Switch Converter

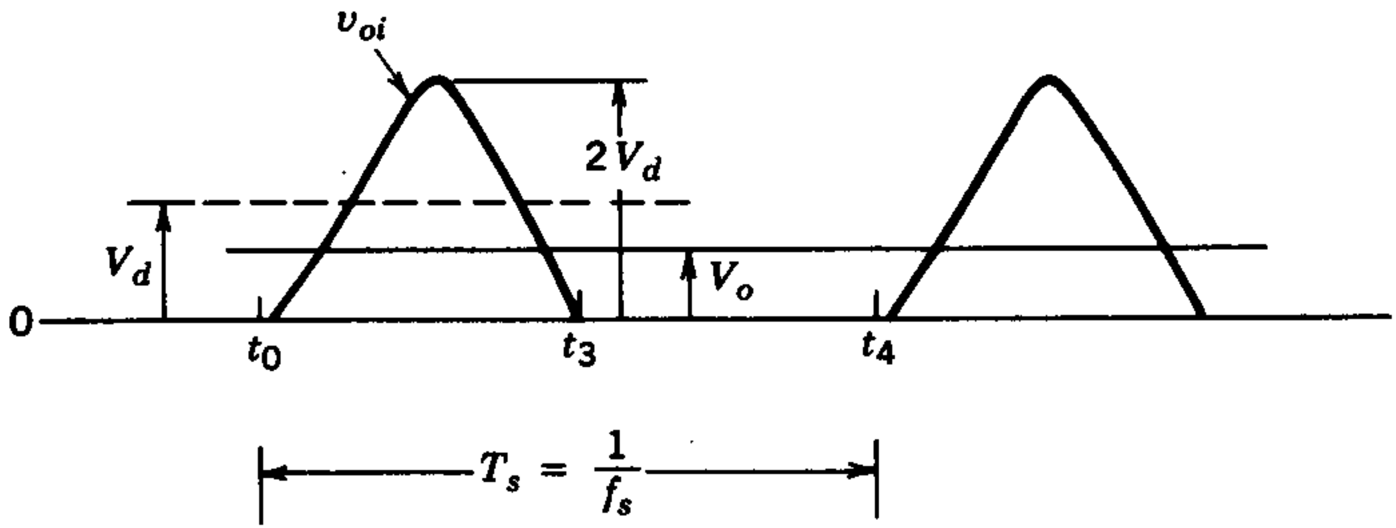


Figure 9-29 v_{oi} waveform in a ZCS resonant-switch dc–dc converter.

- Waveforms; voltage is regulated by varying the switching frequency

ZCS Resonant-Switch Converter

- A practical circuit

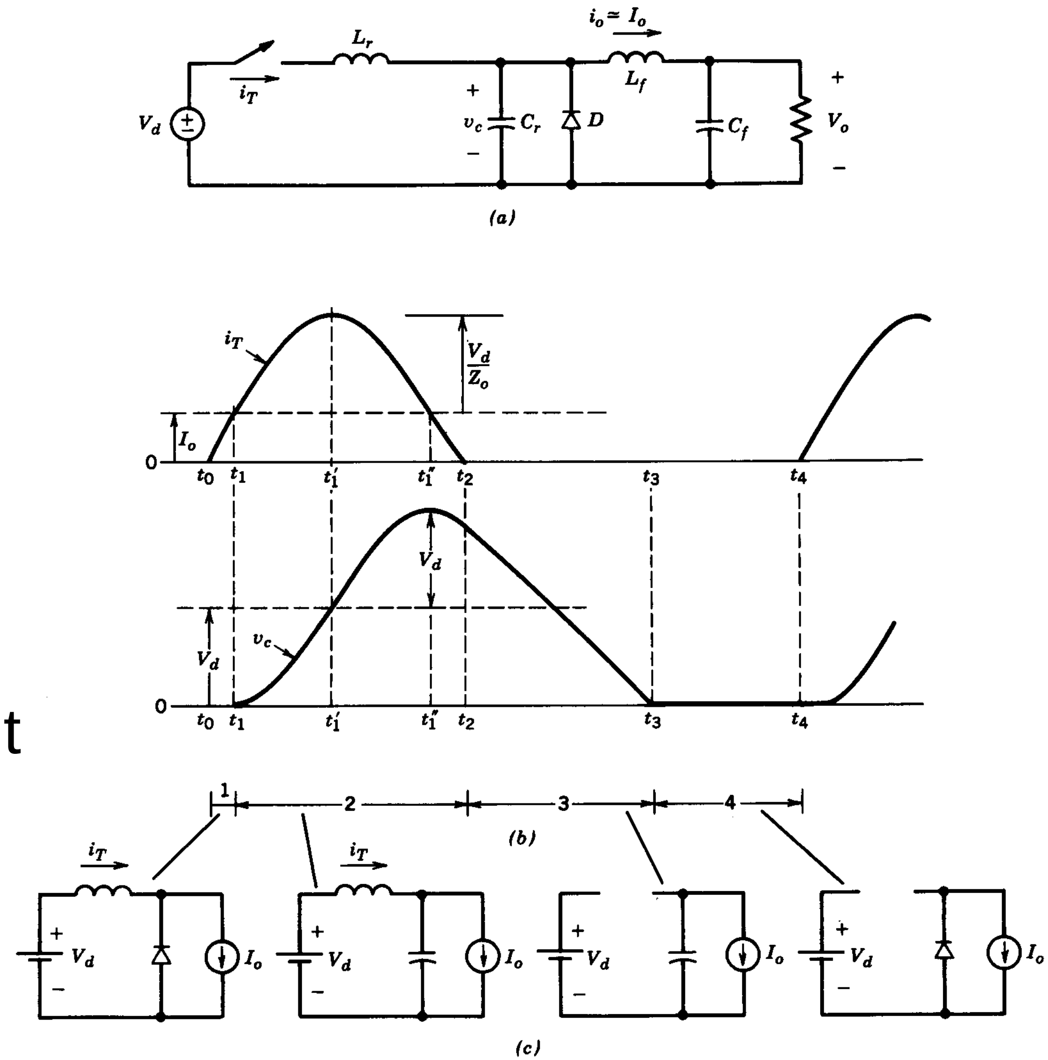


Figure 9-30 ZCS resonant-switch dc–dc converter; alternate configuration.

ZVS Resonant-Switch Converter

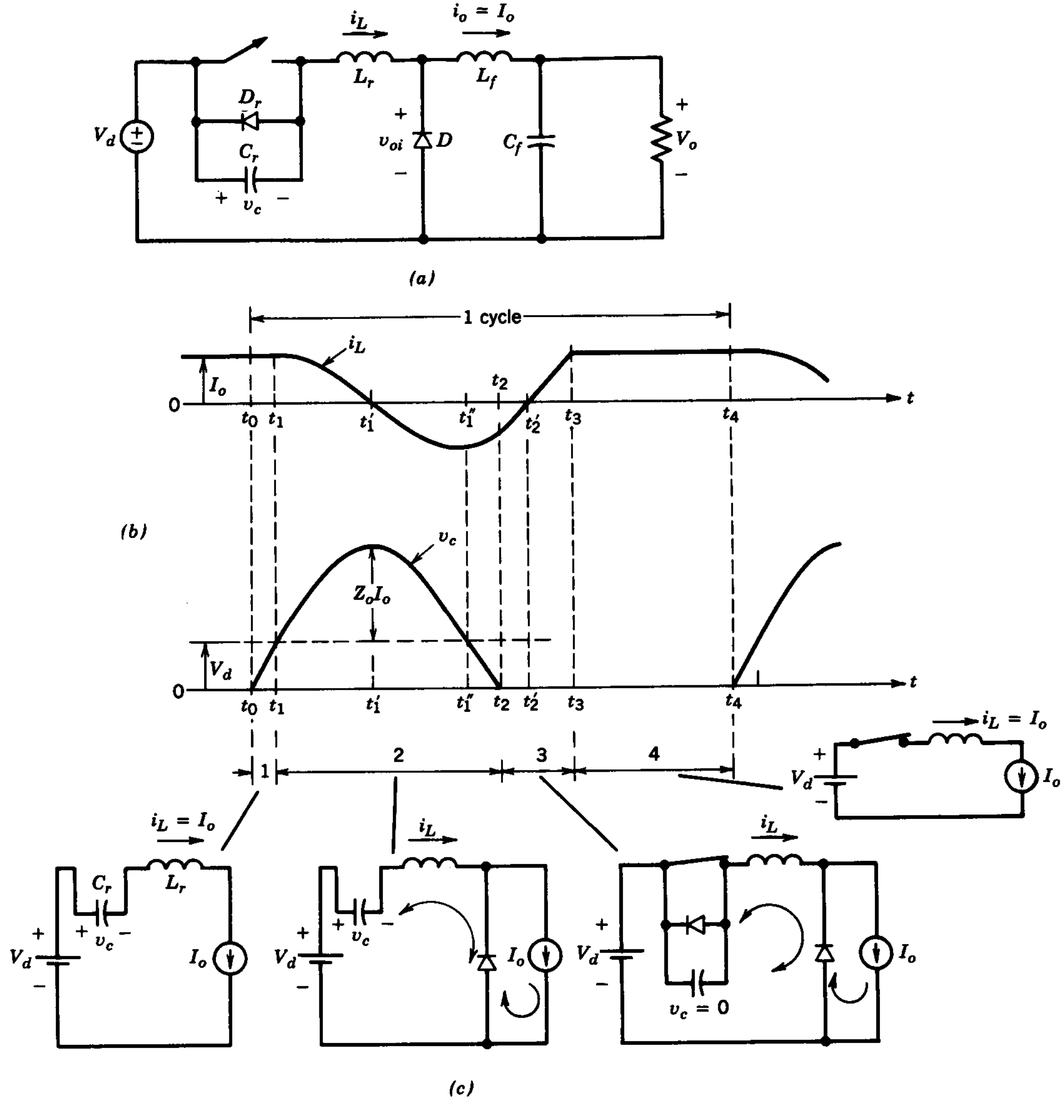


Figure 9-31 ZVS resonant-switch dc–dc converter.

- Serious limitations

ZVS Resonant-Switch Converter

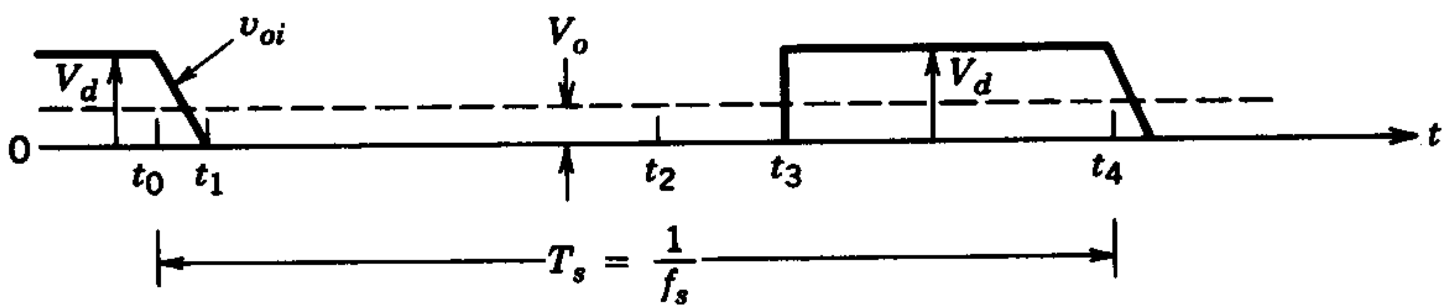


Figure 9-32 The v_{oi} waveform in a ZVS resonant-switch dc–dc converter.

- Waveforms

MOSFET Internal Capacitances

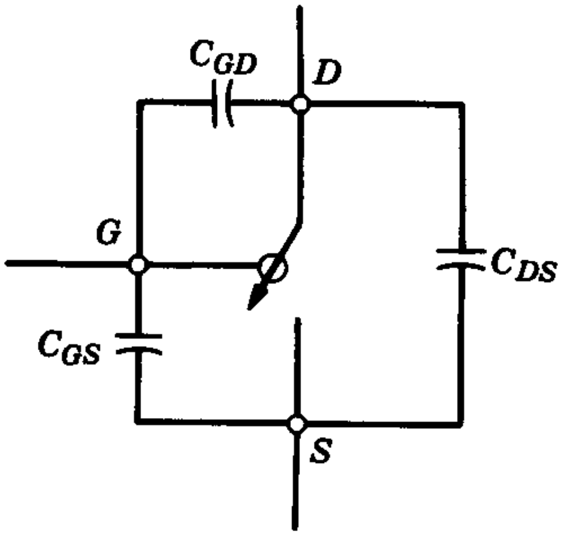


Figure 9-33 Switch internal capacitances.

- These capacitances affect the MOSFET switching

ZVS-CV DC-DC Converter

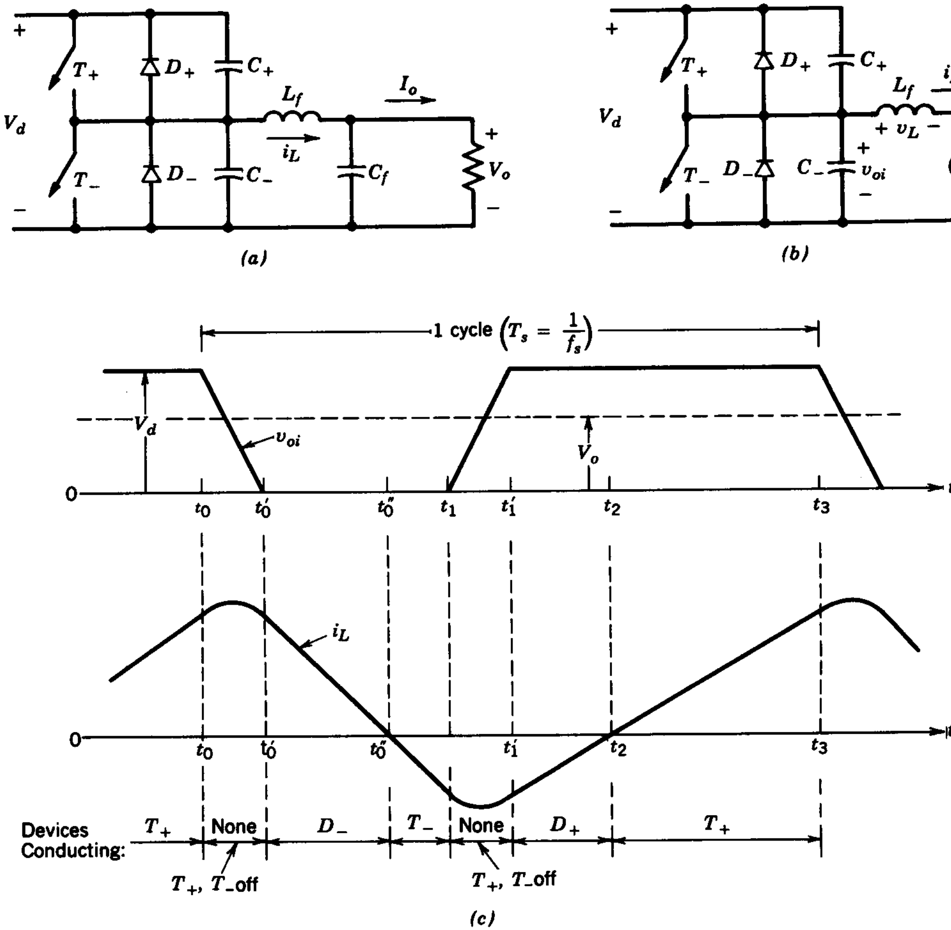


Figure 9-34 ZVS-CV dc–dc converter.

- The inductor current must reverse direction during each switching cycle

ZVS-CV DC-DC Converter

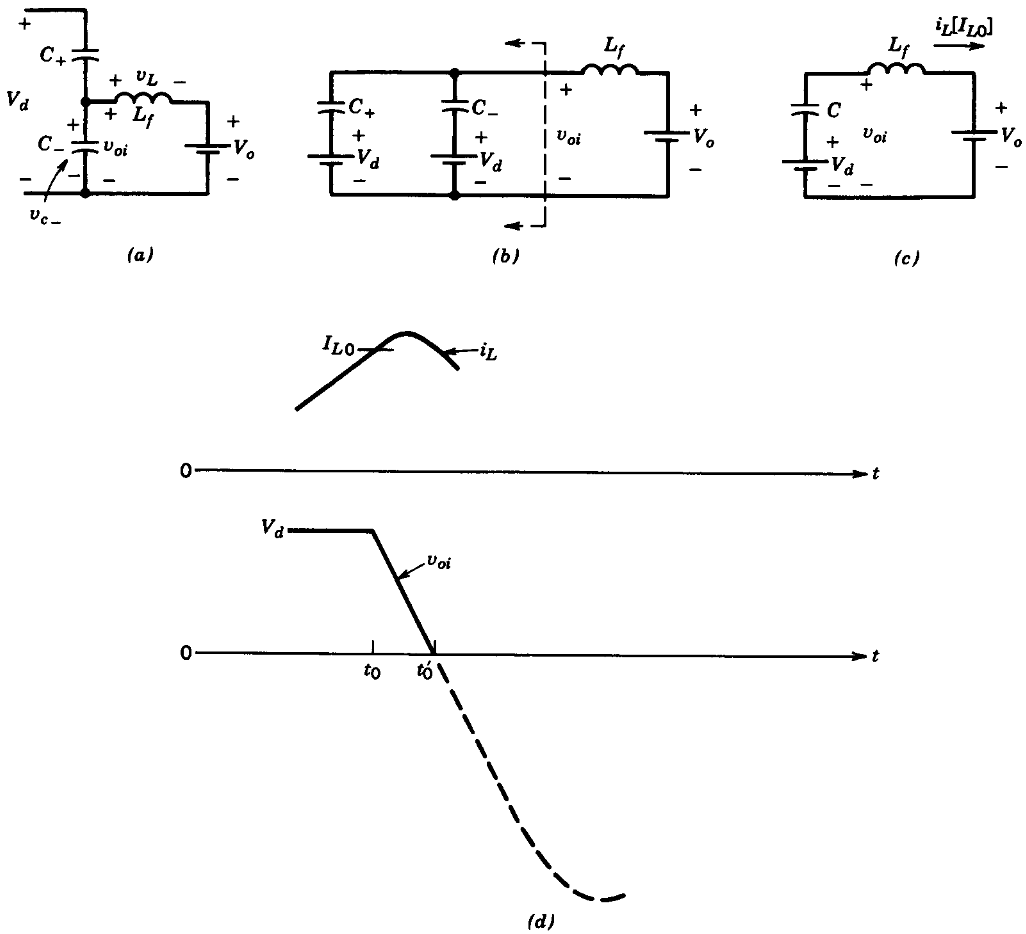


Figure 9-35 ZVS-CV dc−dc converter; T_+, T_- off.

- One transition is shown

ZVS-CV Principle Applied to DC-AC Inverters

- Very large ripple in the output current

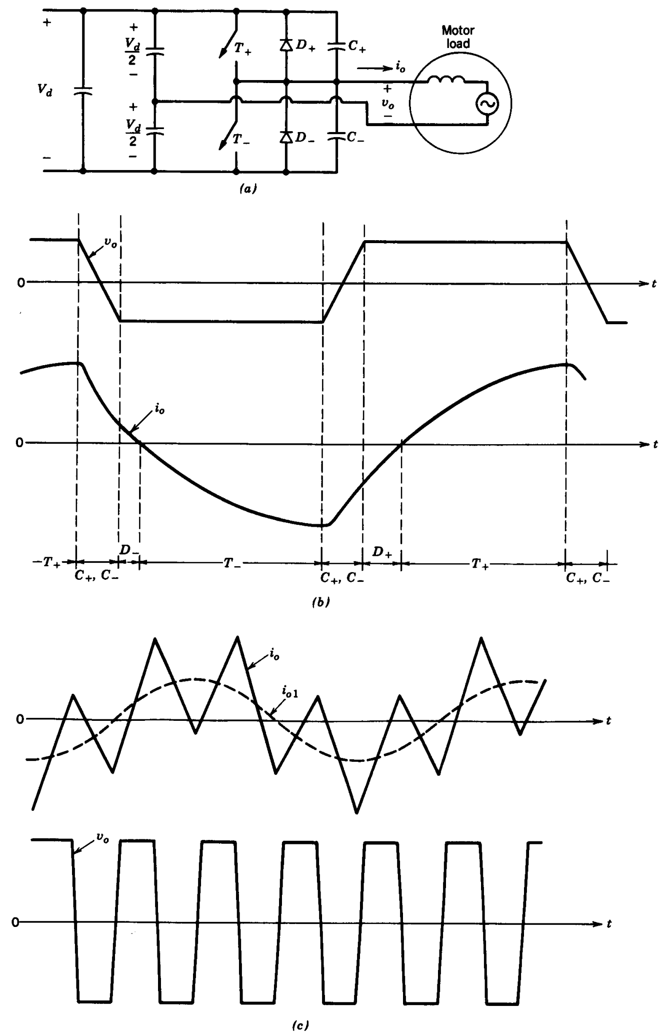


Figure 9-36 ZVS-CV dc-to-ac inverter: (*a*) half-bridge; (*b*) square-wave mode; (*c*) current-regulated mode.

Three-Phase ZVS-CV DC-AC Inverter

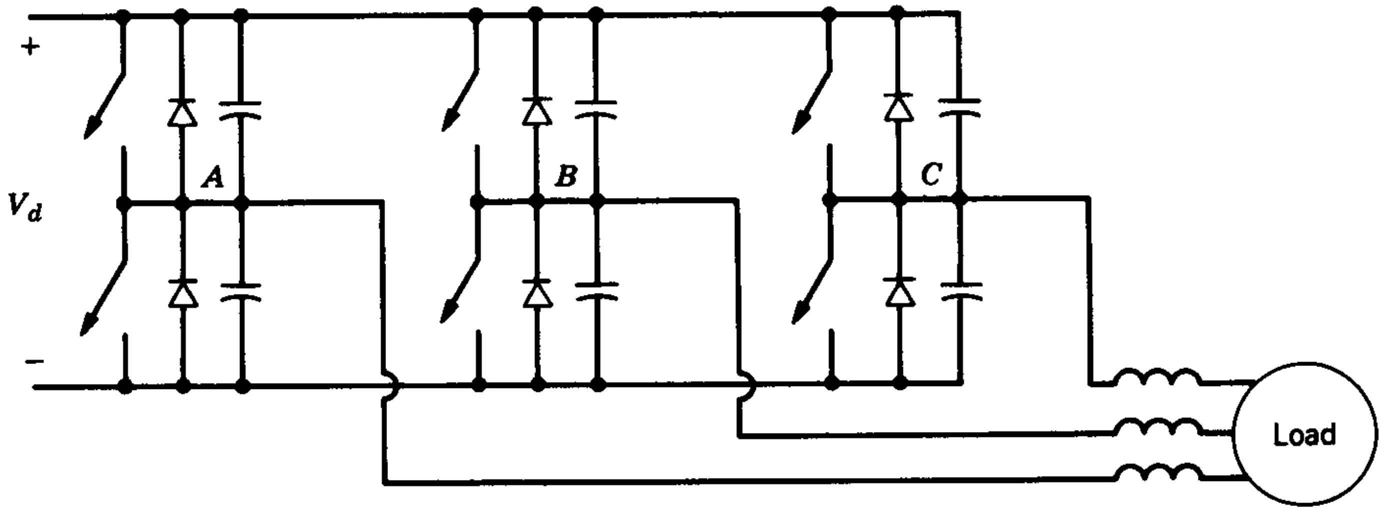


Figure 9-37 Three-phase, ZVS-CV dc-to-ac inverter.

- Very large ripple in the output current

Output Regulation by Voltage Control

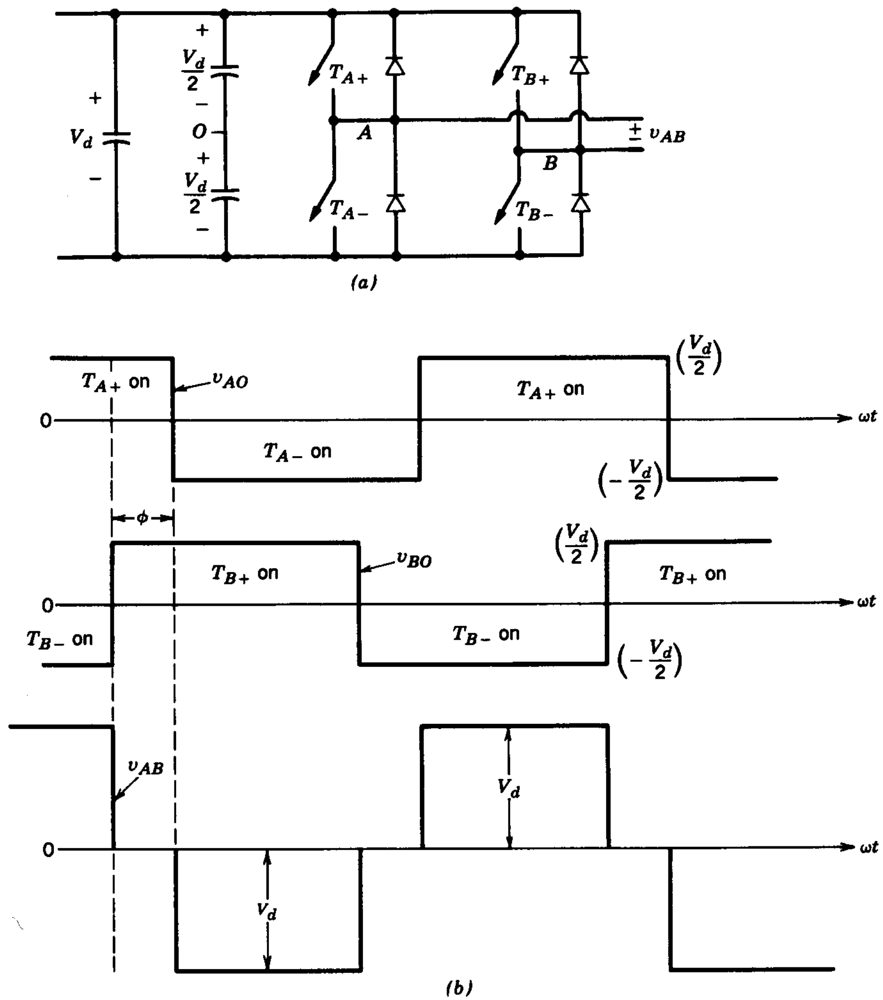


Figure 9-38 Voltage control by voltage cancellation: conventional switch-mode converter.

- Each pole operates at nearly 50% duty-ratio

ZVS-CV with Voltage Cancellation

- Commonly used

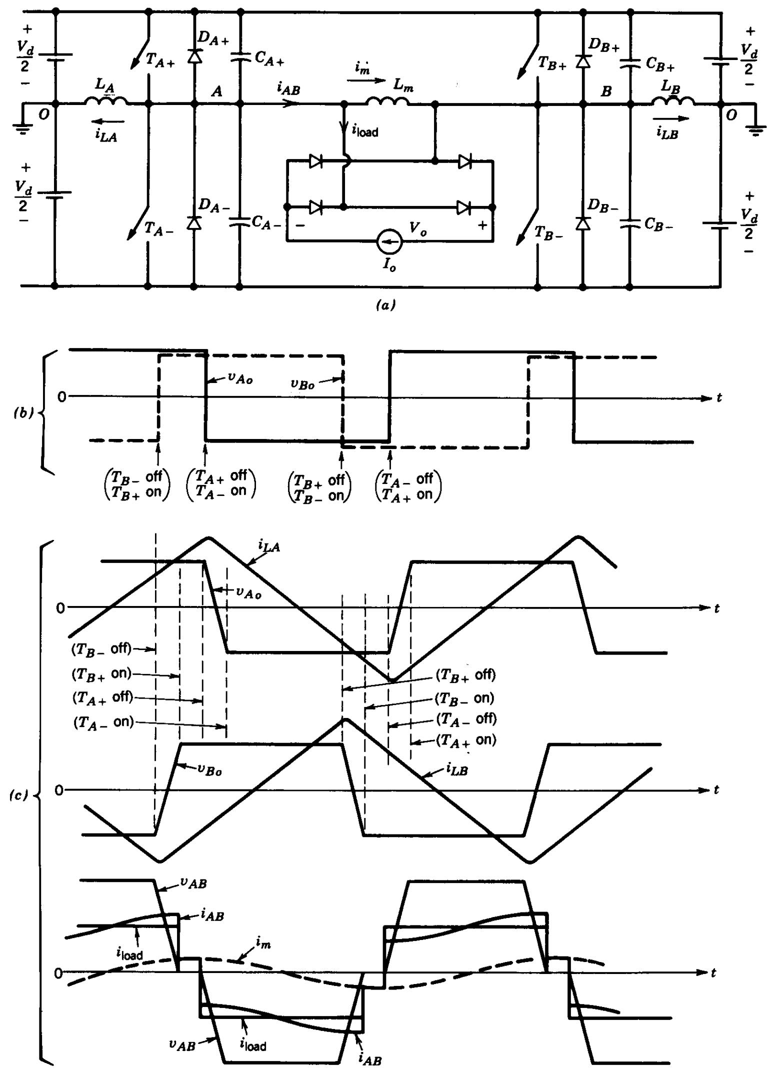
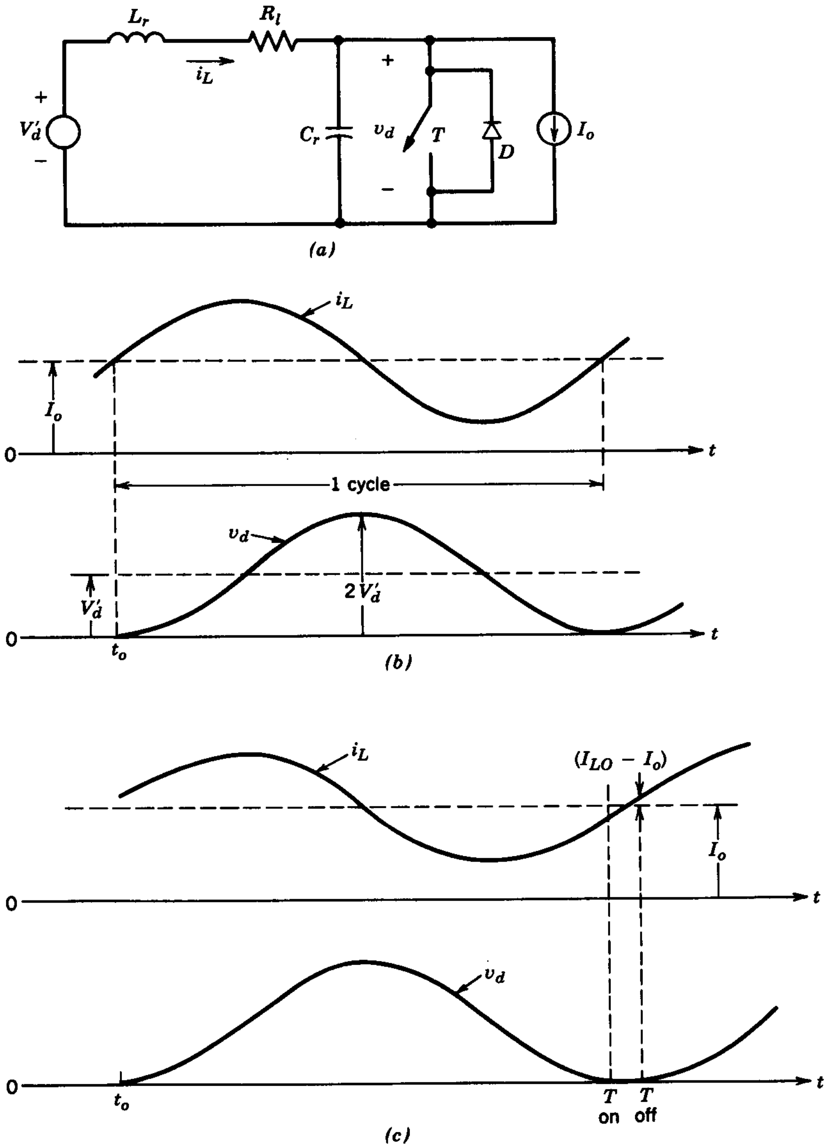


Figure 9-39 ZVS-CV full-bridge dc–dc converter: (*a*) circuit; (*b*) idealized switch-mode waveforms; (*c*) ZVS-CV waveforms.

Resonant DC-Link Inverter



- The dc-link voltage is made to oscillate

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

Three-Phase Resonant DC-Link Inverter

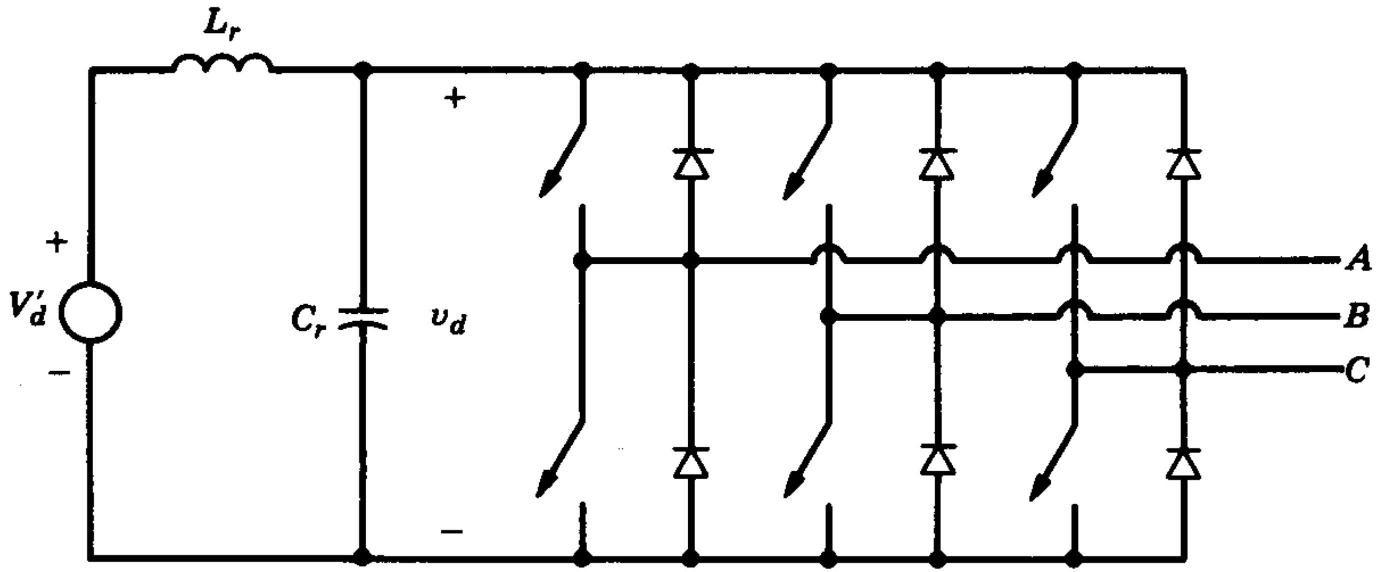


Figure 9-41 Three-phase resonant-dc-link inverter.

- Modifications have been proposed

High-Frequency-Link Inverter

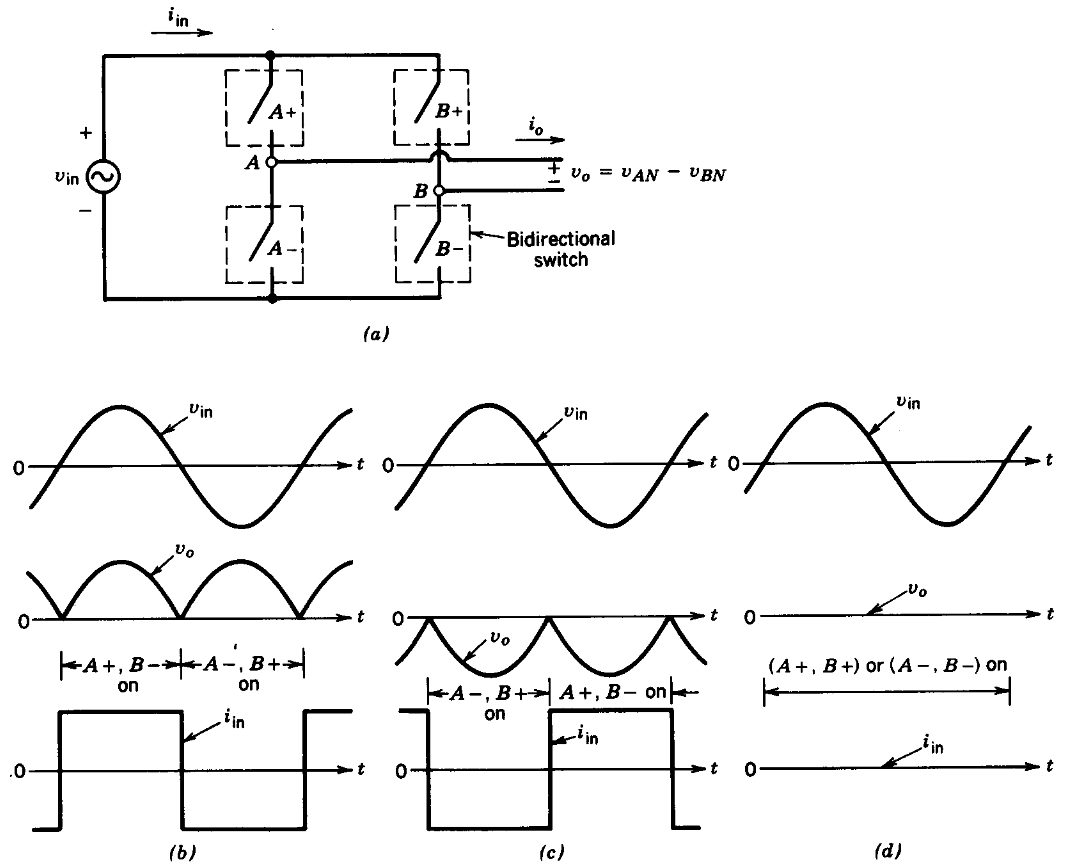


Figure 9-42 High-frequency-link integral-half-cycle inverter.

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

High-Frequency-Link Inverter

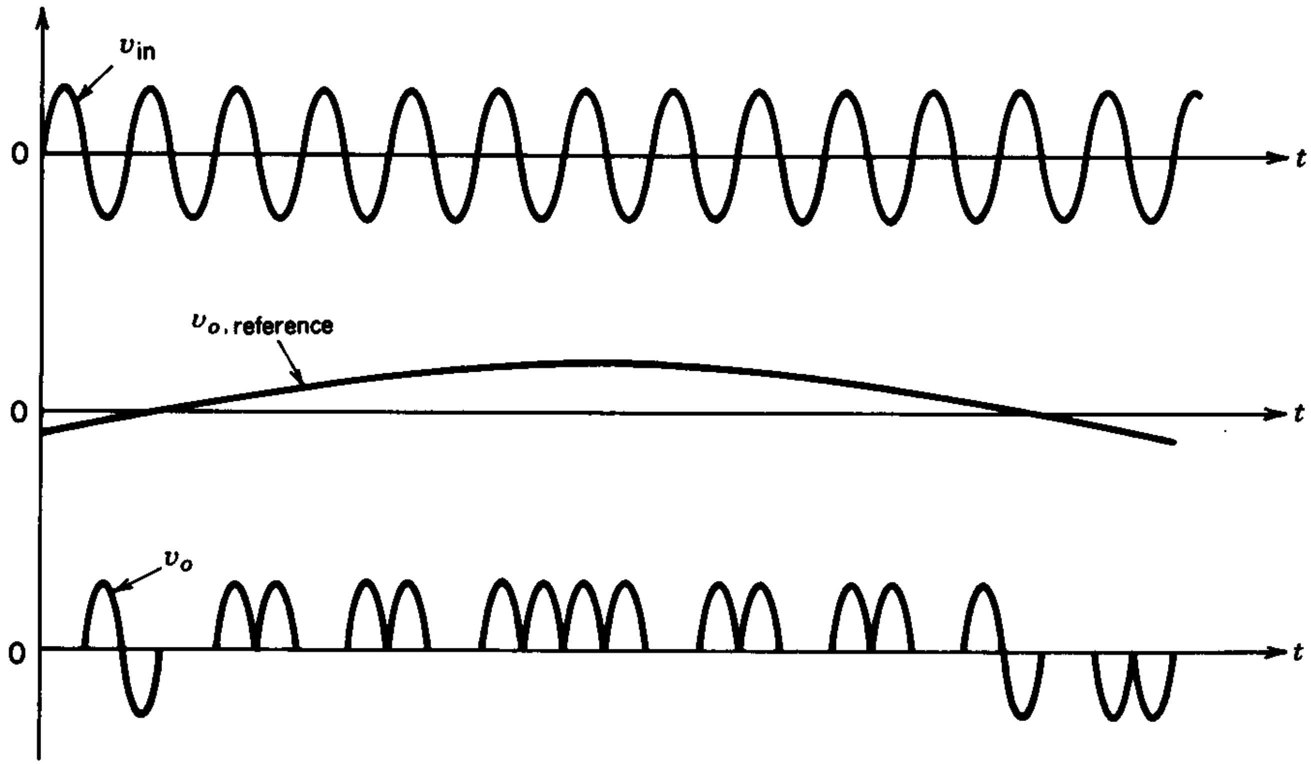


Figure 9-43 Synthesis of low-frequency ac output.

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

High-Frequency-Link Inverter

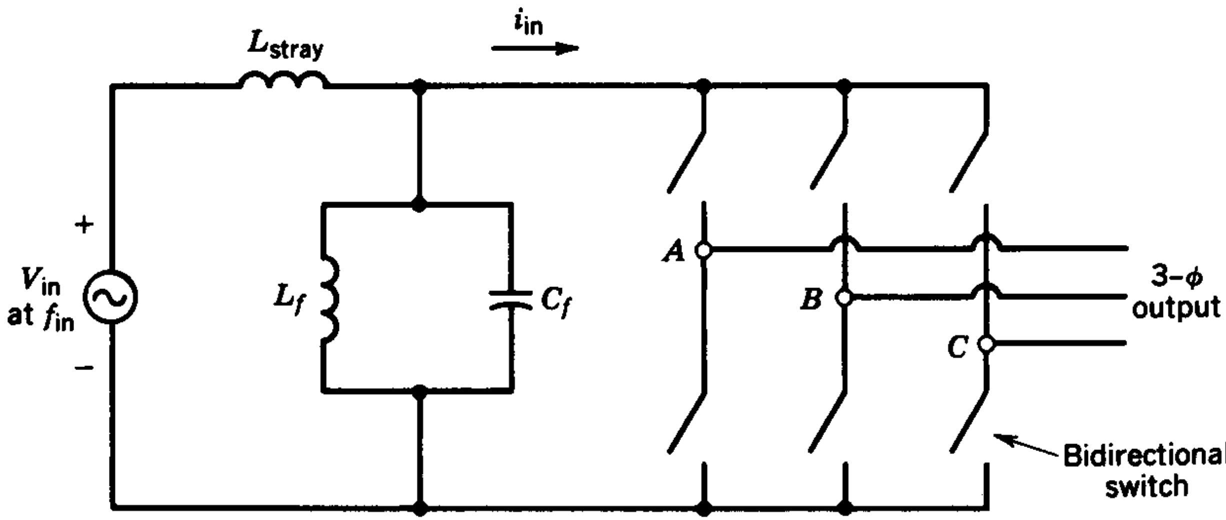


Figure 9-44 High-frequency ac to low-frequency three-phase ac converter.

- Shows how to implement such an inverter