# CONTROL OF ELECTRICAL DRIVE SYSTEMS AND CONVERTERS

**Soft-switching in PWM – converters**

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# Control of Electrical Drive Systems and Converters

**Lecture 1. Three phase converters**

Sinusoidal modulation, harmonics, square wave operation, dc link current, converter model, dead-time, current control.

Problems: 8-10 and 8-7

*Page: 225-243 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

**Lecture 2. Three-phase modulation**

Sinusoidal modulation with added 3rd harmonic, 60 deg modulation, space vector modulation, discontinuous modulation.

*Papers: The use of harmonic distortion to increase the output voltage, Simple Analytical and Graphical Methods for Carrier-Based PWM-VSI Drives*

**Lecture 3. Utility interface applications of power electronics**

Interconnection of energy sources to the grid, control of switch mode interface, improved single and three phase utility interface.

*Page: 475-480, 494 – 502 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

**Lecture 4. Variable-frequency converter classifications**

PWM-VSI, CSI , electromagnetic braking, speed control, square-wave vsi drive

*Page: 418-432 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

**Lecture 5. Soft-switching in PWM – converters**

Hard and soft switching, classification of converters, basic resonant circuits, ZVS – VSI converters, phase shifted converters, resonant link inverters.

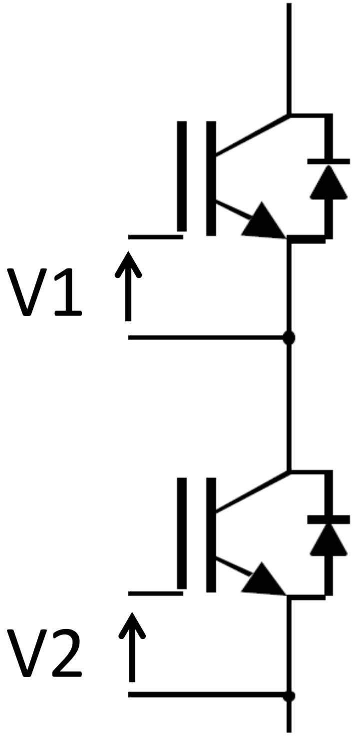
*Page: 249-258,, 280-291 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

# Soft-switching in PWM – converters

- Driver circuits for power switches
- Hard switching → losses during turn-ON/OFF
- Zero-voltage and zero-current switching
- Resonant circuits
- Series/Parallel Load Resonant (SLR) Converter
- ZVS-CV DC-DC and DC-AC Converter
- Resonant DC-Link Inverter
- High-Frequency-Link Inverter
- Overview of the power converters

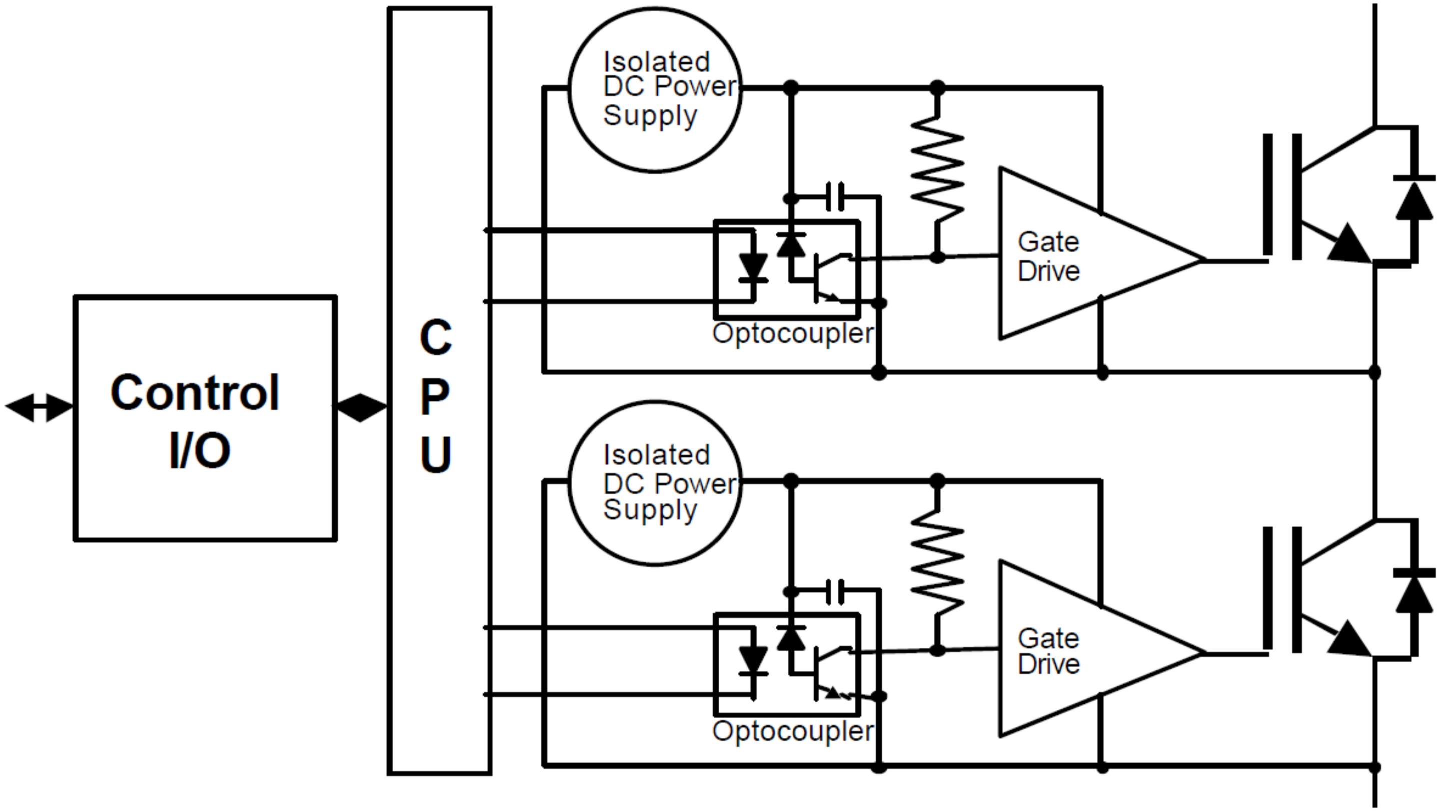
# Driver circuits for the power switches

- To switch on an IGBT a positive voltage has to be applied  on the Gate-Emitter pins
- To switch off, zero or negative voltage has to be applied

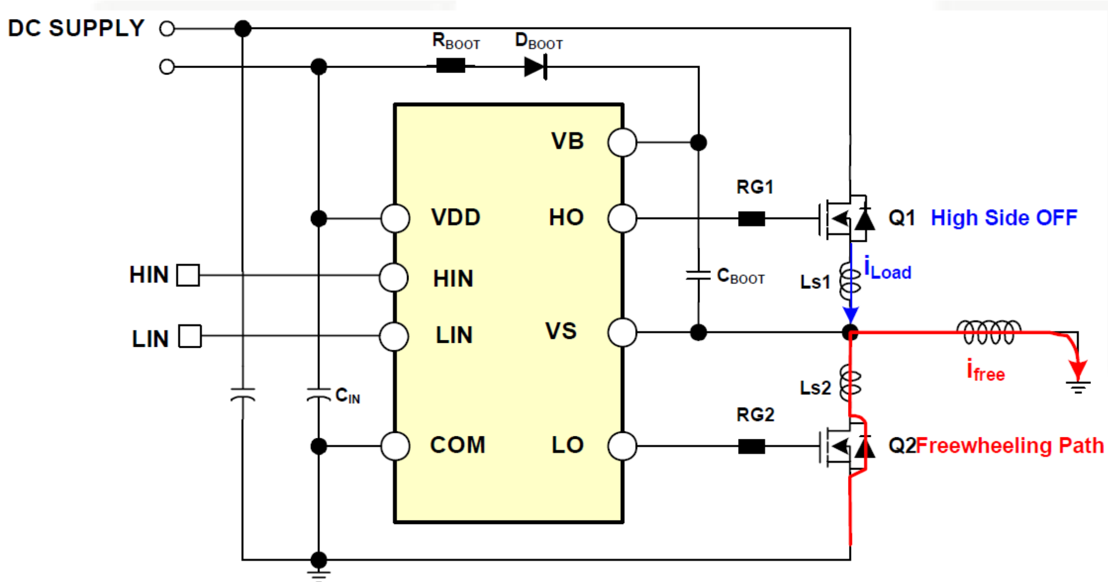


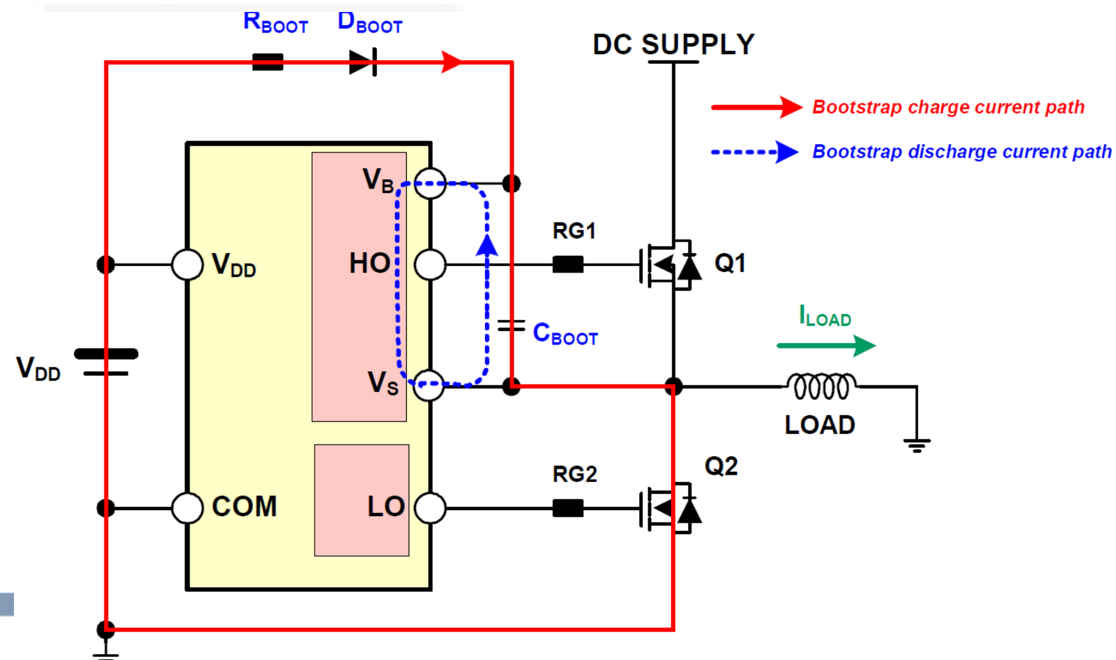

- Where would you connect the ground of the two voltage sources V1 and V2?

# Driver circuit with Isolated DC supply

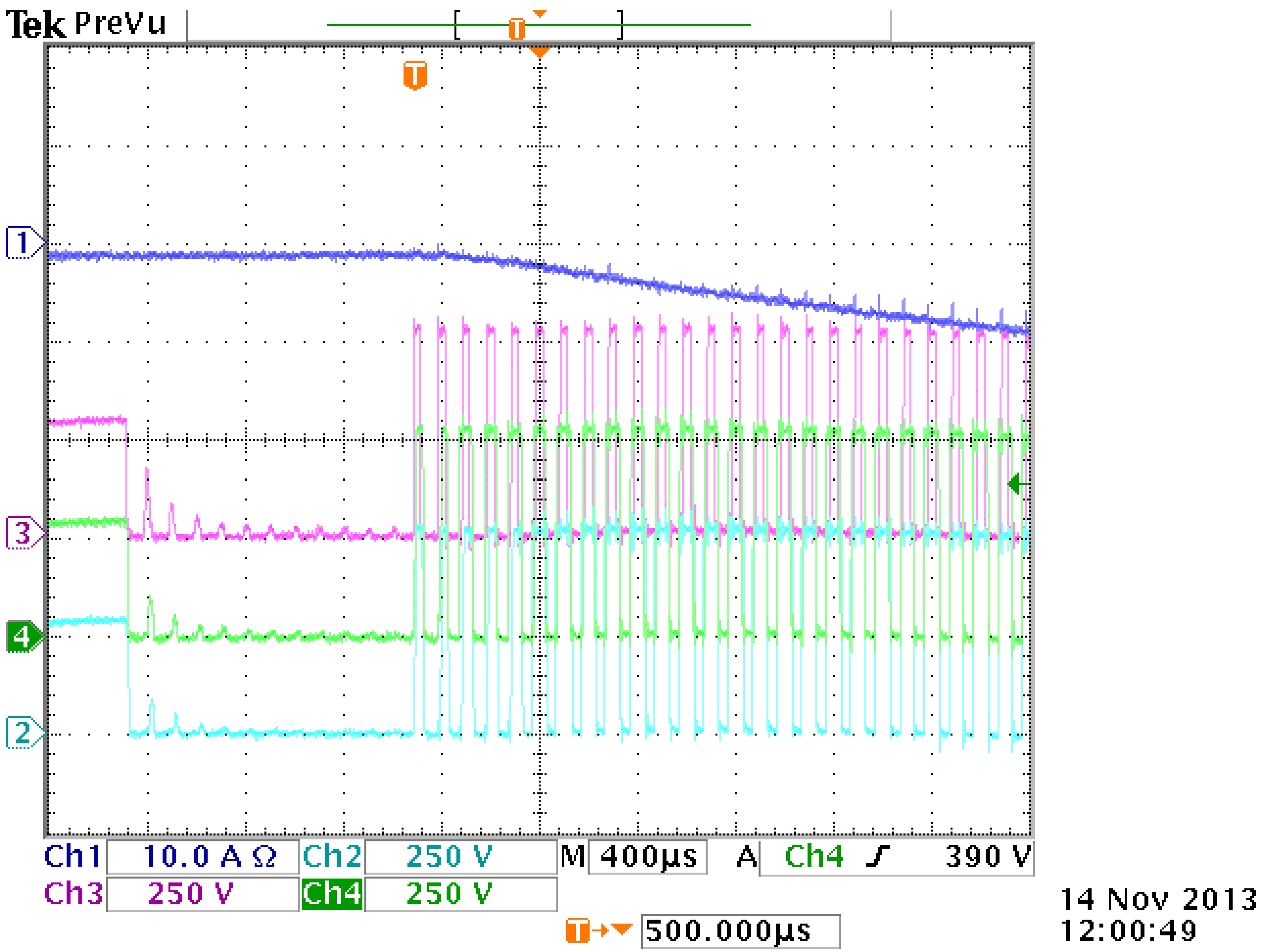


# Bootstrap circuit



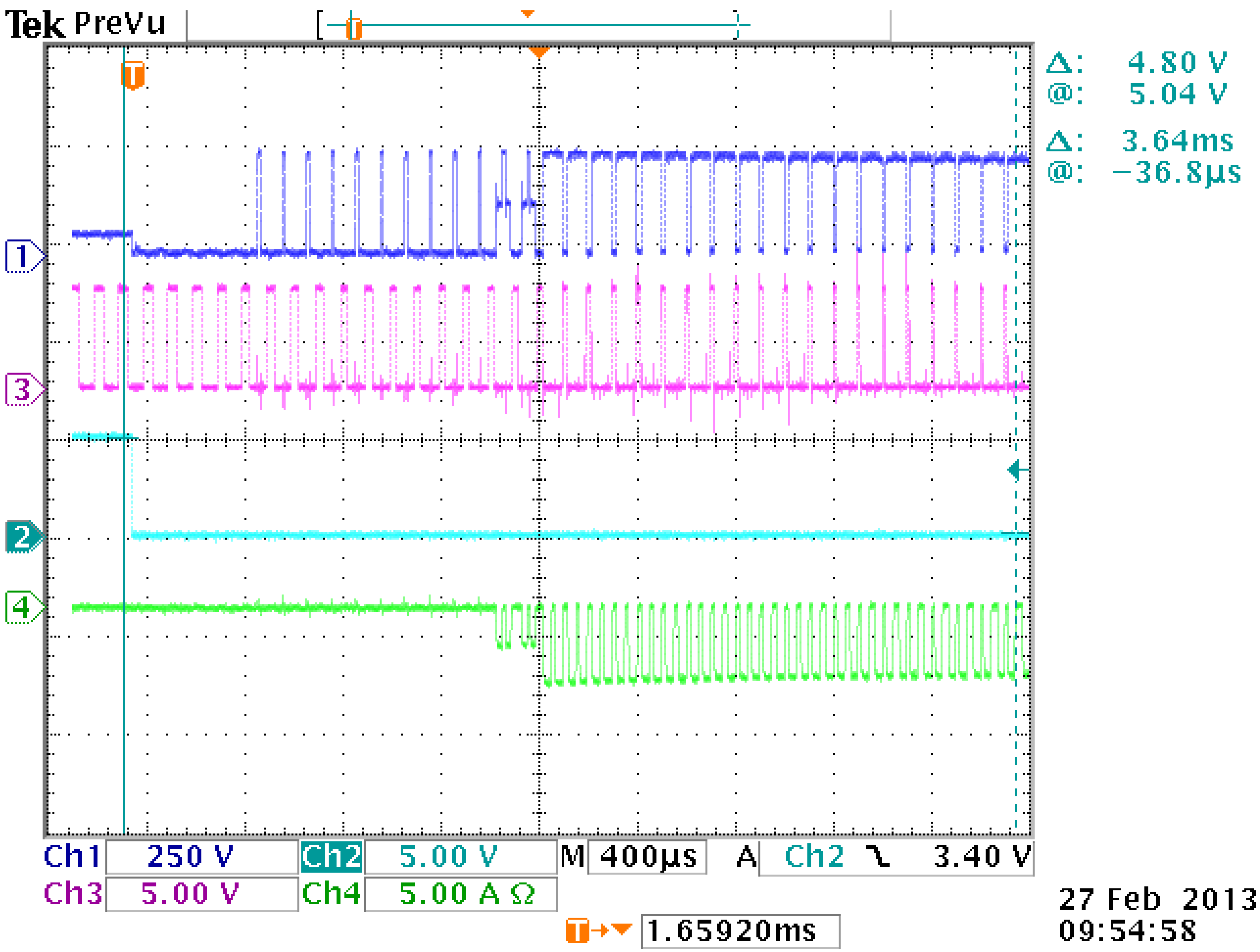



# Danfoss FC302 – IPC3




Ch1 – load current; Ch2-Ch3-Ch4 – output of leg A-B-C

# Danfoss FC302 – IPC3

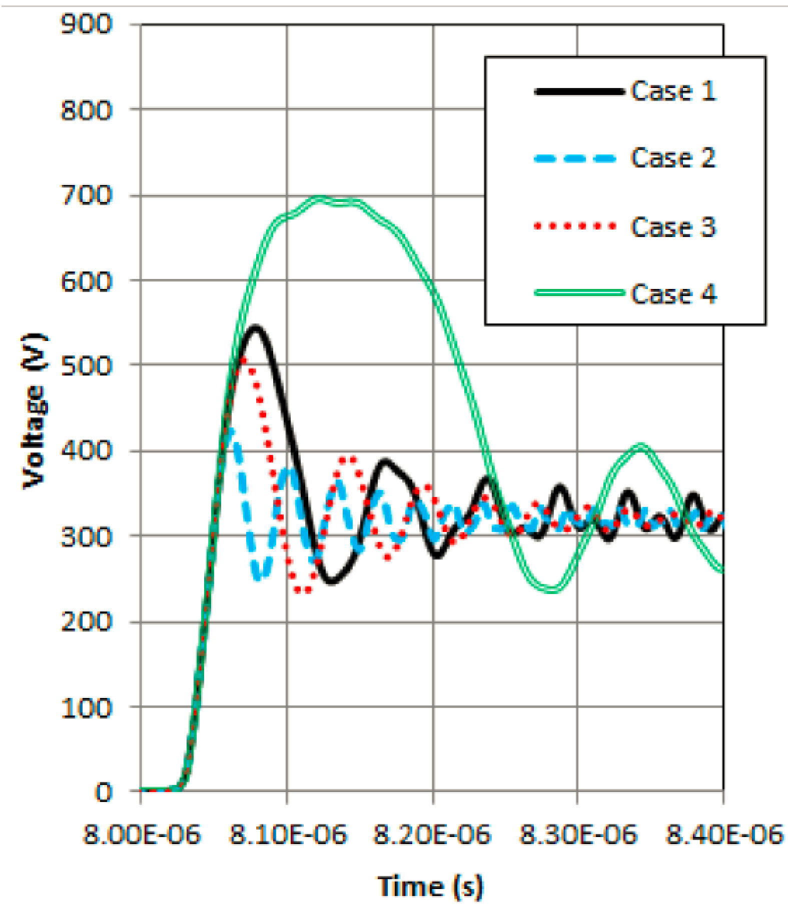


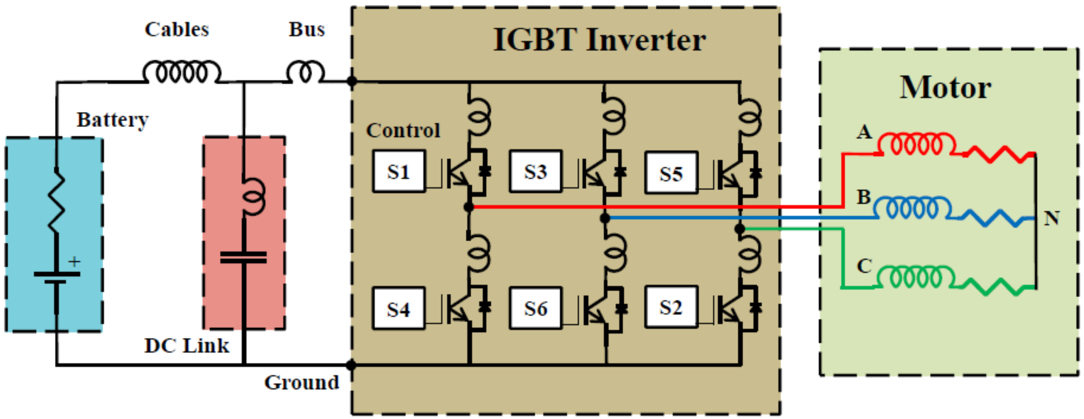

Ch1 – converter output voltage ($V_{AB}$); Ch2 – ENABLE signal

Ch3 – PWM gate signal; Ch4 – resistive current

# Effects of the parasitic inductance

- Large overshoot on the IGBT voltage is caused by the cable/track inductance



# Hard switching of one inverter Leg

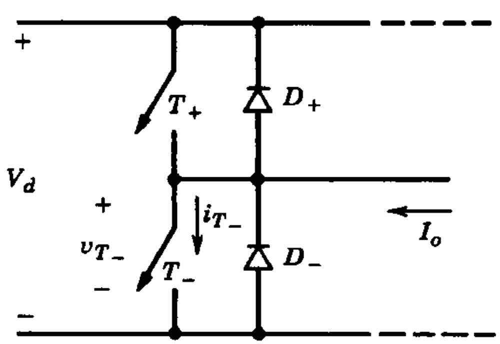



Figure 9-1

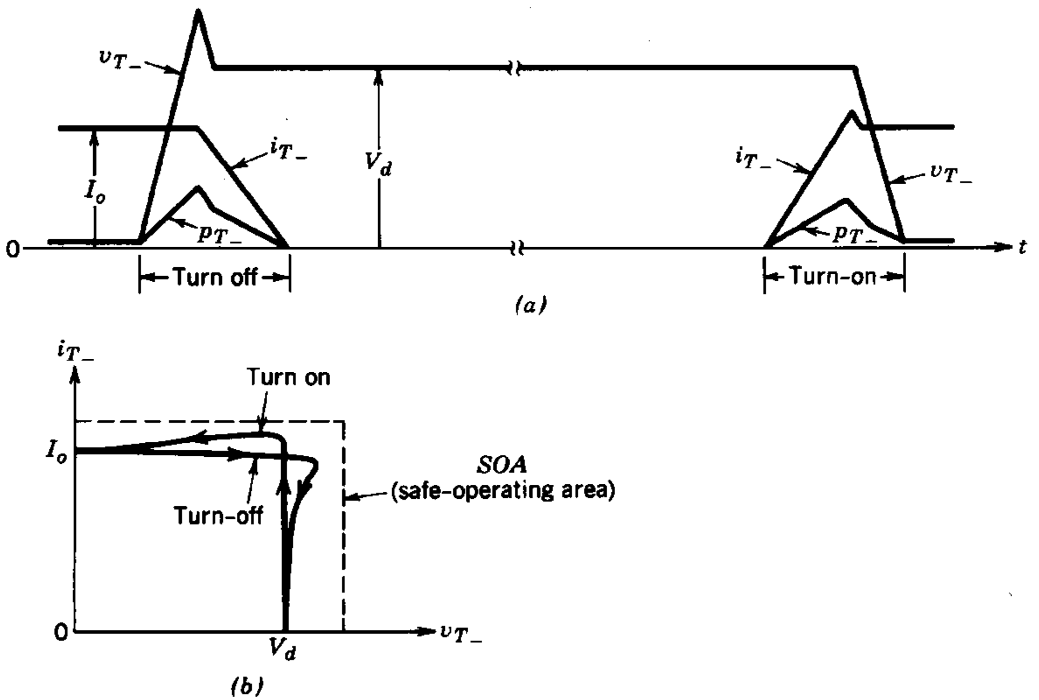



**Figure 9-2** Switch-mode inductive current switchings.

- During the turn-on-off losses appear
- The power modules require cooling

# Zero-voltage and zero-current switching

- Turn-off snubber circuits reduce the switch stress
- The losses are transferred in the snubber components (passive clamping)
- Passive clamping: the extra energy is burned on a resistor
- Active clamping improves the overall efficiency

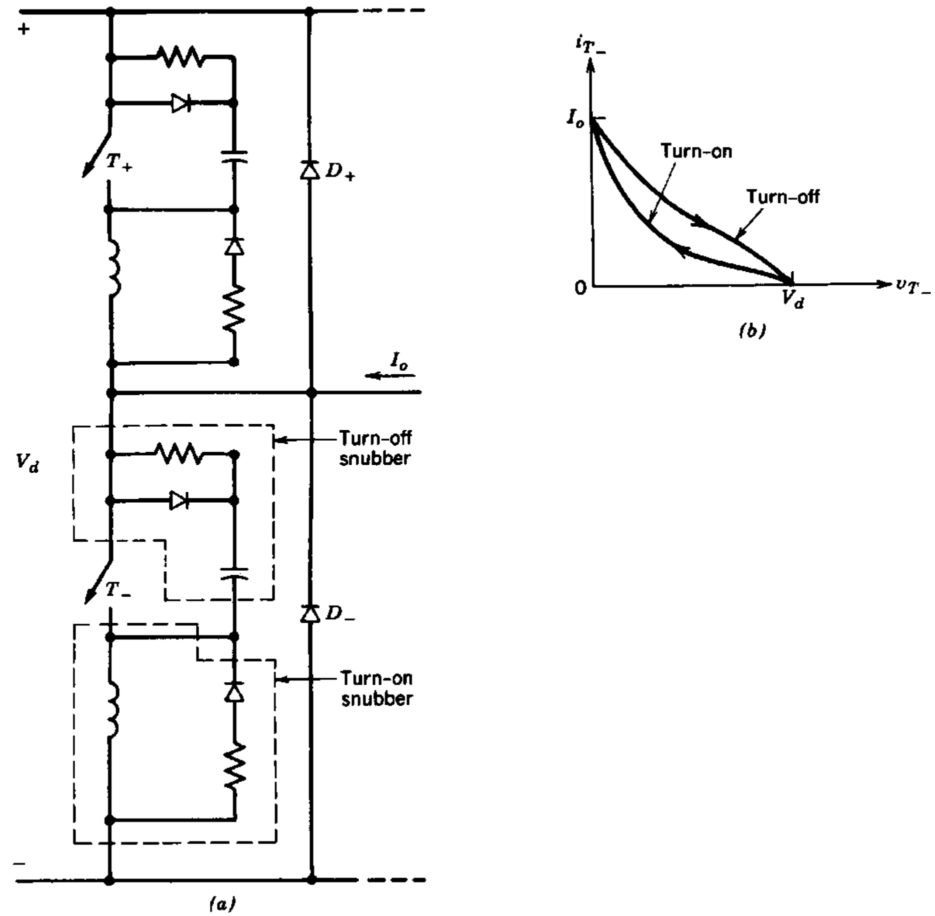
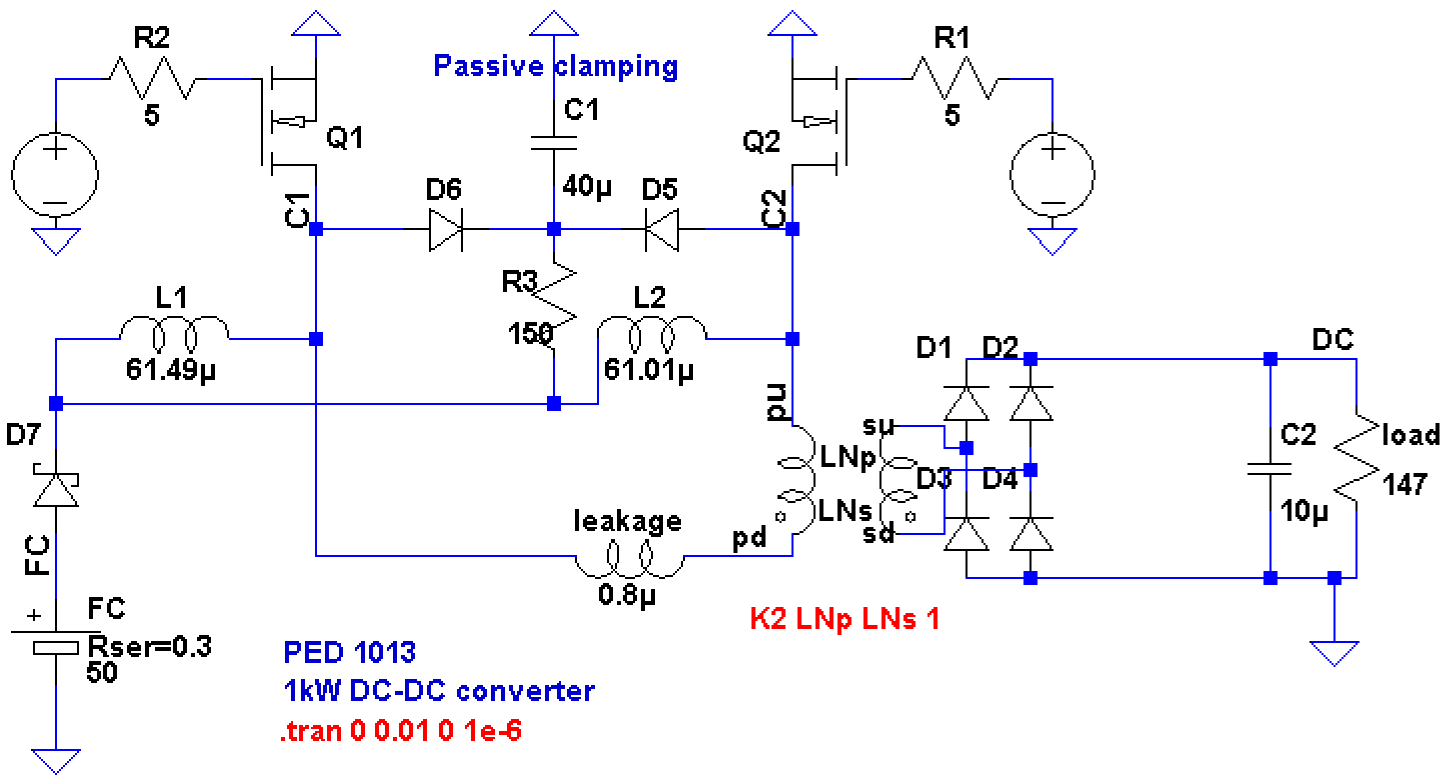



**Figure 9-3** Dissipative snubbers: (*a*) snubber circuits; (*b*) switching loci with snubbers.

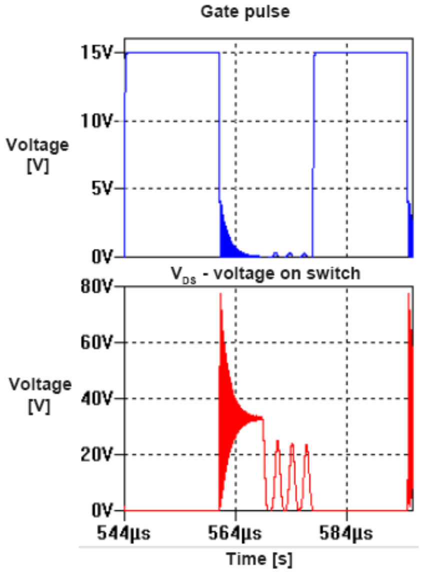
# Switch protection (push-pull converter)

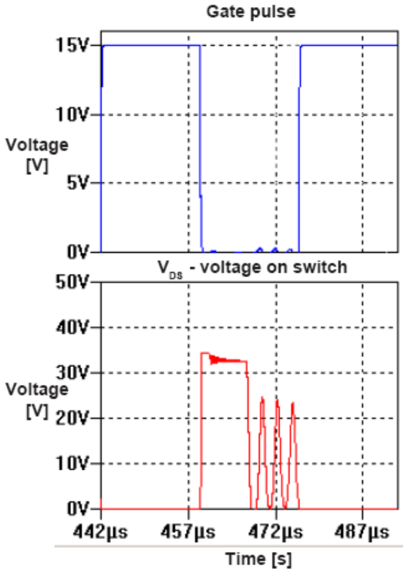
- Transformer leakage inductance → voltage overshoot at turn-OFF
- MOSFET needs protection → RCD voltage clamping snubber



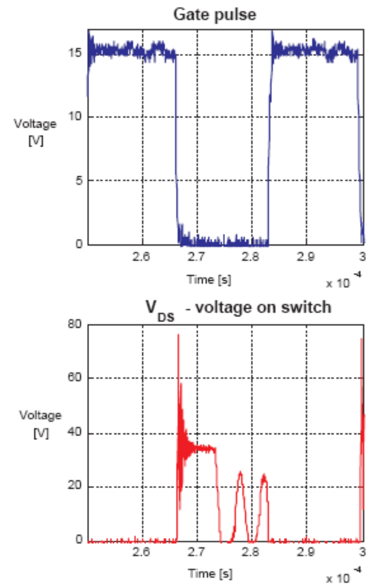
# RCD snubber

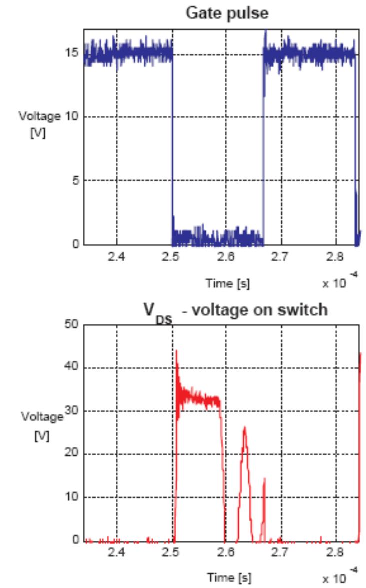
## Simulation results



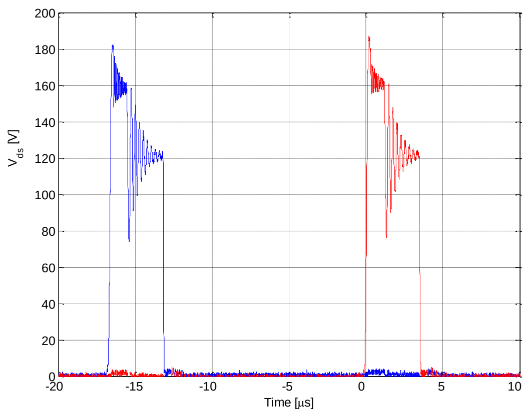



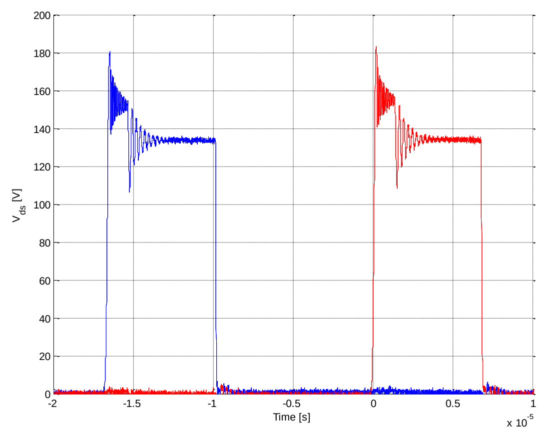

## Experimental results




## Experimental results

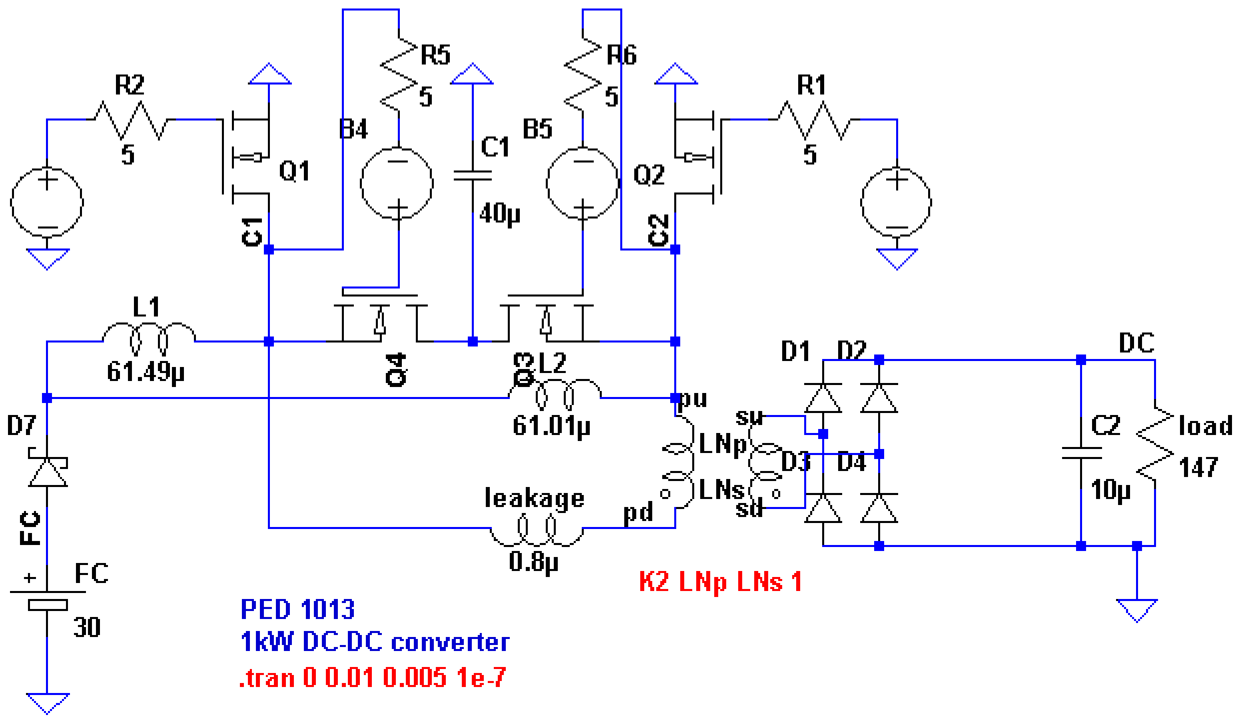



$V_{fc} = 17V;\ I_{fc} = 97A;\ V_{dc} = 360V;$ $\quad$ $V_{fc} = 30V;\ I_{fc} = 43A;\ V_{dc} = 403V;$

# Active clamping

- added auxiliary switches
- loss due to leakage is not dissipated over a resistance, but is transferred to the primary
- overall efficiency is improved



# Active clamping

t0 – t1: Q1 – Q2 are both conducting, voltage on $C_{clamp}$ is $V_{clamp}$

t1 – t2: Q1 –OFF, voltage across Q1 is increasing to $V_{clamp}$

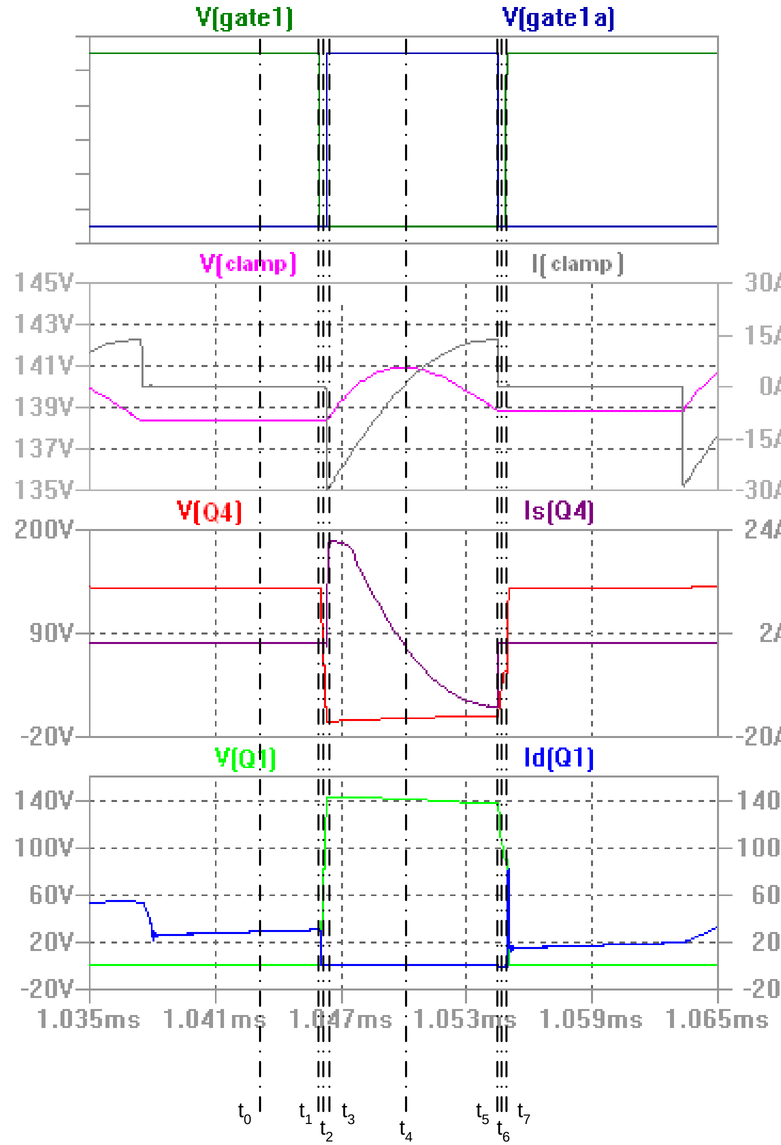
t2 – t3: clamping capacitor is charging

t3 – t4:voltage across Q4 is decreasing to 0, it can be turned ON

t4 – t5: clamping capacitor is discharging

t5 – t6: Q4 –OFF, voltage across Q4 is increasing to $V_{clamp}$, voltage across Q1 is decreasing to 0

t6 – t7: Q1 - ON




DIC with Passive clamping: $\eta = 85\%$

DIC with Active clamping: $\eta = 92\%$

# Switching Trajectories

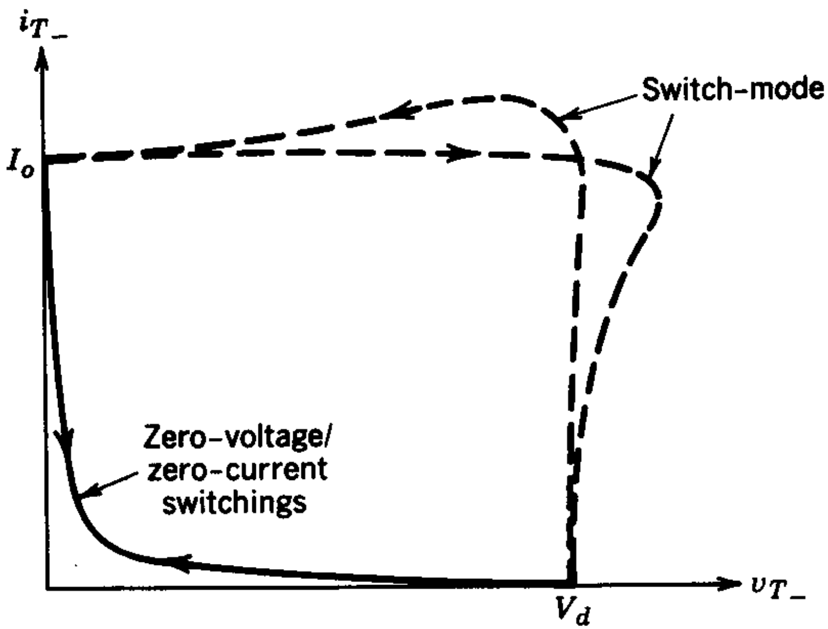



**Figure 9-4** Zero-voltage-/ zero-current-switching loci.

- comparison of hard- versus soft-switching
- in case of resonant converters the switches are stressed with higher voltage due to the resonant tank
- these converters need higher voltage-rating devices, which results in an increase in conduction loss

# Classification of resonant converters

- Load-resonant converters

  Voltage-source series resonant converters

  - Series-loaded resonant converters
  - Parallel-loaded resonant converter
  - Hybrid-resonant converters

  Current-source parallel-resonant converters

  Class E and subclass E resonant converters

- Resonant-switch converters

  Resonant switch DC-DC converters

  - Zero current switching converters (ZCS)
  - Zero voltage switching converters (ZVS)

  Zero voltage switching, clamped-voltage converters

- Resonant DC-link converters
- High-Frequency-Link Integral-Half-Cycle converters

# Undamped Series-Resonant Circuit

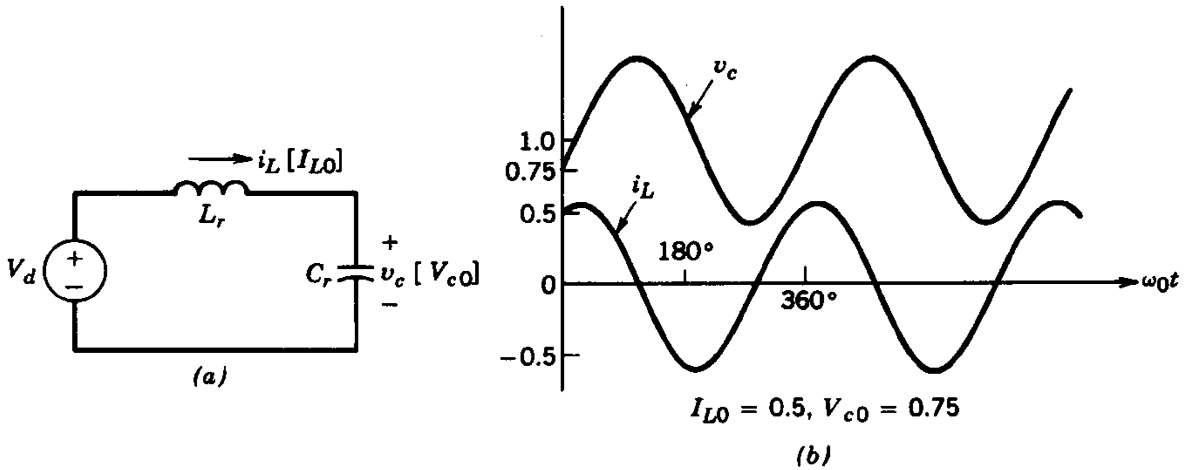



**Figure 9-5** Undamped series-resonant circuit; $i_L$ and $v_c$ are normalized: (a) circuit; (b) waveforms with $I_{L0} = 0.5$, $V_{c0} = 0.75$.

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

$$Z_0 = \sqrt{\frac{L_r}{C_r}} \text{ characteristic impedance}$$

- By applying a $V_d$ voltage on the LC circuit the energy starts to oscillate between the two energy storage components
- Initial conditions at $t_0$: $i_{L0}$ and $V_{c0}$
- Electrical resonance occurs in an AC circuit when the two reactances which are opposite and equal cancel each other out: $X_L = X_C$

# Series-Resonant Circuit with Capacitor-Parallel Load

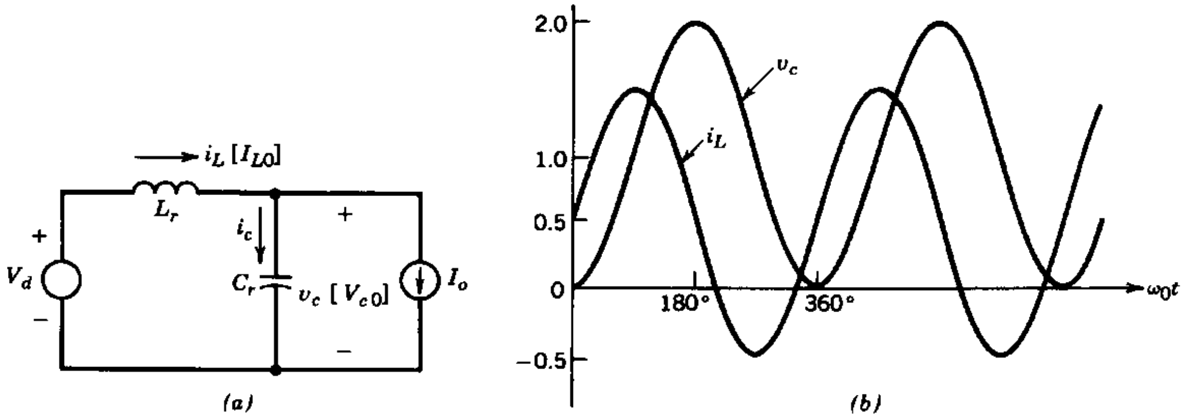



**Figure 9-6** Series-resonant circuit with capacitor-parallel load ($i_L$ and $v_c$ are normalized): (a) circuit; (b) $V_{c0} = 0$, $I_{L0} = I_o = 0.5$.

- by loading the capacitor with a DC current $I_0$ the resonance is maintained

# Impedance of a Series-Resonant Circuit

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

$$Q - quality\ \ factor$$

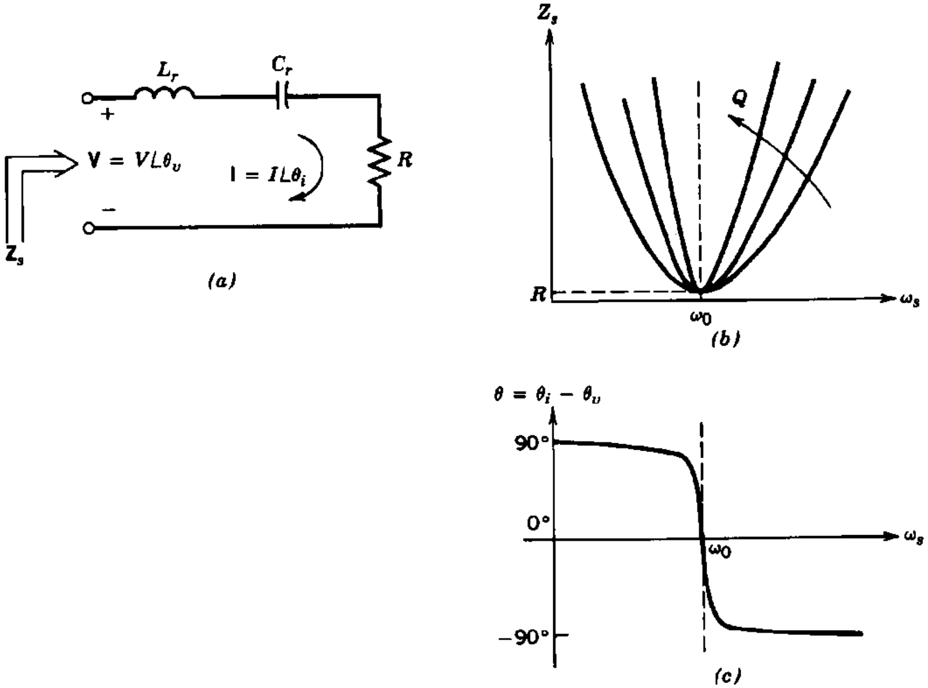
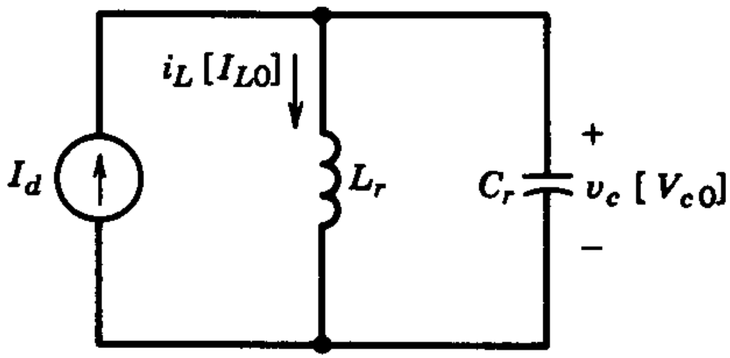



**Figure 9-7** Frequency characteristics of a series-resonant circuit.

- when $w_s$=$w_0$, $Z_s$ is a pure resistance (current and voltage are in phase)
- for frequencies above $w_0$ the circuit acts as inductive, below $w_0$ as capacitive circuit
- Q is very sensitive to frequency deviation from $w_0$ at higher values of Q

# Undamped Parallel-Resonant Circuit




$$\omega_0 = \sqrt{\frac{1}{L_r C_r}}$$

**Figure 9-8** Undamped parallel-resonant circuit.

- Excited by a current source

# Impedance of a Parallel-Resonant Circuit

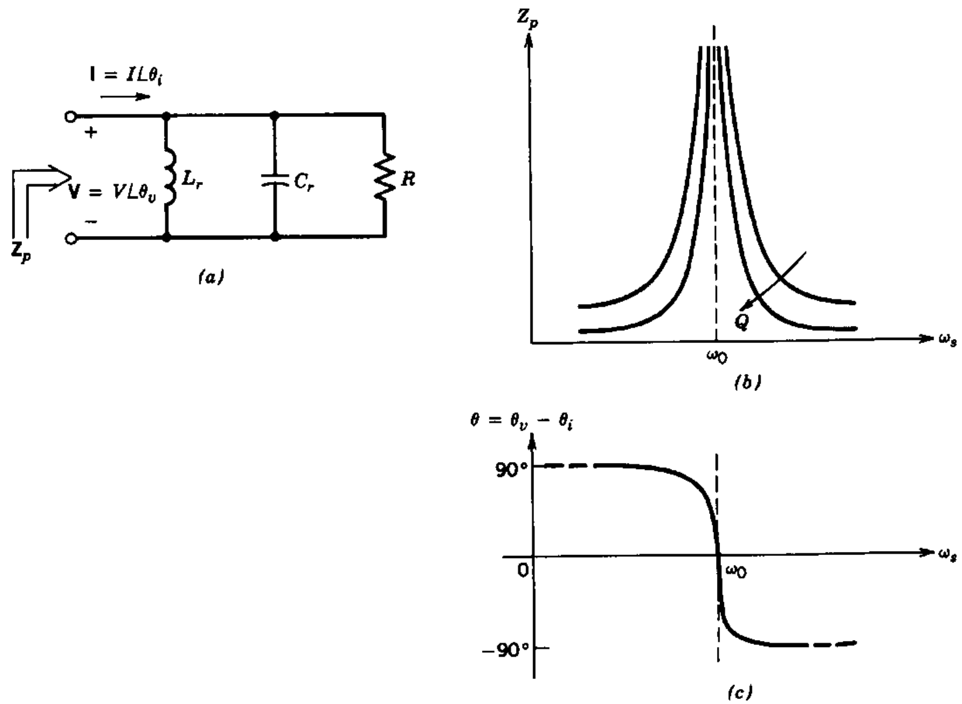



**Figure 9-9** Frequency characteristics of a parallel-resonant circuit.

- for frequencies above $w_0$ the circuit acts as inductive, below $w_0$ as capacitive circuit

# Resonance summary and facts

- for resonance to occur in any circuit it must have at least one inductor and one capacitor.
- resonance is the result of oscillations in a circuit as stored energy is passed from the inductor to the capacitor.
- resonance occurs when $X_L=X_C$ and the imaginary part of the transfer function is zero.
- at resonance the impedance of the circuit is equal to the resistance value as Z=R.
- at low frequencies the series circuit is capacitive as: $X_C>X_L$, this gives the circuit a leading power factor.
- at high frequencies the series circuit is inductive as: $X_L>X_C$ , this gives the circuit a lagging power factor.
- the high value of current at resonance produces very high values of voltage across the inductor and capacitor in case of series resonance
- series resonance circuits are useful for constructing highly frequency selective filters. However, its high current and very high component voltage values can cause damage to the circuit.
- the most prominent feature of the frequency response of a resonant circuit is a sharp resonant peak in its amplitude characteristics.

# Resonance summary and facts

- series resonance circuits are known as voltage resonance circuits
- resonant circuit stores the circuit energy in the magnetic field of the inductor and the electric field of the capacitor
- parallel resonance circuits at resonance will have a large circulating current between the inductor and the capacitor due to the energy of the oscillations, then parallel circuits produce current resonance.
- a parallel combination of L and C is used in filter networks to either select or reject AC frequencies
- as a **parallel resonance** circuit only functions on resonant frequency, this type of circuit is also known as an **Rejecter Circuit** because at resonance, the impedance of the circuit is at its maximum thereby suppressing or rejecting the current whose frequency is equal to its resonant frequency.
- as a **series resonance** circuit only functions on resonant frequency, this type of circuit is also known as an **Acceptor Circuit** because at resonance, the impedance of the circuit is at its minimum so easily accepts the current whose frequency is equal to its resonant frequency.

# ZVS-CV DC-DC Converter

**Zero Voltage Switching Clamped-Voltage**

- DC-DC step-down converter
- ZVS-CV converters usually need two active switches and a few additional resonant elements because a resonant transition during the off interval of both switches is required and the voltage regulation is performed by the constant-witching frequency PWM controller
- two switches: $T_+$ and $T_-$
- $L_f$ very small, the inductor current must reverse direction during each switching cycle
- $C_f$ is large, so the load and $C_f$ can be replaced by a $V_0$ in steady state, see Fig.9-34(b)

# ZVS-CV DC-DC Converter

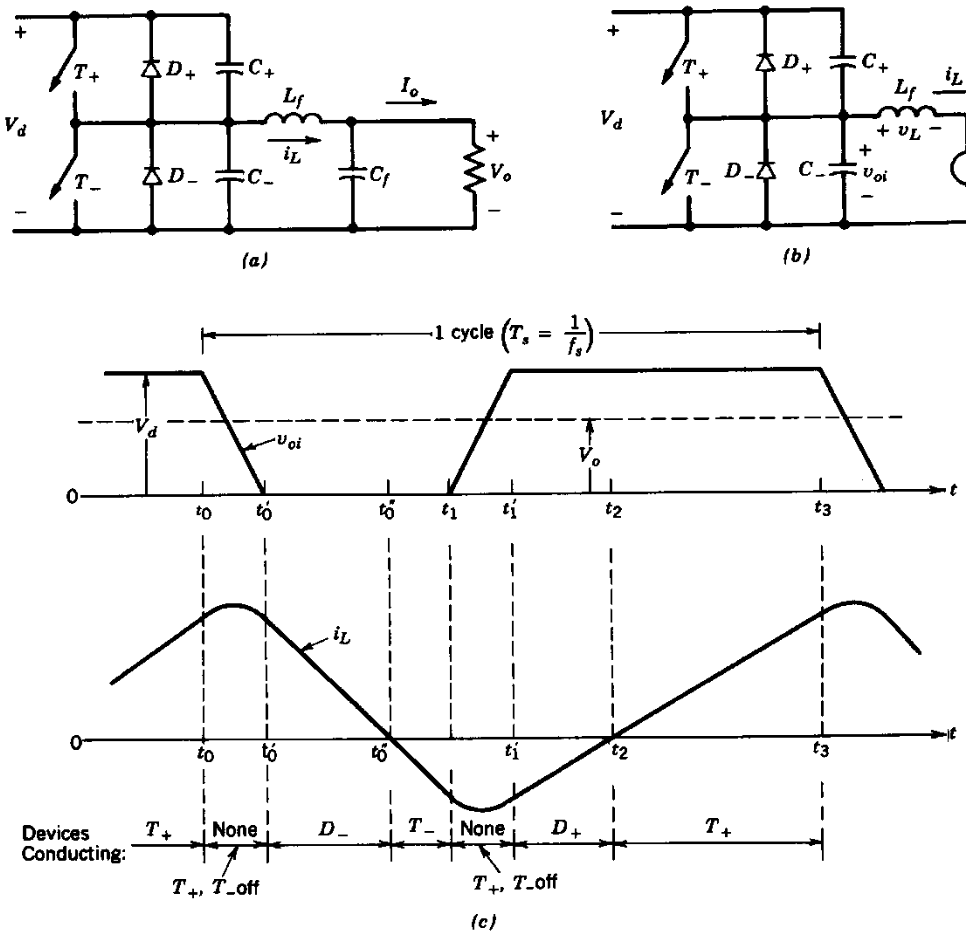



**Figure 9-34** ZVS-CV dc–dc converter.

- $T_+$ conducting $i_L>0$; $v_L>0$
- $T_+$ is turned off at $t_0$ at zero voltage, since the voltage across the switch builds up slowly compared to the switching time
- Both switches are off
- At $t_0'$ $v_{oi}$, voltage across $C_-$ reaches zero and the current $i_L$ flows through both $C_+$ and $C_-$
- After $t_0'$ $i_L$ decreases linearly and flows through $D_-$
- $T_-$ is turned on and at $t_0''$ $i_L$ reverses direction and flows through $T_-$
- At $t_1$ $T_-$ is turned off at zero voltage
- After $t_1$-$t_1'$ $i_L$ flows through $D_+$
- T+ is turned on at zero voltage when $D_+$ is conducting
- At $t_2$ $i_L$ becomes positive and $T_+$ conducts
- At $t_3$ $T_+$ is turned off at zero voltage

# ZVS-CV DC-DC Converter

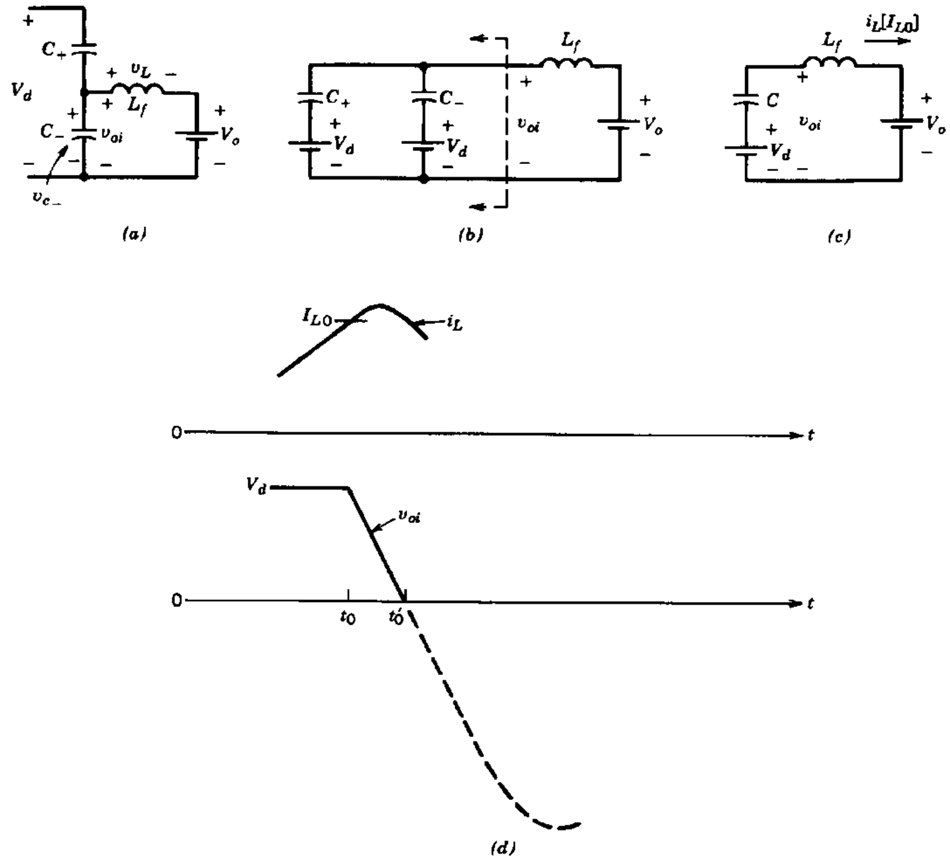



**Figure 9-35** ZVS-CV dc–dc converter; $T_+$, $T_-$ off.

- $T_+$ conducting $i_L$>0; $v_L$>0
- $T_+$ is turned off at $t_0$ at zero voltage, since the voltage across the switch builds up slowly compared to the switching time
- Both switches off as shown on 9-35(a), but the circuit can be redrawn as seen on 9-35(b)

- By considering $I_{L0}$ constant during blanking time, $V_{oi}$ would change linearly which simplifies the circuit analysis

# ZVS-CV Principle Applied to DC-AC Inverters

- DC-DC converters can be modified to become DC-AC converters to be able to supply inductive loads
- Half-bridge configuration
- Switching losses eliminated since turn on/off are at zero voltage, only if both switches conduct during each switching cycle
- Square wave mode or PWM mode
- Very large ripple in the output current

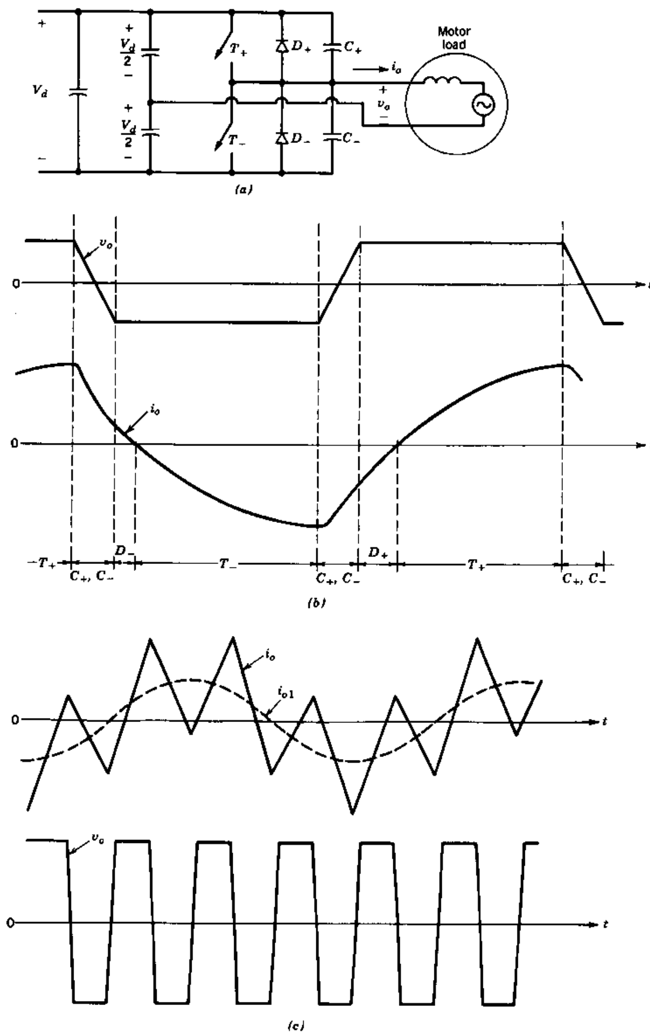



Figure 9-36 ZVS-CV dc-to-ac inverter: (a) half-bridge; (b) square-wave mode; (c) current-regulated mode.

# Three-Phase ZVS-CV DC-AC Inverter

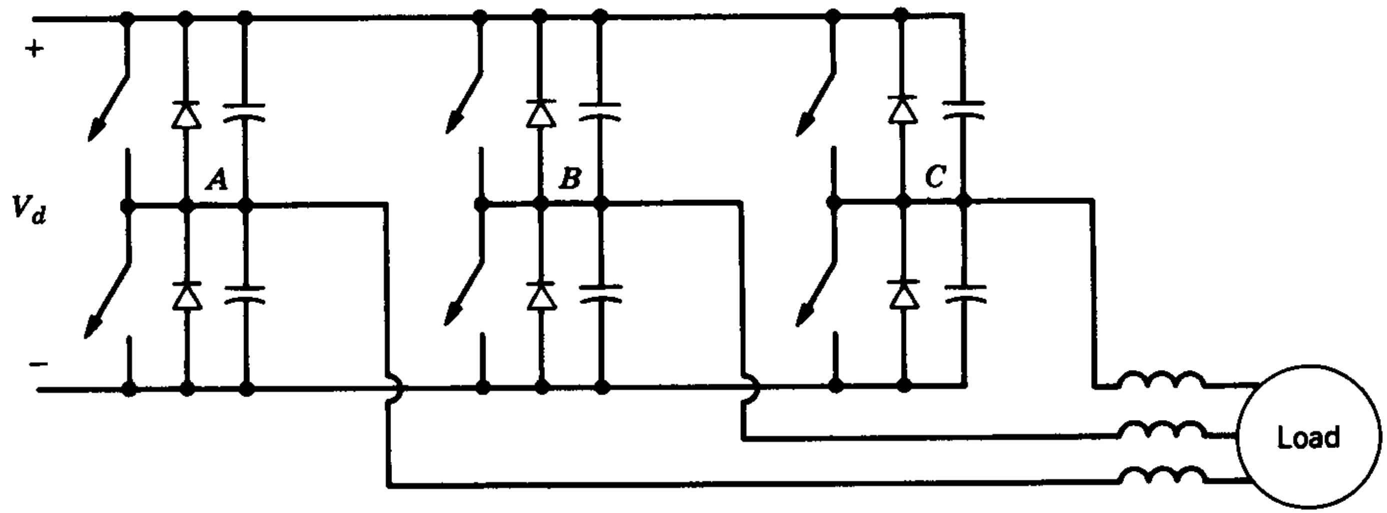



**Figure 9-37** Three-phase, ZVS-CV dc-to-ac inverter.

- concept from figure 9-36(a) extended to three-phase configuration
- very large ripple in the output current

# Output Regulation by Voltage Control

- ZVS-CV technique can be extended to single-phase DC_AC inverter with voltage cancellation: Figure 9-38(a)
- Each leg operates at nearly 50% duty-ratio, but phase delay is controlled to control the output $V_{AB}$

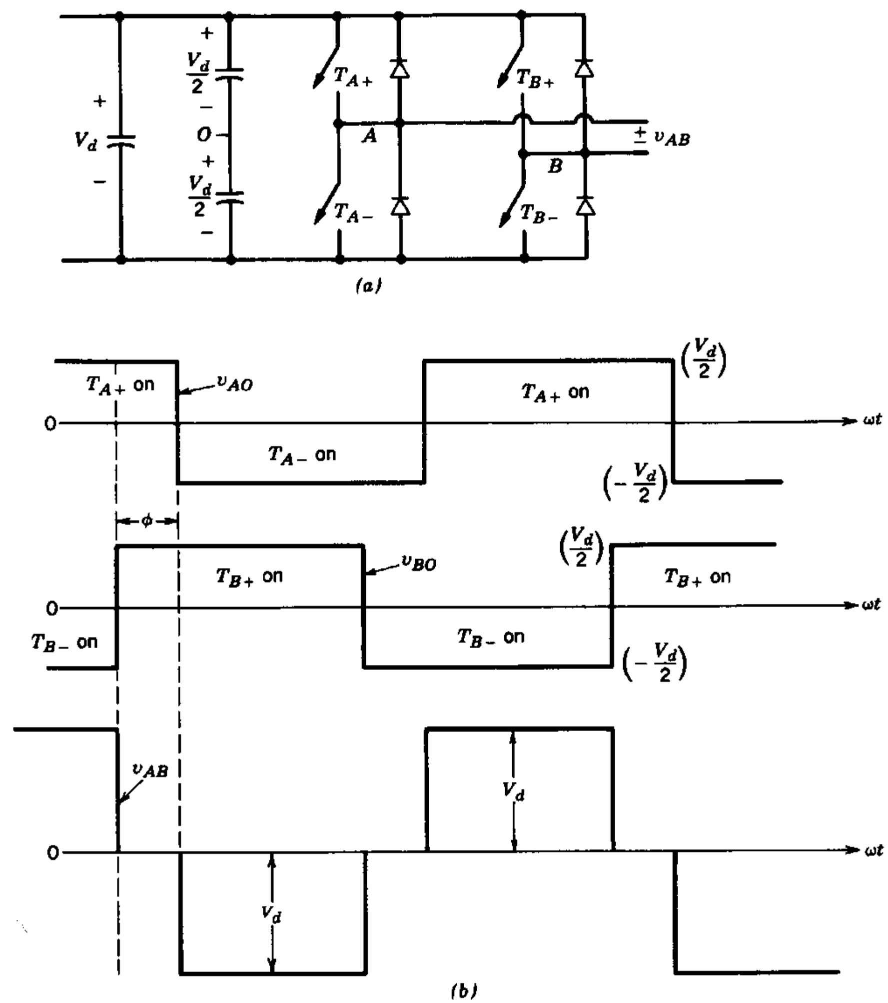


**Figure 9-38** Voltage control by voltage cancellation: conventional switch-mode converter.

# ZVS-CV with Voltage Cancellation

- Figure 9-36(a) can be modified by adding an inductance $L_A$, $C_{A+}$ and $C_{A-}$ to leg-A, same for leg-B
- Output voltage
- Resulting waveforms

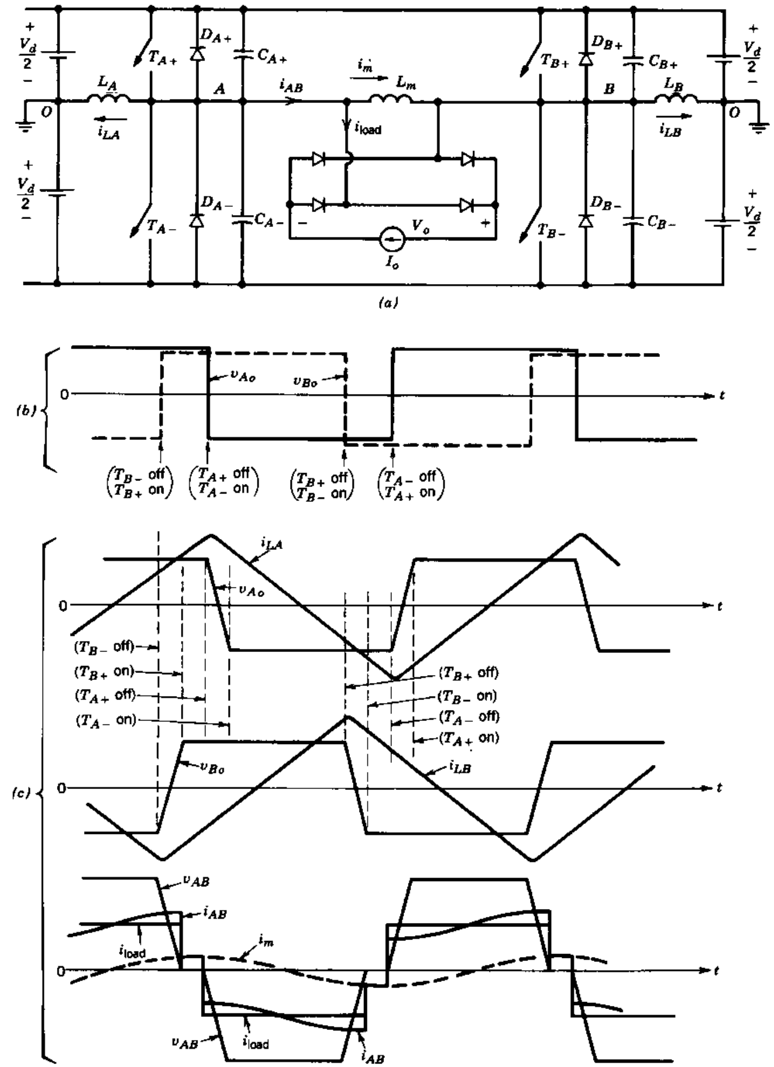


Figure 9-39 ZVS-CV full-bridge dc–dc converter: (a) circuit; (b) idealized switch-mode waveforms; (c) ZVS-CV waveforms.

# Three-Phase Resonant DC-Link Inverter

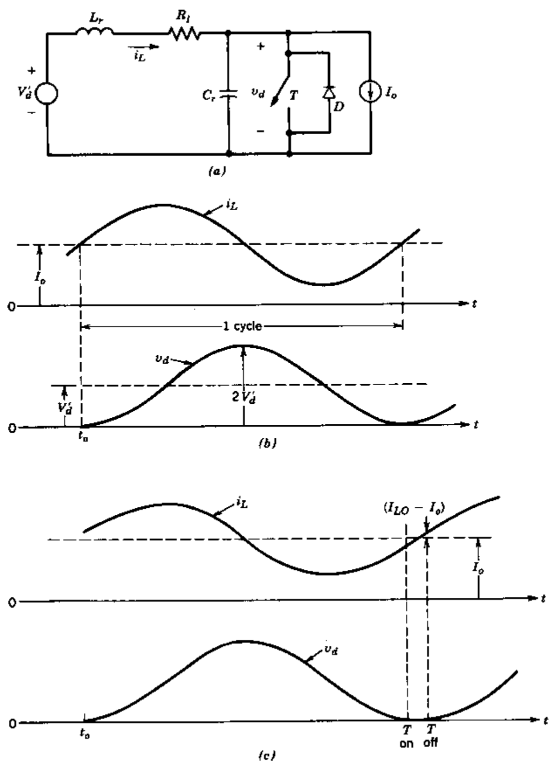



**Figure 9-40** Resonant-dc-link inverter, basic concept: (a) basic circuit; (b) lossless $R_l = 0$; (c) losses are present.

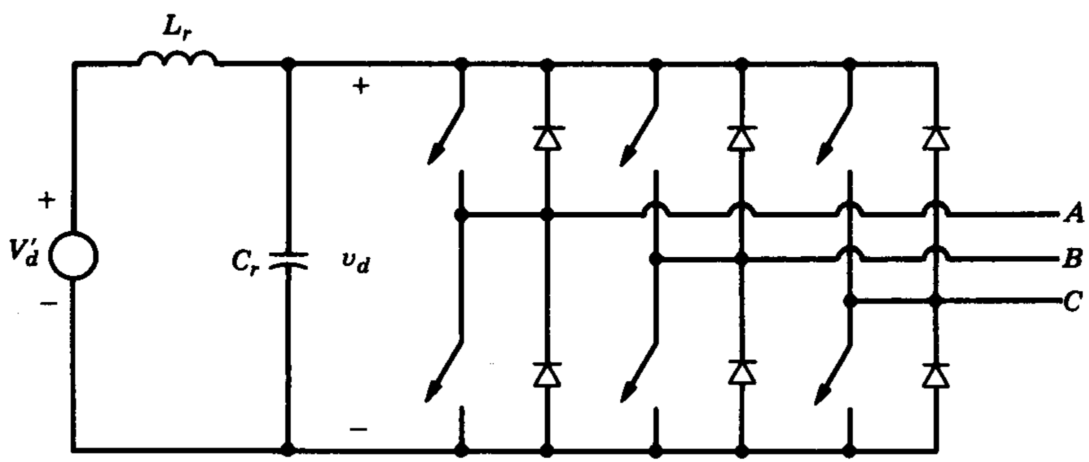



**Figure 9-41** Three-phase resonant-dc-link inverter.

• general two level three phase topology, switching losses can be minimized if the turn on-off is done at zero voltage using a resonant circuit introduced between the DC voltage source and the DC-link of the PWM inverter

# High-Frequency-Link Inverter

- The input is a single-phase high-frequency AC voltage
- Switching losses are minimized if turned on-off during the zero crossing of the input voltage
- Basic principle for selecting integral half-cycles of the high-frequency ac input

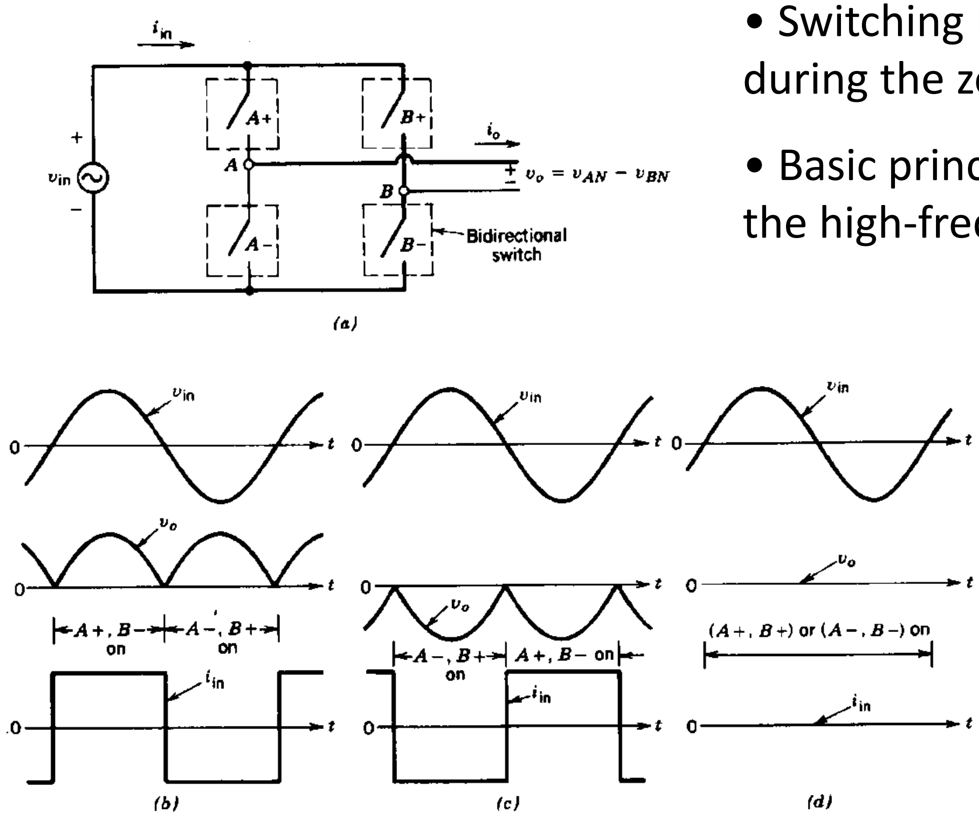



**Figure 9-42** High-frequency-link integral-half-cycle inverter.

- All switches are bi-directional: two switches in antiparallel with blocking diodes
- Output is a synthesized low-frequency AC to drive a motor

# High-Frequency-Link Inverter

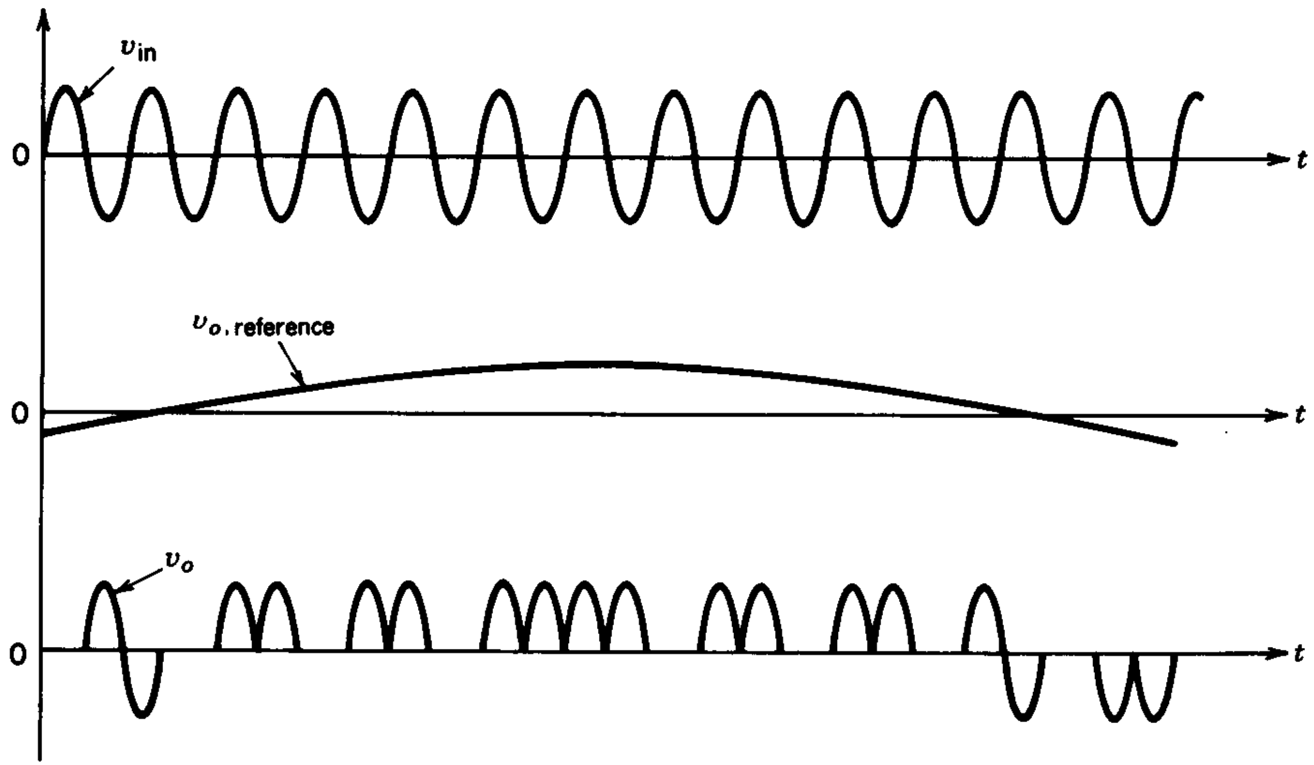



**Figure 9-43** Synthesis of low-frequency ac output.

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

# High-Frequency-Link Inverter

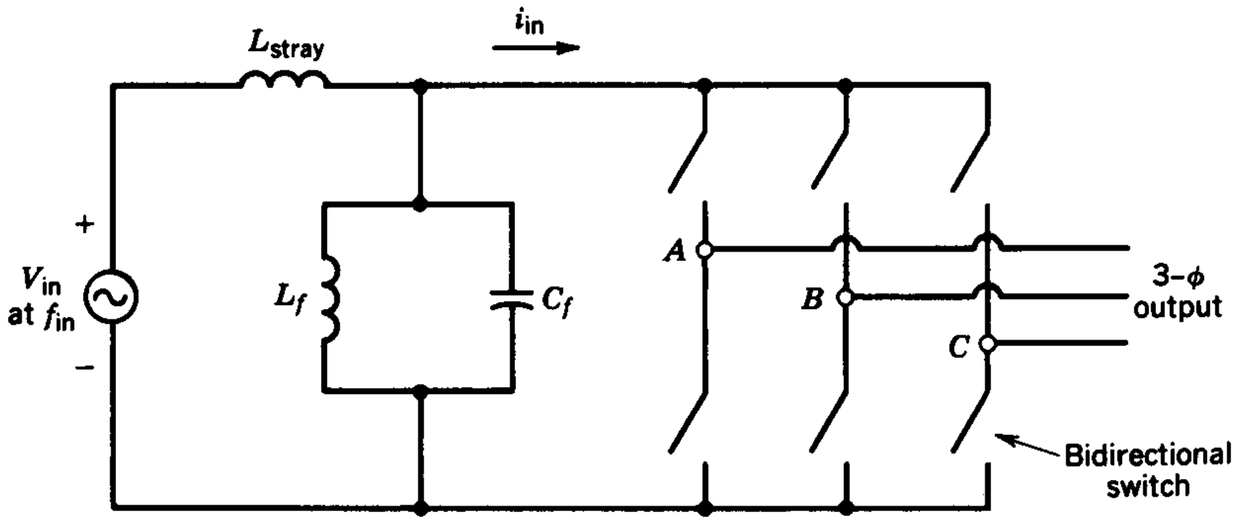
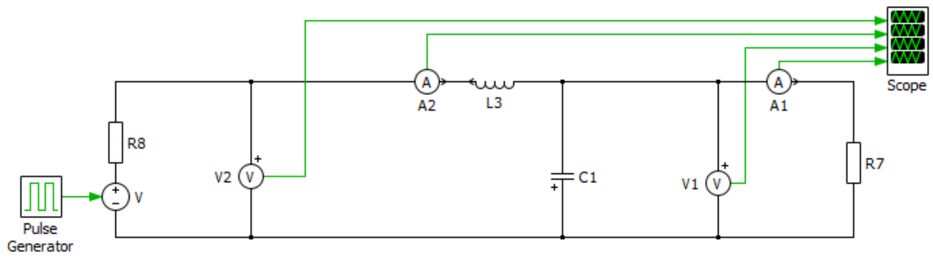


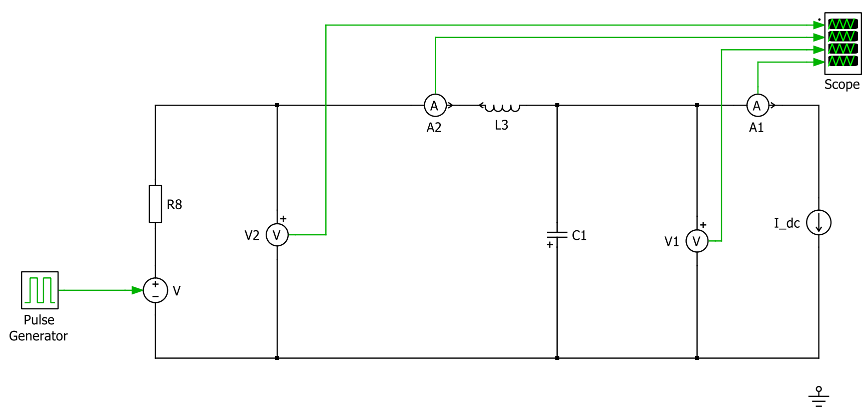

**Figure 9-44** High-frequency ac to low-frequency three-phase ac converter.

- implementation is also possible to deliver three-phase AC output
- a parallel resonant filter is used, which is tuned to resonate at $f_{in}$

# Exercise

- Simulate Figure 9-5 and 9-6 using PLECS
- Modify 9-5 with a load resistance
- Discuss the waveforms



# Overview of the power converters

**Lecture 1. Three phase converters**

Sinusoidal modulation, harmonics, square wave operation, dc link current, converter model, dead-time, current control

**Lecture 2. Three-phase modulation**

Sinusoidal modulation with added 3$^{rd}$ harmonic, 60 deg modulation, space vector modulation, discontinuous modulation.

**Lecture 3. Utility interface applications of power electronics**

Interconnection of energy sources to the grid, control of switch mode interface, improved single and three phase utility interface.

**Lecture 4. Variable-frequency converter classifications**

PWM-VSI, CSI , electromagnetic braking, speed control, square-wave vsi drive

**Lecture 5. Soft-switching in PWM – converters**

Hard and soft switching, classification of converters, basic resonant circuits, ZVS – VSI converters, phase shifted converters, resonant link inverters.

# Overview of the power converters

**Lecture 1. Three phase converters**

- Topology of three phase VSI
- Carrier based modulation
- Spectrum of the PWM voltage waveforms
- Modulation index
- Overmodulation
- Effects of blanking time (dead-time)
- Current control

# Overview of the power converters

**Lecture 2. Three-phase modulation**

- With three phase system a rotating voltage vector is created
- ST-PWM with added 3rd harmonic

  - increase the linear range
- Space vector modulation

  - smallest current ripple can be acheived
- Discontinuous modulation

  - reduce the switching losses
- Analytical spectrum calculation

  - the spectrum can be determinated by using math. eq.
- Current measurement

# Overview of the power converters

**Lecture 3. Utility interface applications of power electronics**

- PV systems (single- and three-phase connection)
- Wind and small hydro
- Storage systems
- Active filters
- Bidirectional power flow
- Improved three-phase utility interface
- Electromagnetic interference

# Overview of the power converters

**Lecture 4. Variable-frequency converter classifications**

- Variable-frequency converter classifications
- Variable-frequency PWM-VSI drives - electromagnetic braking
- Variable-frequency CSI drives
- Comparison of variable-frequency drives
- Line-frequency variable-voltage motor drives
- “Soft-start” of induction motors

# Overview of the power converters

**Lecture 5. Soft-switching in PWM – converters**

- Hard switching losses
- Zero-voltage and zero-current switching
- Resonant circuits
- Series/Parallel Load Resonant (SLR) Converter
- ZVS-CV DC-DC and DC-AC Converter
- Resonant DC-Link Inverter
- High-Frequency-Link Inverter

# Control of Electrical Drive Systems and Converters

**Lecture 1. Three phase converters**

Sinusoidal modulation, harmonics, square wave operation, dc link current, converter model, dead-time, current control.

Problems: 8-10 and 8-7

*Page: 225-243 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

**Lecture 2. Three-phase modulation**

Sinusoidal modulation with added 3$^{rd}$ harmonic, 60 deg modulation, space vector modulation, discontinuous modulation.

*Papers: The use of harmonic distortion to increase the output voltage, Simple Analytical and Graphical Methods for Carrier-Based PWM-VSI Drives*

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*Page: 475-480, 494 – 502 in the book 'Power Electronics Converters, Application and Design. N. Mohan, T.M. Undeland and W.P. Robbins, John Wiley ISBN 0-471-58408-8'*

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# Feedback / improvement

- Different exercises ? ADD SOME HINTS AND QUESTIONS TO THE MAJOR STEPS OF THE EXERCISE.
- Focus more on ?
- PED vs MCE theme ?

- Lecturer:
  - slides
  - presentations
  - explanations

# Design tips for converters

- How do you determine the min.-max. DC-link capacitance?
- How do you determine the min.-max. switching frequency?
- How do you determine the break resistance?
- How do you determine the PI controller parameters?