CONTROL OF ELECTRICAL DRIVE SYSTEMS AND CONVERTERS

Variable-frequency converter classifications

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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'

Exercise

- In the figure below a UPS system is shown, similar to the ones made by AXA in Odense, and it is used in most Danish airports. The UPS system supplies the airplane with ground power.

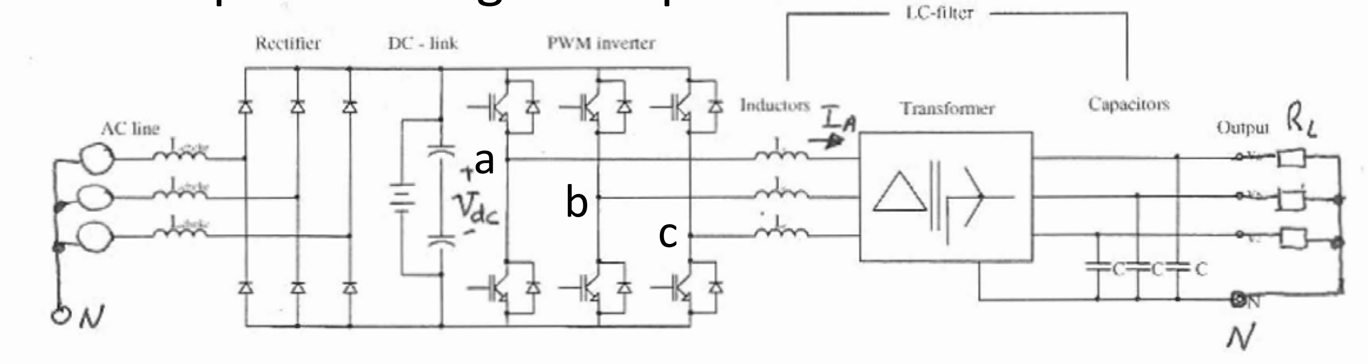


Fig. 1. Circuit of a typical PWM-based three-phase UPS system.

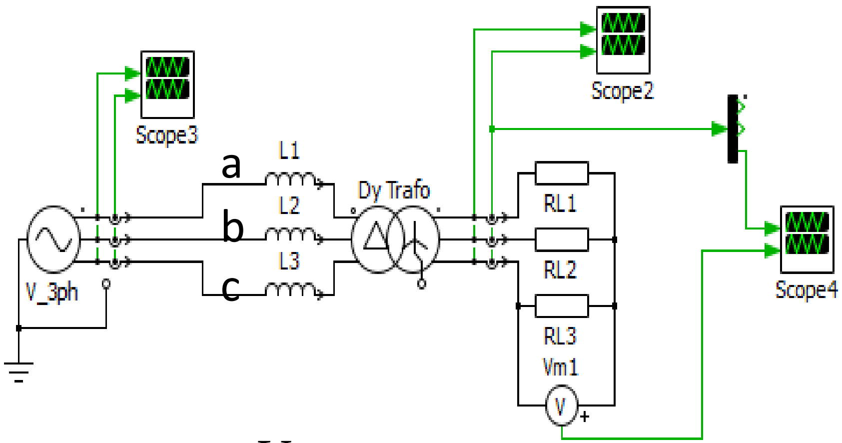
Data:

$L = 182\mu H$ $\quad$ $Winding\ ratio: 1/N_t = N_\Delta / N_Y = 1/0.42$ $\quad$ $f_s = 10kHz$

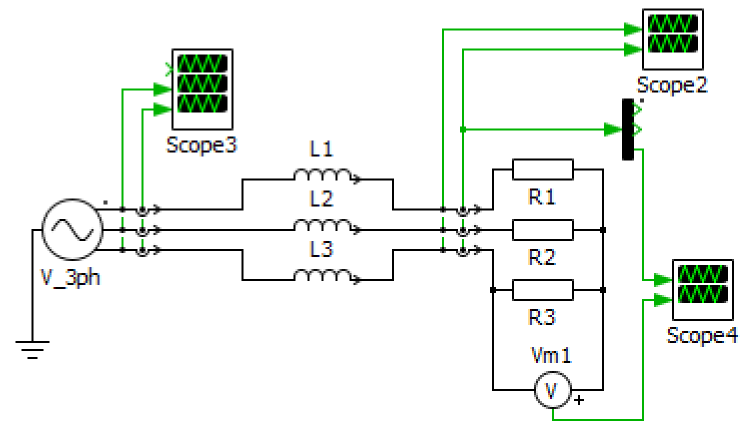
$f_1 = 50Hz$ $\quad$ $P_{RL} = 20kW$ $\quad$ $V_{LL} = 400V_{rms}$

- Disregard the voltage drop across the capacitors C and the voltage drop across L_{choke}
- 1: Calculate $V_{dc} = \sqrt{2}V_{ll} = 566V$
- 2: Calculate the RMS value of I_A, assuming sinusoidal modulation with 3rd harmonic injected, and m_a=0.9 $V_{ab} = \frac{V_{dc}}{\sqrt{2}} m_a = 360V_{rms}$

Equivalent circuit



$$\Rightarrow$$



$$V_{RL} = \frac{V_S}{\sqrt{3}}$$

$$I_{RL} = \frac{V_{RL}}{R_L} = \frac{V_S}{\sqrt{3}R_L}$$

$$P_{RL} = V_{RL} I_{RL} = \frac{V_S^2}{3R_L}$$

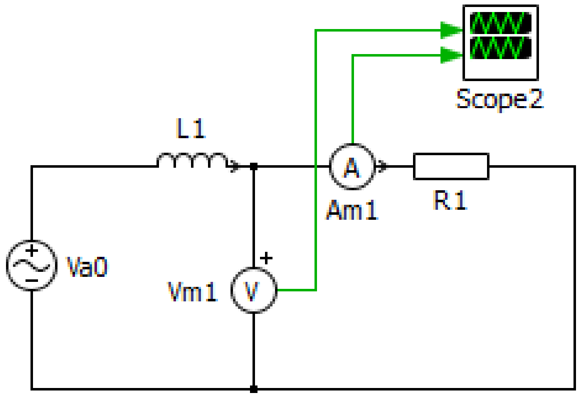
$$V_{a0} = \frac{V_{ab}}{\sqrt{3}} = \frac{V_P}{\sqrt{3}}$$

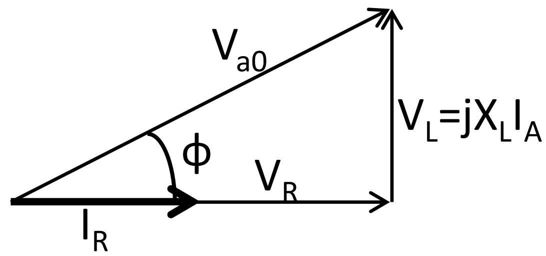
$$I_A = \frac{V_{a0}}{R} = \frac{V_P}{\sqrt{3}R}$$

$$P_R = V_{a0} I_A = \frac{V_P^2}{3R}$$

$$\left.\begin{array}{l} P_{RL} = P_R \Leftrightarrow \dfrac{V_S^2}{3R_L} = \dfrac{V_P^2}{3R} \\ V_S = N_t V_p \sqrt{3} \end{array}\right\} \Rightarrow R = \frac{R_L}{3N_t^2}$$

Calculation of the current





$$X_L = 2\pi f_1 L = 0.057$$

$$V_{a0} = \frac{360}{\sqrt{3}} = 207.84V_{rms}$$

$$\left.\begin{aligned} P_R &= V_{a0} I_A \cos(\varphi) \\ I_A &= \frac{V_{a0}\sin(\varphi)}{X_L} \end{aligned}\right\} \Rightarrow P_R = \frac{V_{a0}^2 \sin(\varphi)\cos(\varphi)}{X_L} = \frac{V_{a0}^2 \sin(2\varphi)}{2X_L}$$

$$\Rightarrow \varphi = \frac{1}{2} a\sin\left(\frac{2P_R X_L}{V_{a0}^2}\right) = 0.026$$

$$I_A = \frac{P_R}{V_{a0}\cos(\varphi)} = 96.22A_{rms} \Rightarrow R = \frac{P_R}{I_A^2} = 2.16\Omega \Rightarrow R_L = 3RN_t^2 = 1.143\Omega$$

Agenda

- Variable frequency converter classification
- Variable frequency PWM-VSI drives
- Electromagnetic braking
- Adjustable-speed control of PWM-VSI drives
- Induction motor servo drives
- Variable frequency square-wave VSI drives
- Variable frequency CSI drives
- Comparison of variable frequency drives
- Line frequency variable-voltage drives
- Reduced voltage starting of induction motors
- Speed control by static slip power recovery

Main requirement: Variable-frequency converter

- to adjust the frequency of the output voltage according to the reference speed
- to adjust the amplitude of the output voltage to maintain a constant air-gap flux in the constant torque region

Variable-frequency converter classifications

PWM-VSI with diode rectifier

Square-wave VSI with controlled rectifier

CSI with controlled rectifier (with large inductor)

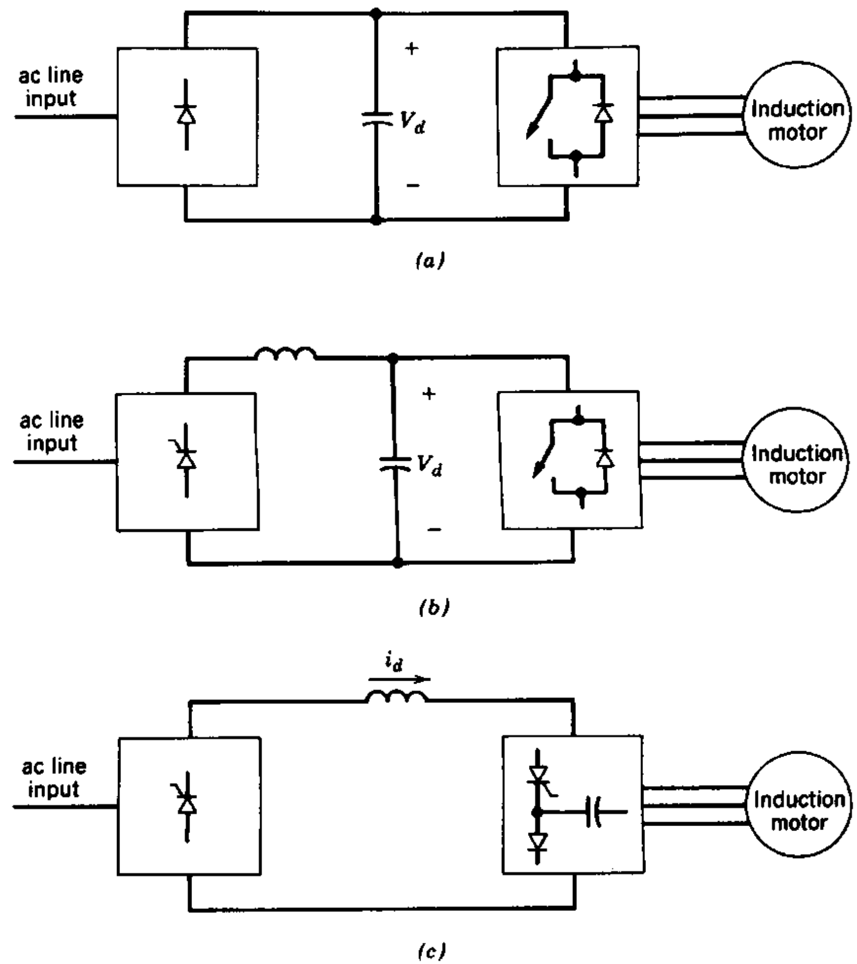


Figure 14-18 Classification of variable-frequency converters: (*a*) PWM-VSI with a diode rectifier; (*b*) square-wave VSI with a controlled rectifier; (*c*) CSI with a controlled rectifier.

VSI: ideal DC voltage source at the input
CSI: ideal DC current source at the input

Electromagnetic braking

- When the speed of the rotor is decreased, the kinetic energy stored in the motion (due to the inertia of the rotor) is transformed back in electric energy (motor works as generator)
- The energy generated during deceleration is injected to the Dc-link through the anti-parallel diodes of the full-bridge converter
- In case the drive is supplied from the grid through a passive rectifier (diode-bridge) the energy cannot be supplied back to the grid
- What happens with this energy surplus?

Electromagnetic braking

- The extra energy can be burned in the motor, through the resistance of the wires and motor losses (pure dynamic performance)
- Better dynamics can be achieved by using a break resistor
- In case of a four-quadrant inverter the extra energy is supplied back in the grid

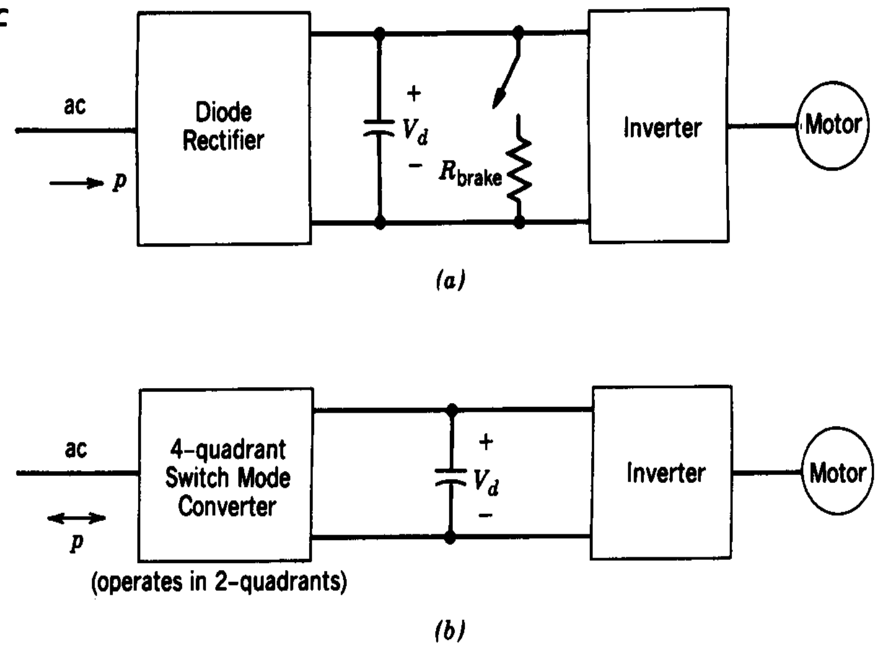


Figure 14-20 Electromagnetic braking in PWM-VSI: (*a*) dissipative braking; (*b*) regenerative braking.

Adjustable-speed control of PWM drives

- the frequency and amplitude of the output voltage of the VSI is controlled, thereby controlling the speed of the drive
- no feedback is necessary, but for better accuracy current and voltage measurements can be used

- Speed reference
- Ramp limiter
- Slip compensation for improved speed regulation
- High dynamic performance is not the objective here
- Voltage boost at low speed
- Current limit (limits the acceleration and deceleration)

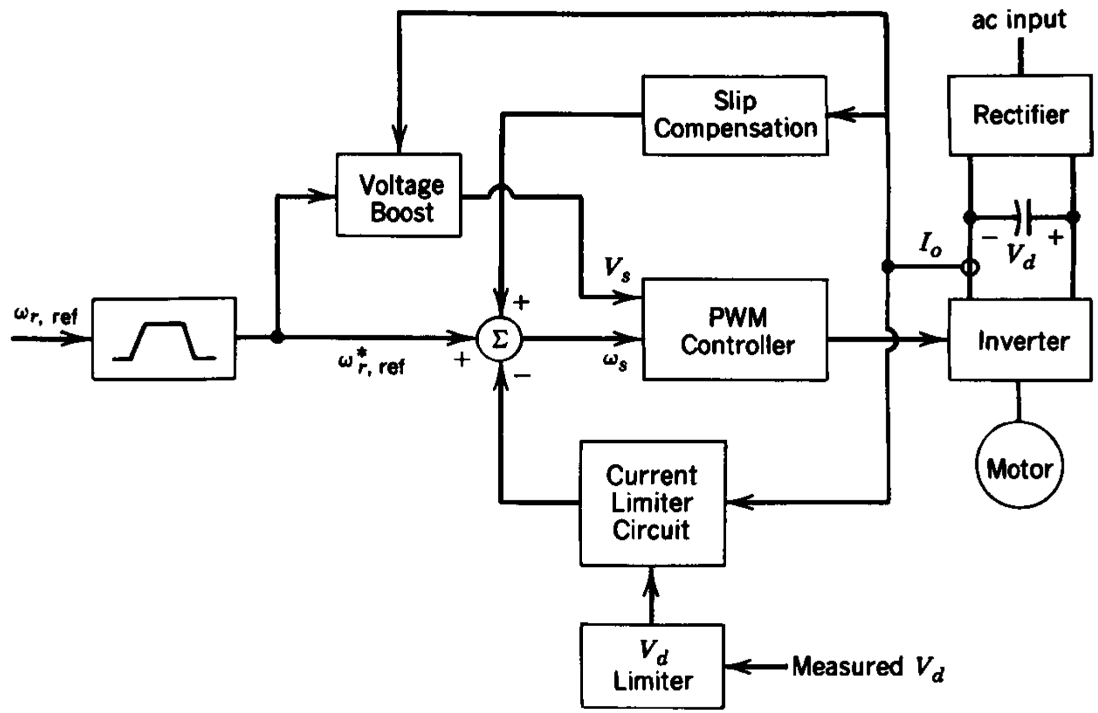


Figure 14-21 Speed control circuit. Motor speed is not measured.

Adjustable-speed control of PWM drives

Switching frequency can vary as a function of the reference frequency

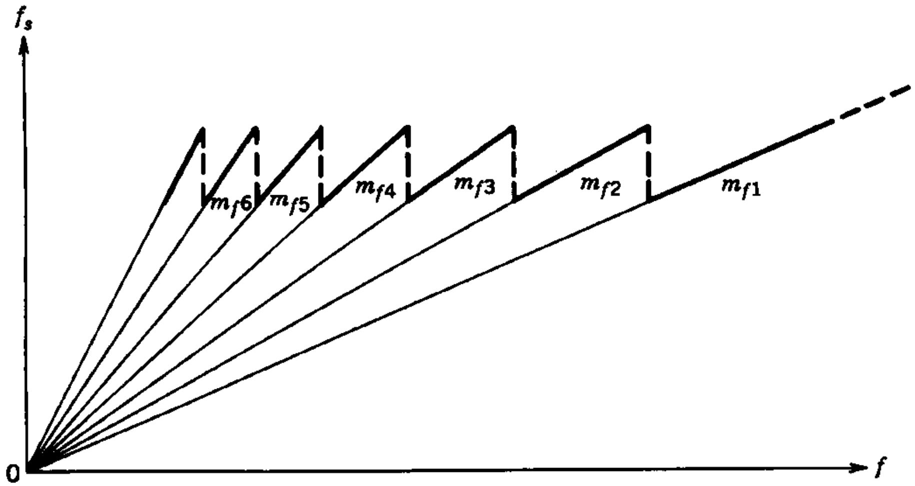


Figure 14-22 Switching frequency versus the fundamental frequency.

- in case of small m_f synchronous PWM should be applied (V_{tri} is in sync with $V_{control}$)

- m_f should be an integer number: V_{tri} varies with $V_{control}$ not to have any subharmonics of the fundamental in the spectrum of the output voltage

This is why there are jumps in m_f, that leads to jittering at frequencies where these jumps occur (**jittering** - undergoing small rapid variations)

Field-Oriented control

- The torque is controlled via adjusting the stator currents of the motor
- Motor parameters are needed, accurate values, temperature variation

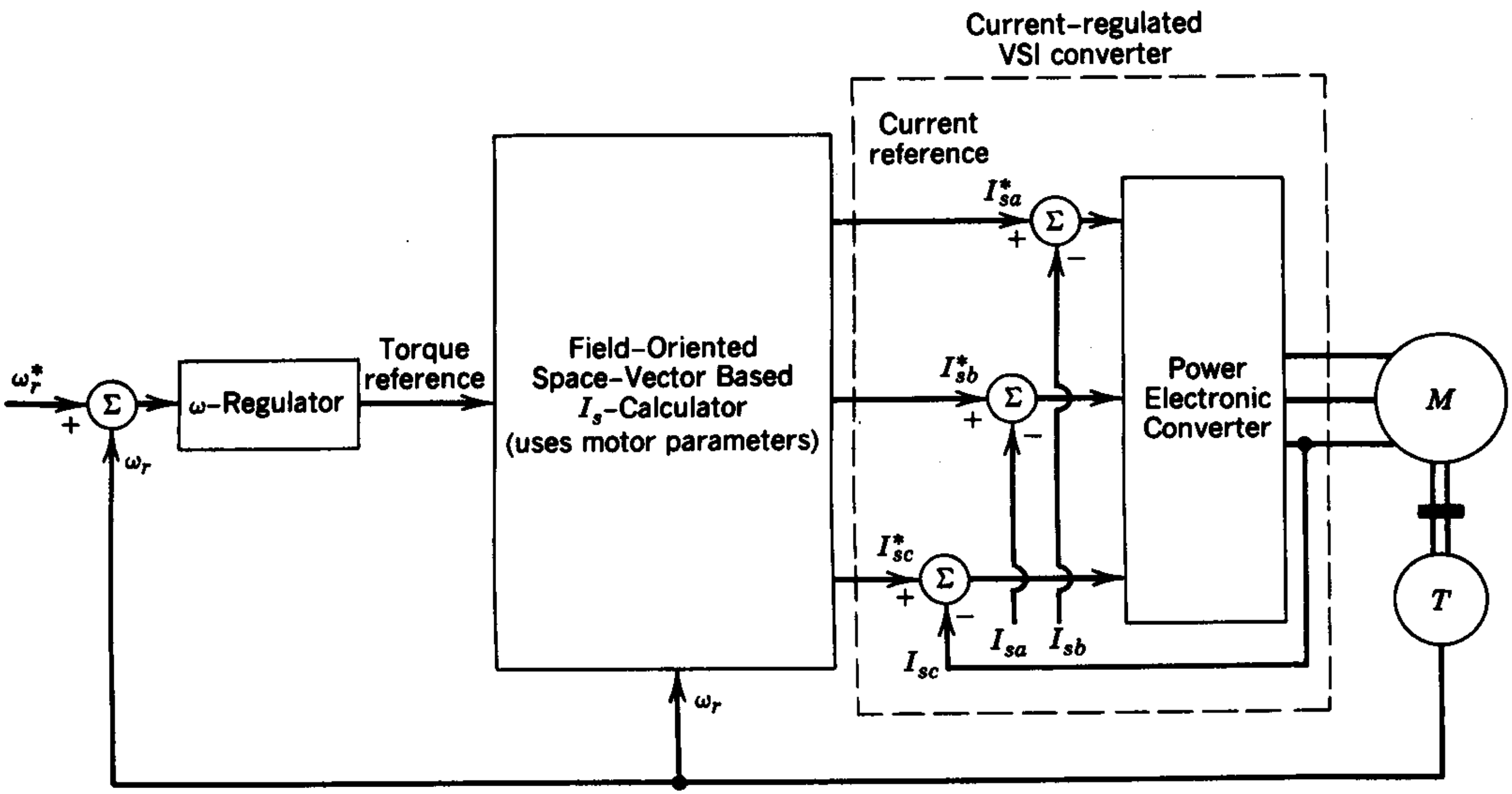


Figure 14-23 Field-oriented control for induction motor servo drive.

Square-wave VSI drives

- Each inverter switch is on for 180 degrees, there are always three switches on
- Motor current is controlled via controlling V_d using a controlled rectifier
- Voltage harmonics decrease with harmonic order
- High harmonics content in the current (low order harmonics), high peaks
- Torque ripple due to harmonics
- Speed ripple at low speeds

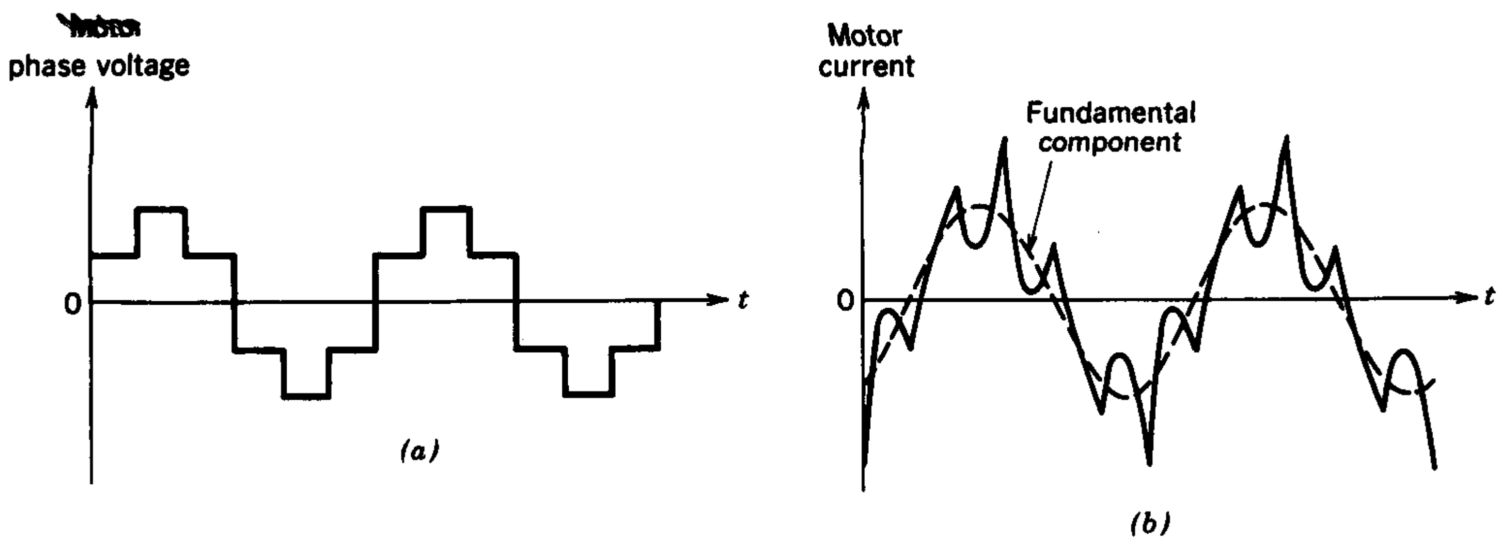


Figure 14-24 Square-wave VSI waveforms.

Square-wave VSI drives

- Line rectifier and motor voltages:

$$V_d = 1.35 \cdot V_{LL} \cos\alpha \qquad \text{Eq(14-52)}$$

$$V_{LL}^{motor} = 0.78 \cdot V_d \qquad \text{Eq(14-53)}$$

V_d - DC-link voltage Eq(5-68)

V_{LL} - line-to-line RMS voltage of source

V_{LL}^{motor} - line-to-line RMS voltage of motor

α - fireing angle of the controlled rectifier

From Eq(14-52) and Eq(14-53):

$$V_{LL}^{motor} = 1.05 \cdot V_{LL} \qquad \text{Eq(14-54)}$$

$$\frac{\omega_r}{\omega_{r,rated}} \approx \frac{V_{LL}^{motor}}{V_{LL}} \approx \cos\alpha \qquad \text{Eq(14-55)}$$

From Eq(6-47a) and Eq(14-55):

$$PF = 0.955 \cdot \cos\alpha = 0.955 \frac{\omega_r}{\omega_{r,rated}}$$

- At high speeds the line power factor is much better than in case of an IM connected directly to the grid
- At low speeds the power factor will be low, using a square-wave drive

CSI Drives

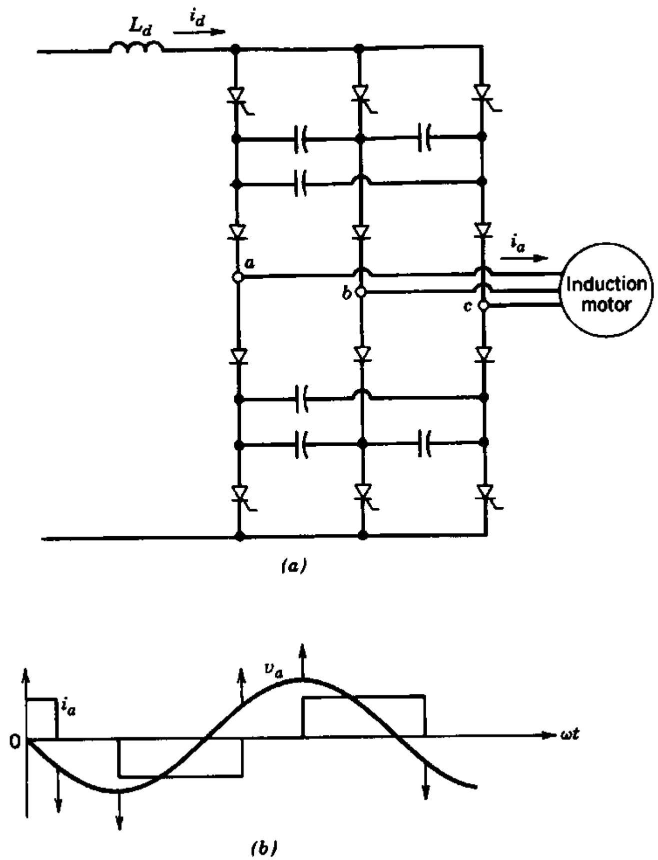


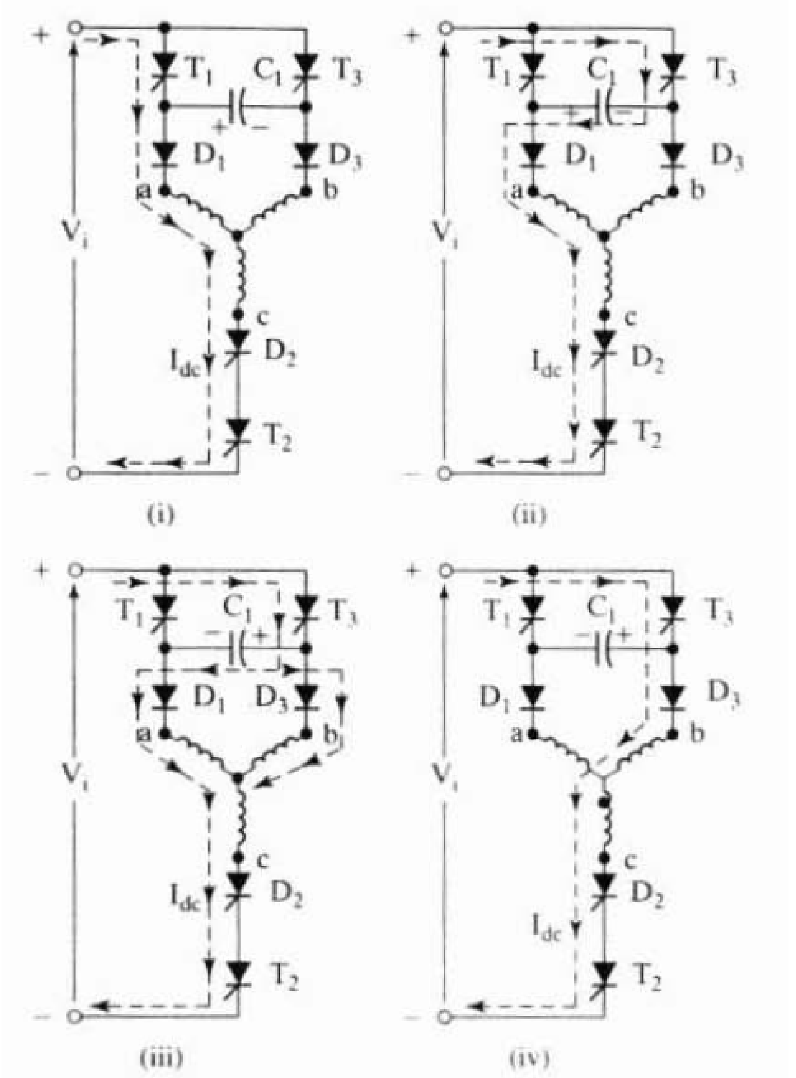
Figure 14-25 CSI drive: (*a*) inverter; (*b*) idealized phase waveforms.

- Mostly PWM-VSI drives are used, but for high-power CSI with thyristors can be a viable solution

Current source inverter (CSI)

Commutation sequence for CSI from phase-a to phase-b

- Two conducting at each instant (T_1-T_2)
- C_1 is charged positive; see subfigure (i)
- Current path is through T_1D_1-T_2D_2
- T_3 is turned-ON; voltage across T_1 is reverse biased;
- Current path is through T_3D_1-T_2D_2
- T_1 is turned-OFF, C_1 is charged negative; see subfigure (ii)
- D_3 is forward biased, D_1D_3 both conduct at the same time; see subfigure (iii)
- D_1 becomes reverse biased and only D_3 will conduct; see subfigure (iv)



Ref: R. Krishnan, Electric Motor Drives, pp.383

Comparison of Adjustable frequency drives

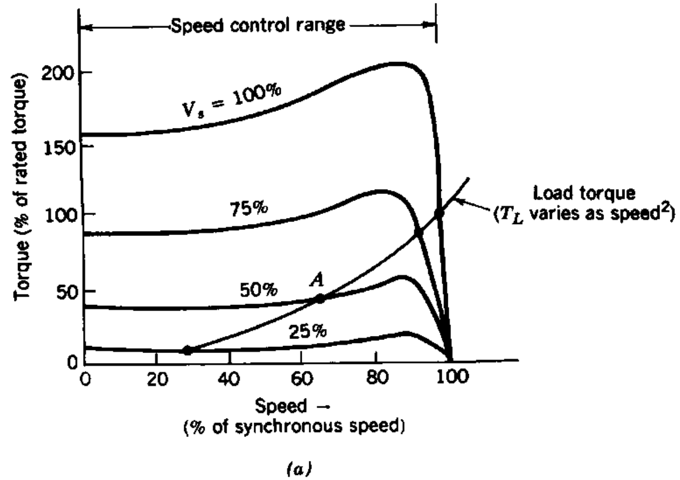
Table 14-2 Comparison of Adjustable Frequency Drives

Parameter	*PWM*	*Square Wave*	*CSI*
Input power factor	+	−	−−
Torque pulsations	++	−	−
Multimotor capability	+	+	−
Regeneration	−	−	++
Short-circuit protection	−	−	++
Open-circuit protection	+	+	−
Ability to handle undersized motor	+	+	−
Ability to handle oversized motor	−	−	−
Efficiency at low speeds	−	+	+
Size and weight	+	+	−−
Ride-through capability	+	−	−

- PWM-VSI is by far the most commonly selected topology
- some of the drawbacks/limitations can be eliminated with extra circuits

Speed Control by Adjusting the Stator Voltage

- Motor torque varies with the speed^2 (small rated slip)



- Motor torque is constant

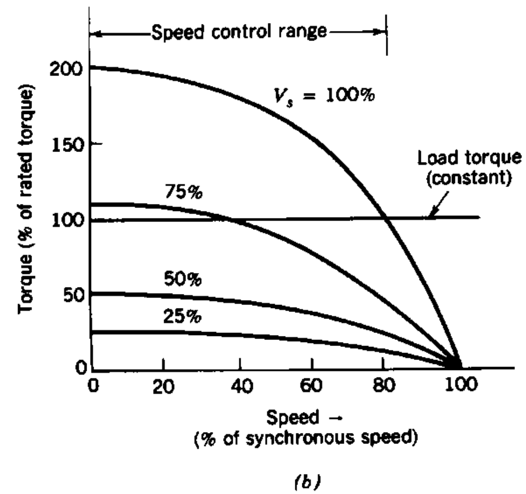


Figure 14-26 Speed control by stator voltage control: (*a*) motor with a low value of s_{rated}, fan-type load; (*b*) motor with a large s_{rated}, constant-torque load.

- Speed control by stator voltage control is inefficient at low speeds due to high rotor losses cased by the large slip (small single-phase motors)

Controlling the Stator Voltage Magnitude

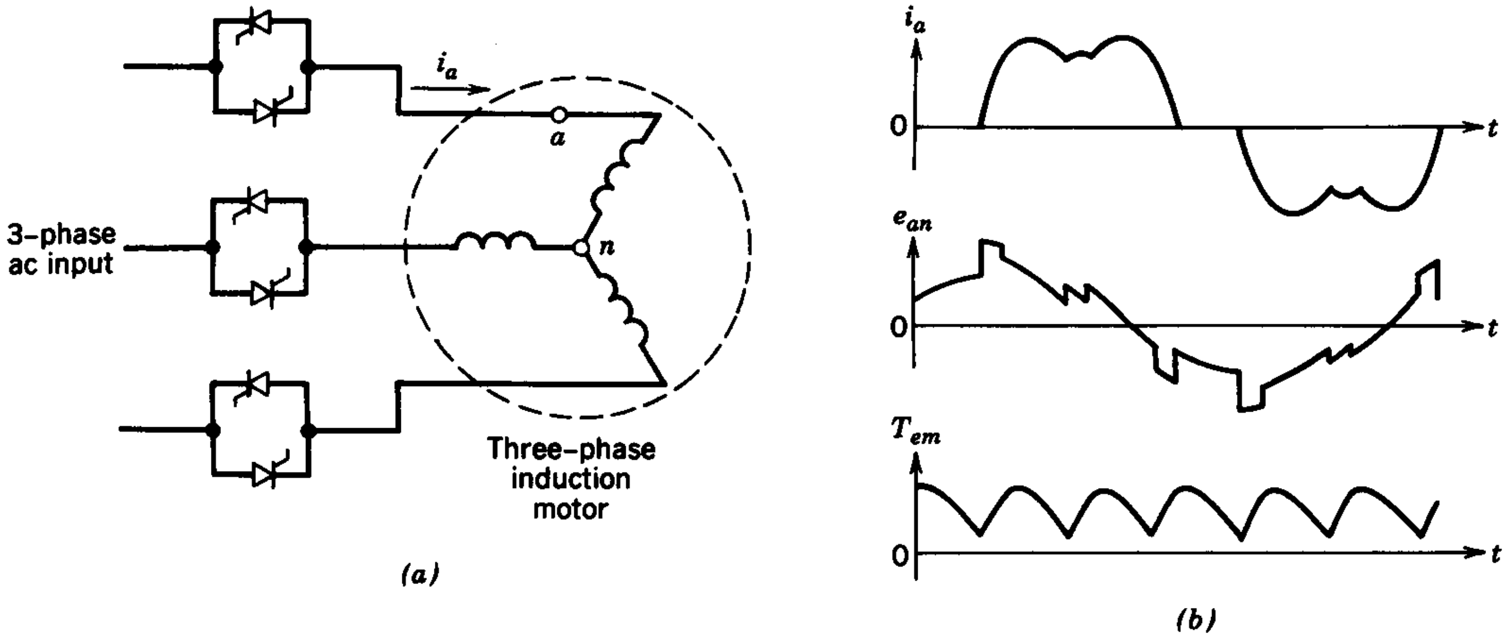


Figure 14-27 Stator voltage control: (*a*) circuit; (*b*) waveforms.

- reduces starting current by applying reduced stator voltage
- results in distorted current and torque pulsations
- during normal operation thyristors are short-circuited (no losses)

Torque-Speed Curves for Wound-Rotor Machines

- torque-speed curves vary with the rotor resistance
- by varying the rotor resistance the speed of the rotor is varied (f.ex. using slip rings)
- highly energy-inefficient unless using energy recovery schemes
- extract the power from the rotor and feed it back to the supply using…

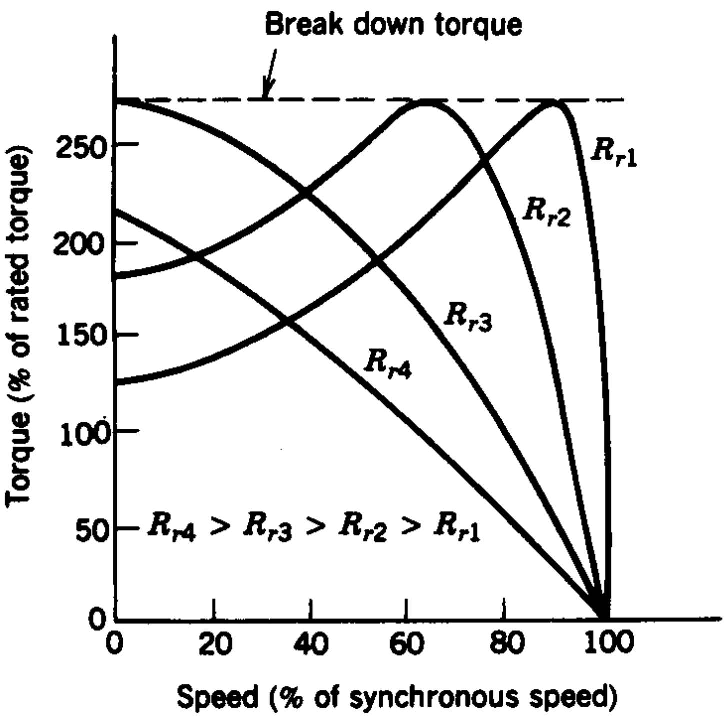


Figure 14-28 Torque–speed curves for a wound-rotor induction motor.

Static Slip Energy Recovery System

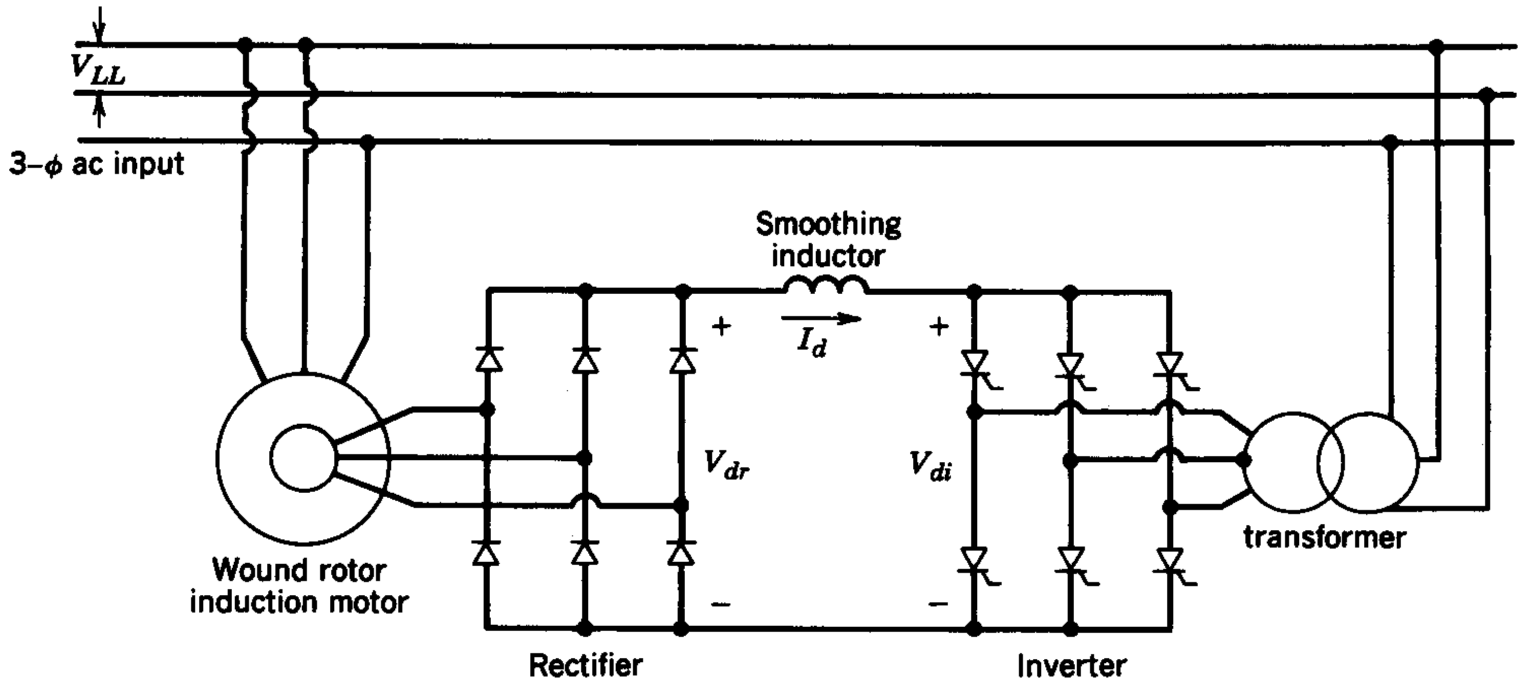


Figure 14-29 Static slip recovery.

- Applications in very large power ratings where the speed is to be adjusted over a very limited range
- Voltages induced in the rotor generate rotor currents, these are rectified and fed back to the supply via a thyristor controlled inverter and a step-up transformer

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Exercise

Drives-lab in PON107-3.107

- MM4: V/f scalar control (PLECS or Drives-lab)
- MM4: electromagnetic braking (PLECS or Drives-lab)