Chapter 4 Power Converters

Learning Objectives

- Understand waveforms of various circuits
- Distinguish single- and three-phase converters
- Realize effects of firing angle
- Understand operating principles of different DC/DC converters

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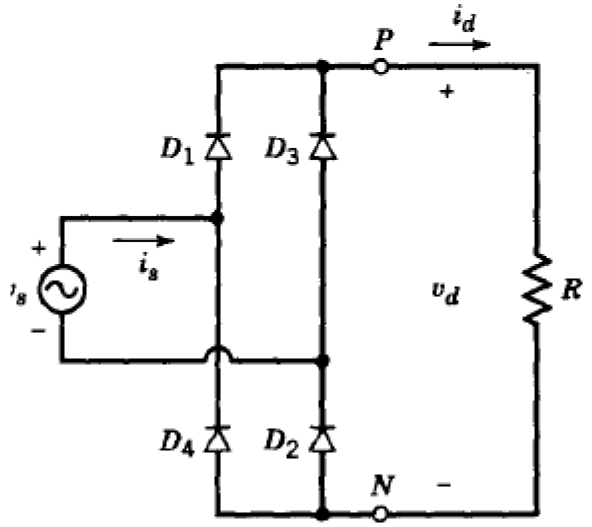
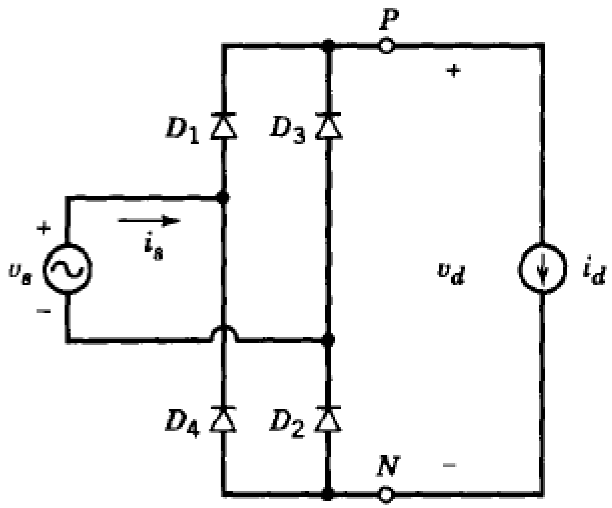
4.1 Single-Phase Diode Bridge Rectifiers





- An idealized bridge circuit with no line inductance are analysed
- A pure resistive load is very unlikely to be realized in practical case
- A constant dc current is a very good approximation in a situation when a large inductor may be connected in the circuit

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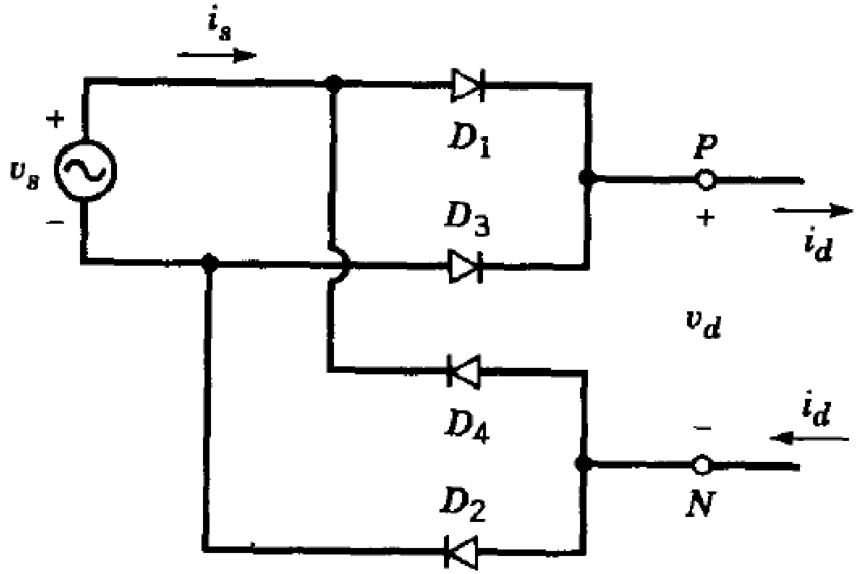
4.1 Single-Phase Diode Bridge Rectifiers



- At anytime, the dc-side output voltage is

$$v_d(t) = |v_s|$$

- Similarly, the ac-side current is

$$i_s = \begin{cases} i_d & v_s > 0 \\ -i_d & v_s < 0 \end{cases}$$

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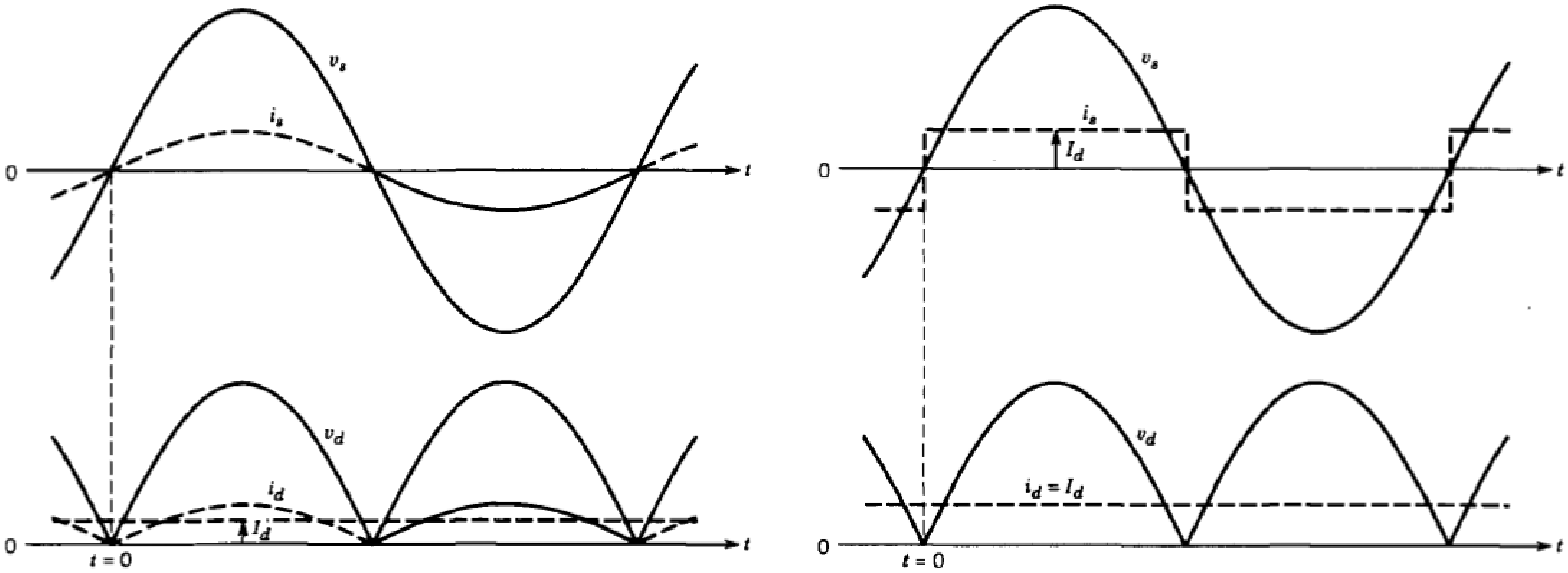
4.1 Single-Phase Diode Bridge Rectifiers



4.1 Single-Phase Diode Bridge Rectifiers

- The average output voltage is

$$V_{d0} = \frac{1}{T/2}\int_0^{T/2}\sqrt{2}\,V_s \sin(\omega t)\,dt = \frac{\sqrt{2}V_s}{\omega\,T/2}(cos\omega t)\Big|_{T/2}^{0} = \frac{2}{\pi}\sqrt{2}V_s$$

- Hence

$$V_{d0} = \frac{2}{\pi}\sqrt{2}V_s = 0.9V_s$$

where V_s is the rms value of the input voltage

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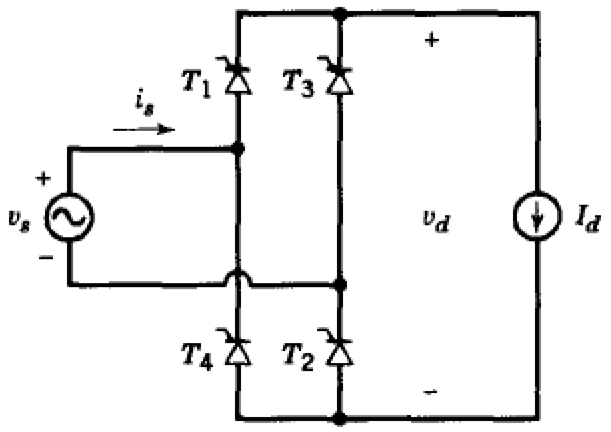
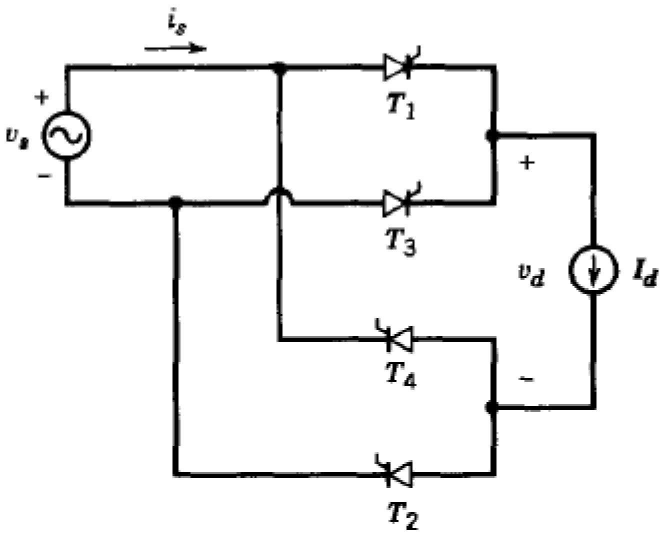
4.2 Single-Phase Converter



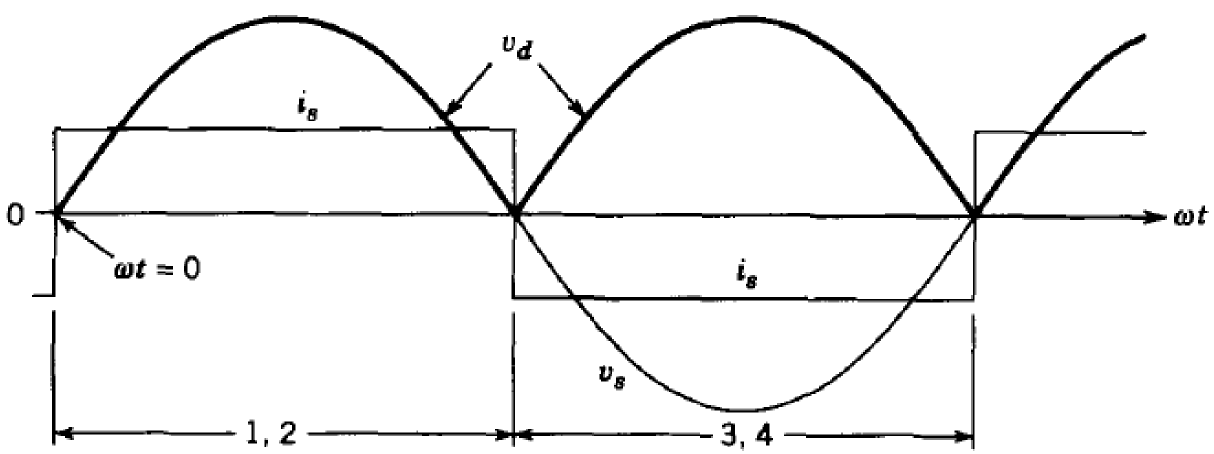


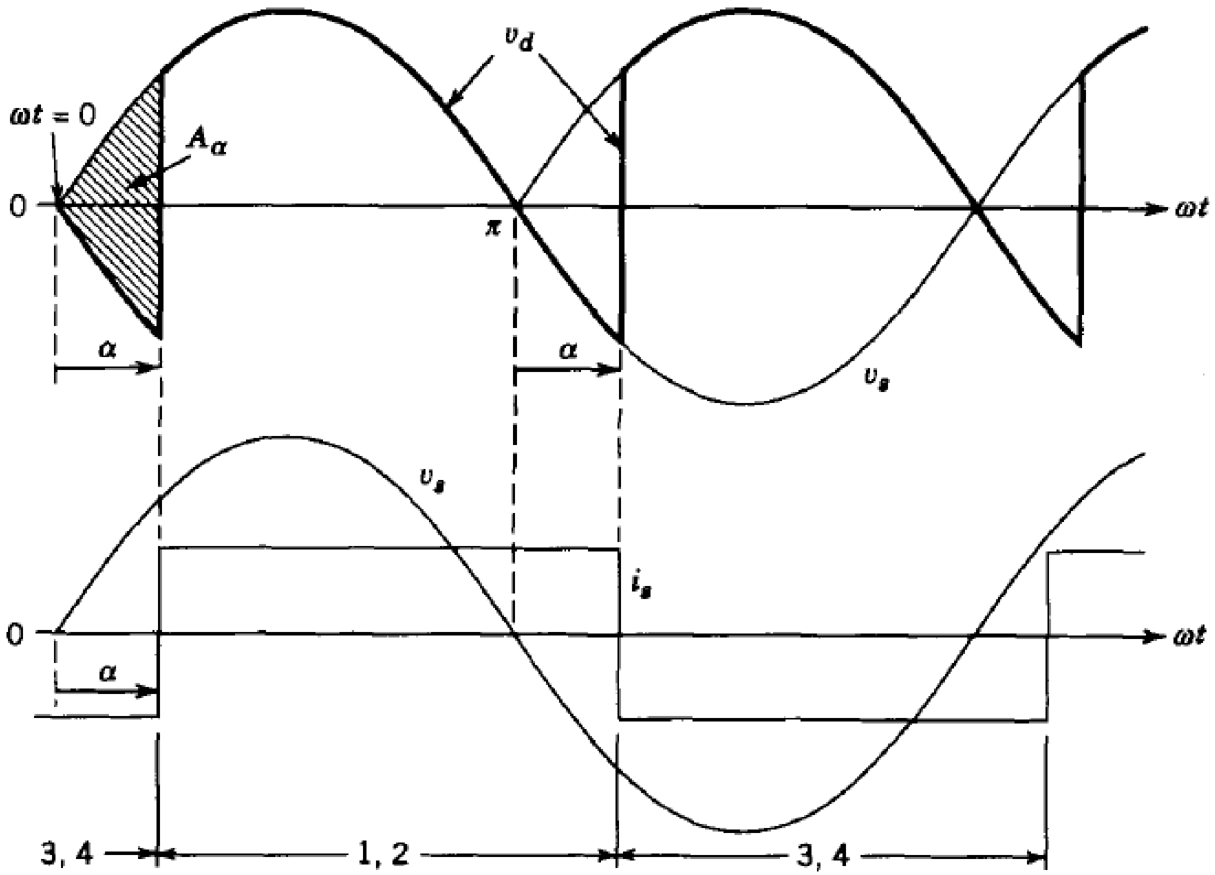
- Output voltage can be found by finding the difference between the time integral when $\alpha = 0$ and the shaded area A_α

$$V_{d\alpha} = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} \sqrt{2}V_s \sin(\omega t)\, d(\omega t) = \frac{2\sqrt{2}}{\pi} V_s cos\alpha = 0.9 V_s cos\alpha$$

- Power delivered to a constant current load can also be worked out in terms of α

4.2 Single-Phase Converter





Concept Check 4.1

A separately excited DC motor, 10 hp, 220 V, 1200 rpm, is connected with an ideal single-phase full converter. Its rated armature current is 40 A with armature resistance of 0.25 Ω and armature inductance of 10 mH. The AC supply voltage is 265 V while the motor constant is 0.18 V/rpm. Assume motor current is continuous and ripple-free. If a firing angle is 30°, find

(a) Speed of the motor (Ans: 1092.2 rpm)

(b) Motor torque (Ans: 68.8 Nm)

(c) Power to the motor (Ans: 8264 W)

Concept Check 4.1

Concept Check 4.1

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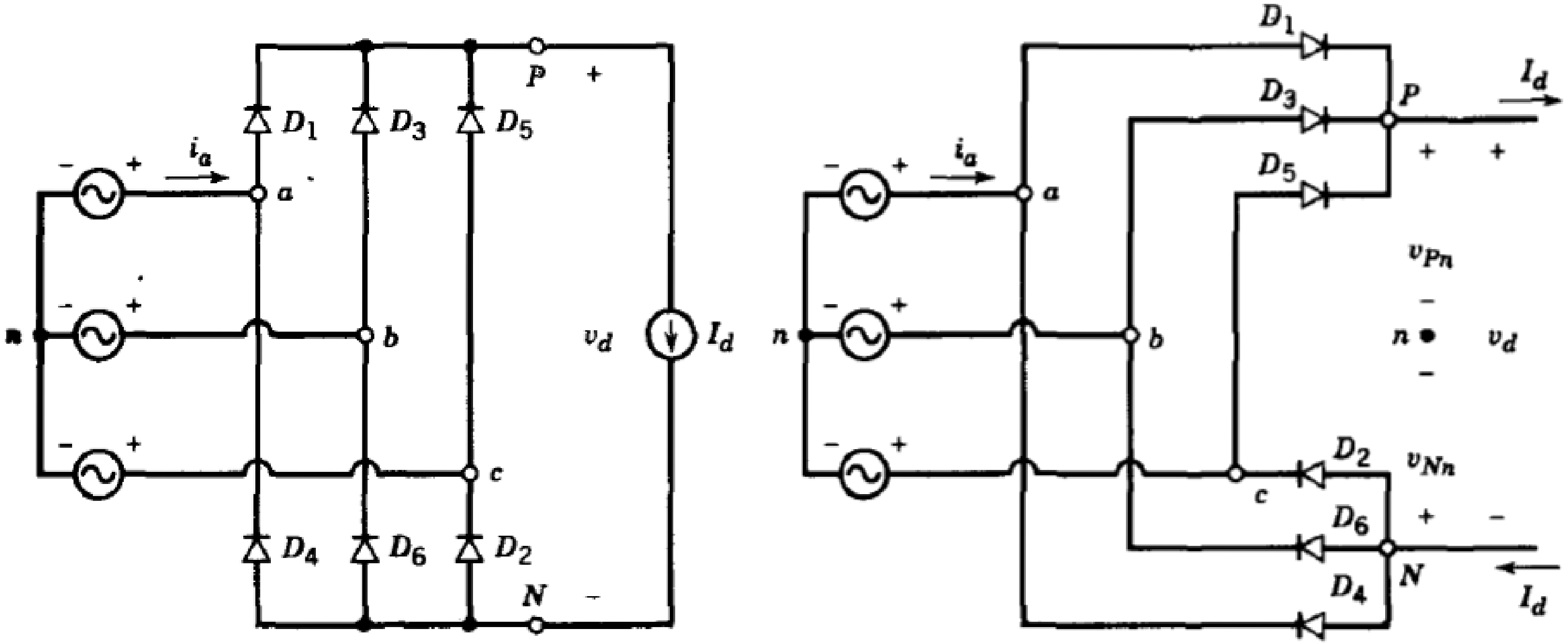
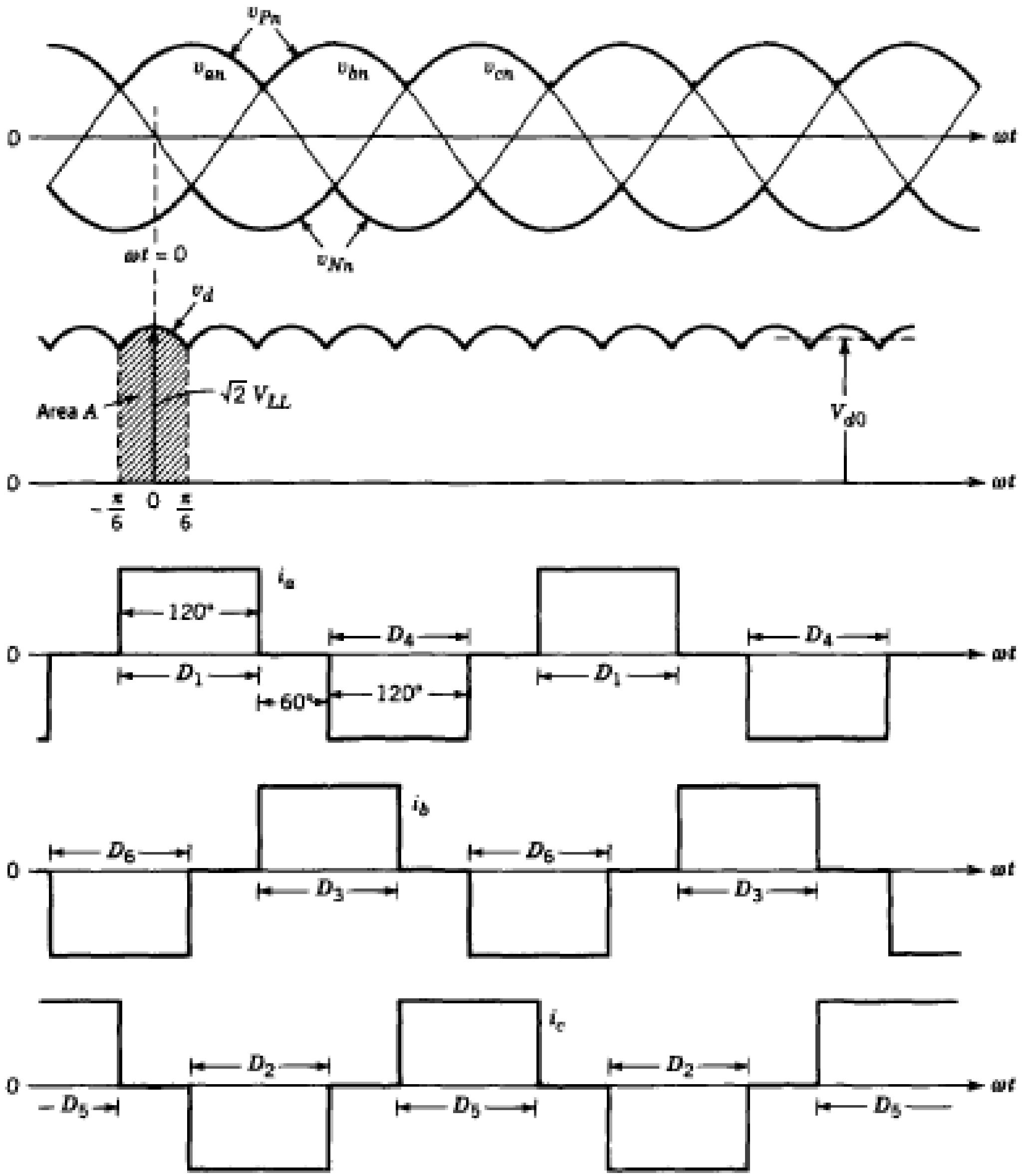
4.3 Three-Phase, Full-Bridge Rectifier



- Consider the case with no line inductance
- A 3-phase rectifier circuit somehow is similar to the case of 1-phase circuit
- A pair of diodes conduct at one time with voltage waveform across the load with respect to point *n*

4.3 Three-Phase, Full-Bridge Rectifier



4.3 Three-Phase, Full-Bridge Rectifier

- If the same voltage waveform is modified with point *N*, the dc-side voltage becomes

$$v_d = v_{Pn} - v_{Nn}$$

- The instantaneous voltage waveform consists of six segment per cycle of line frequency so that it is often known as *six-pulse* rectifier
- Consider one of the six segment

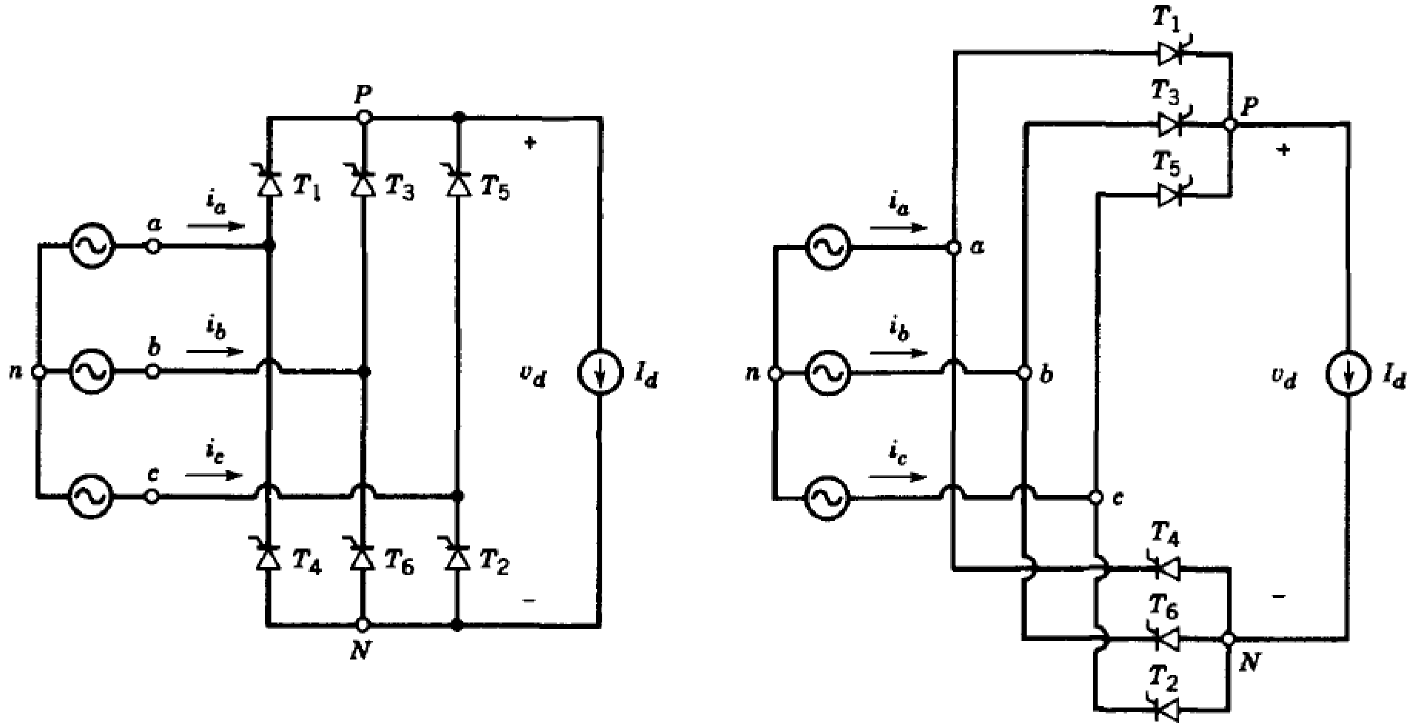
$$v_d = v_{ab} = \sqrt{2}V_{LL}\cos(\omega t) \qquad for\ -\frac{1}{6}\pi < \omega t < \frac{1}{6}\pi$$

- By integrating v_{ab} and dividing it by $\pi/3$, it yields

$$V_{d0} = \frac{1}{\pi/3}\int_{-\pi/6}^{\pi/6}\sqrt{2}V_{LL}cos(\omega t)d(\omega t) = \frac{3}{\pi}\sqrt{2}V_{LL}$$

$$= \frac{3}{\pi}\sqrt{6}V_p$$

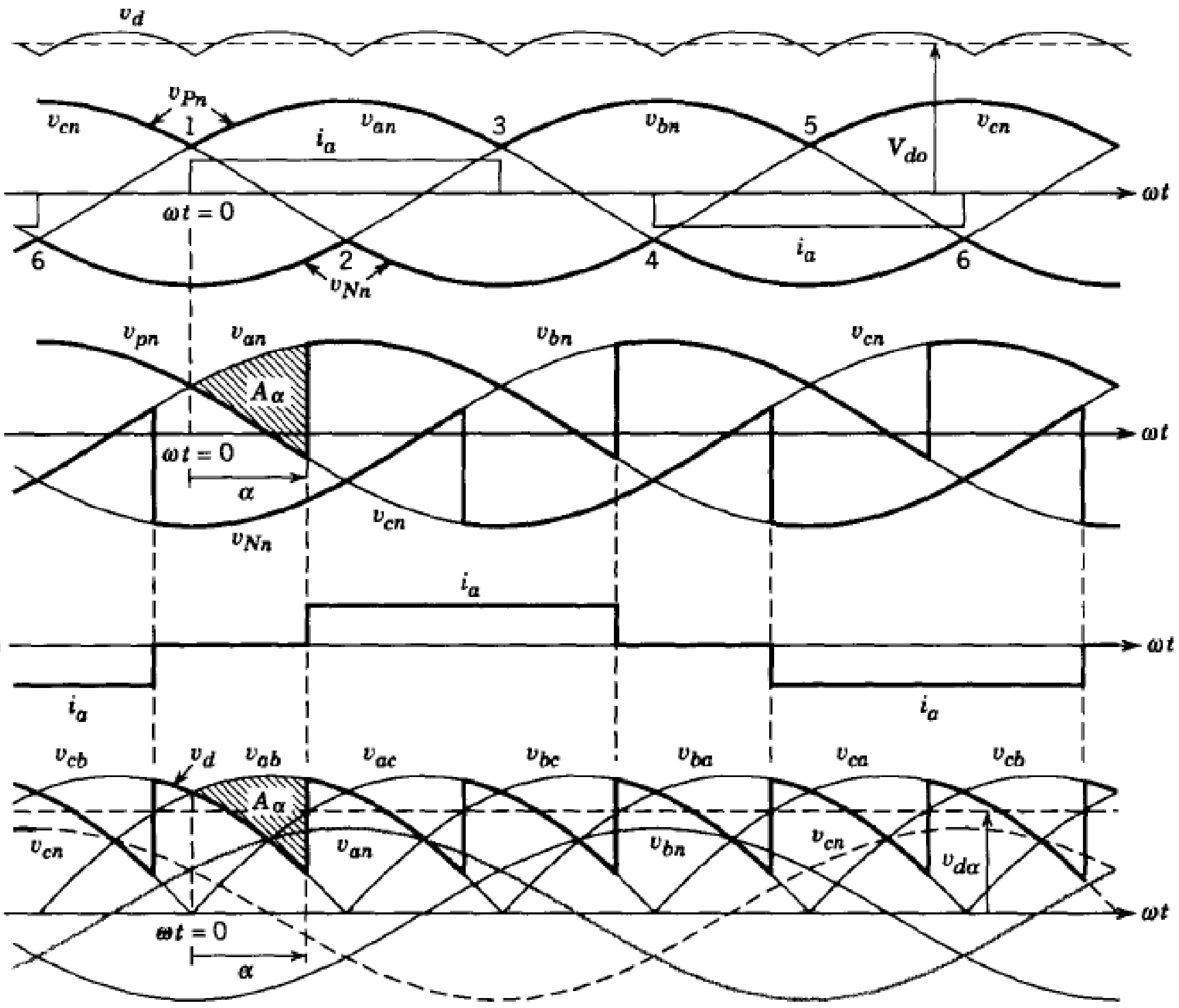
4.4 Three-Phase Converter



- Firing angle α results in reduction of output voltage
- Based on previous derivation

$$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL} = 1.35 V_{LL}$$

4.4 Three-Phase Converter



4.4 Three-Phase Converter

- Consider reduction in the average ac voltage with a delay angle

$$V_{d\alpha} = V_{do} - \frac{A_{\alpha}}{\pi/3}$$

- With reference to the waveform

$$A_{\alpha} = \int_{0}^{\alpha} \sqrt{2} V_{LL} \sin(\omega t)\, d(\omega t)$$

$$V_{d\alpha} = \frac{3\sqrt{2}}{\pi} V_{LL} cos\alpha = 1.35 V_{LL} cos\alpha$$

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Concept Check 4.2

A separately excited DC motor, 125 hp, 600 V, 1800 rpm, is connected with a three-phase full converter. The converter is operated from a three-phase, 480 V, 60 Hz supply. The rated armature current of the motor is 165 A with armature resistance of 0.0874 Ω, armature inductance of 6.5 mH and motor constant is 0.33 V/rpm. Assume the converter and AC supply are ideal. If a firing angle is 30°, find

(a) Assume at no-load condition, the armature current is 10 % of the rated current. Find no-load speeds at firing angles of 0° and 30° (Ans: 1959 rpm; 1696 rpm)

(b) Find the firing angle for rated speed of 1800 rpm at rated motor current (Ans: 20.1°)

(c) Find the speed regulation for the firing angle obtained in (b) (Ans: 2.18 %)

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Concept Check 4.2

Concept Check 4.2

Concept Check 4.2

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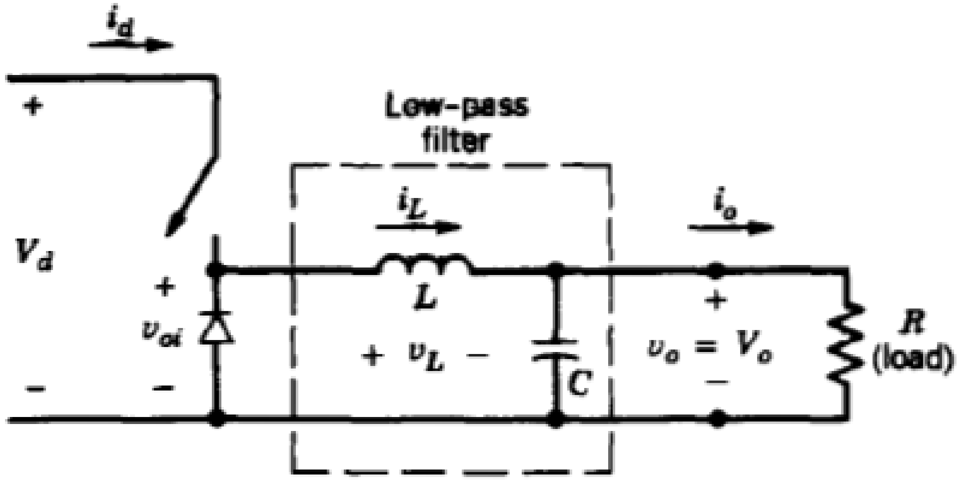
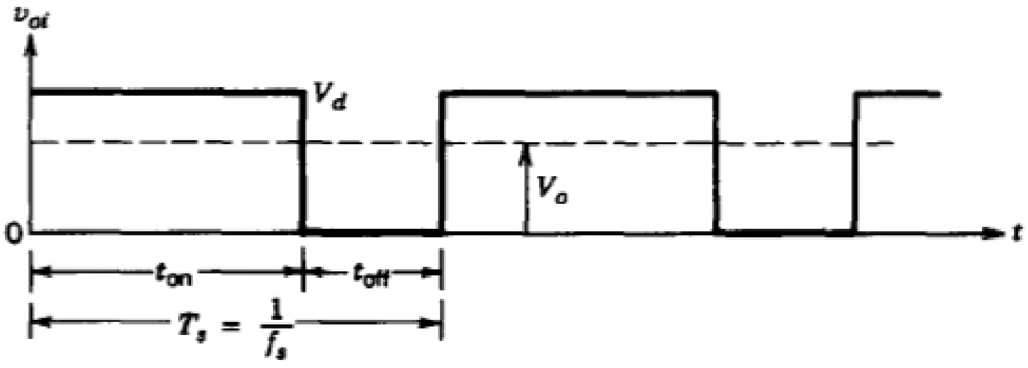
4.5 Step-Down (Buck) Converter



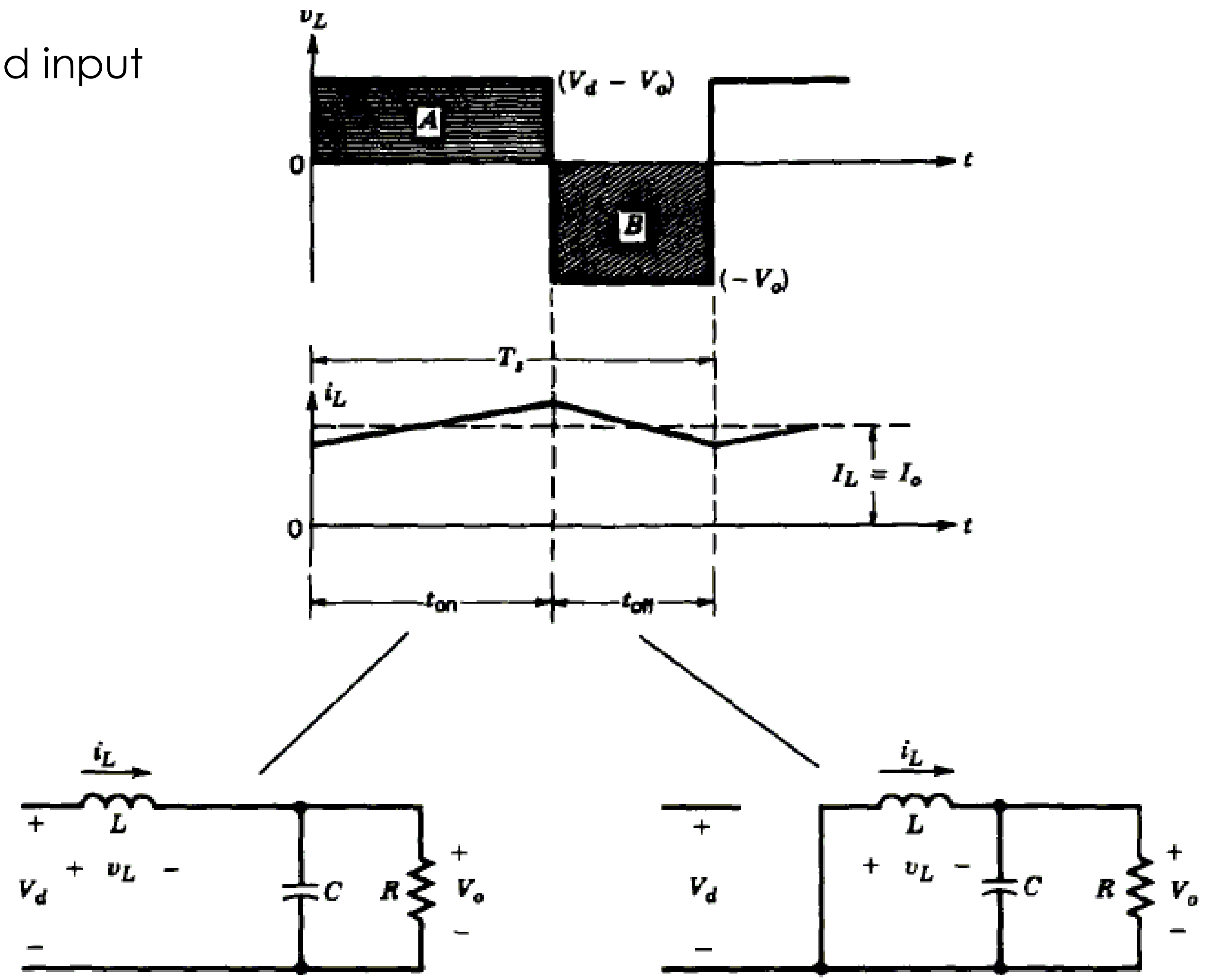


- Pulse Width Modulation (PWM) is used to control duty ratio
- Average output voltage is obtained by taking average waveform across the diode
- There are two operating modes, namely continuous conduction mode (CCM) and discontinuous conduction mode (DCM)
- In CCM, current in the inductor does not go to zero at any time

4.5 Step-Down (Buck) Converter

- Relation between output and input

$$\frac{V_o}{V_d} = D$$



Concept Check 4.3

A separately excited DC motor is controlled by a chopper with DC supply of 120 V. The motor consists of armature resistance of 0.5 Ω, armature inductance of 20 mH and motor constant is 0.05 V/rpm. The motor drives a constant-torque load that needs an average armature current of 20 A. Assume the motor current is continuous.

(a) Find the range of speed control (Ans: $0 < N < 2200$ rpm)

(b) Find the duty cycle (Ans: $1/12 < D < 1$)

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Concept Check 4.3

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Concept Check 4.3

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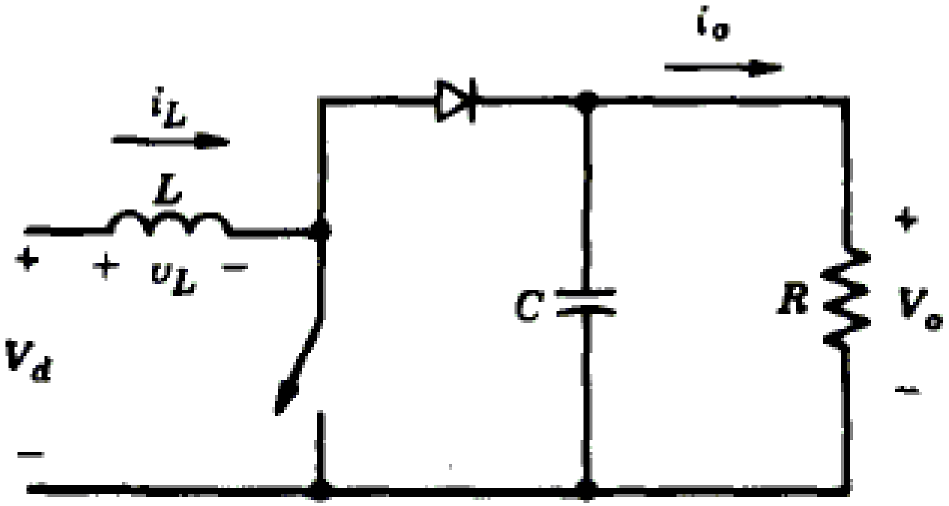
4.6 Step-Up (Boost) Converter



- Same as buck converter, PWM is used to control duty ratio
- Boost converter is able to produce an output voltage higher than its input
- Similar as buck converter, boost converter can also provide CCM and DCM

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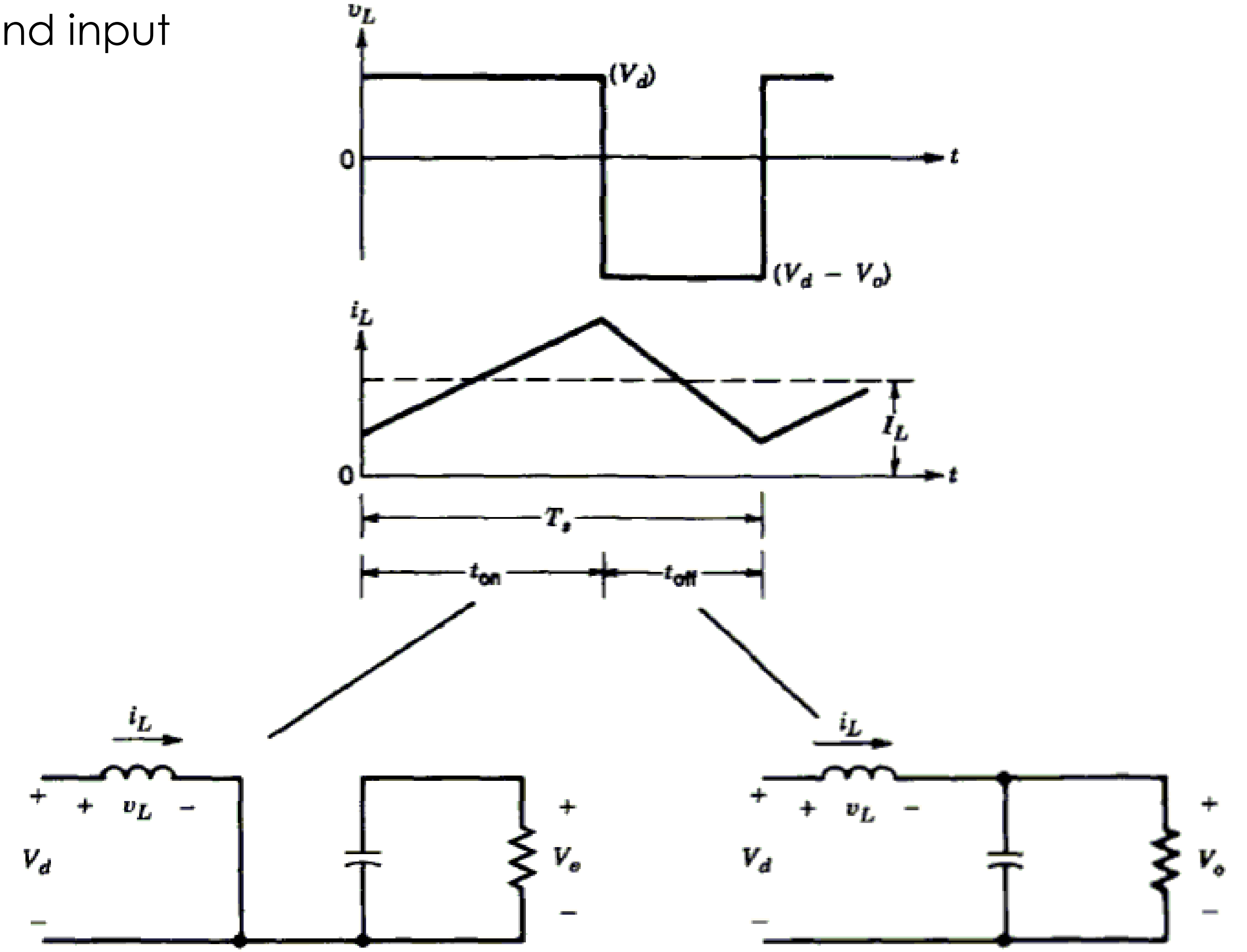
4.6 Step-Up (Boost) Converter

- Relation between output and input

$$\frac{V_o}{V_d} = \frac{1}{1-D}$$



Concept Check 4.4

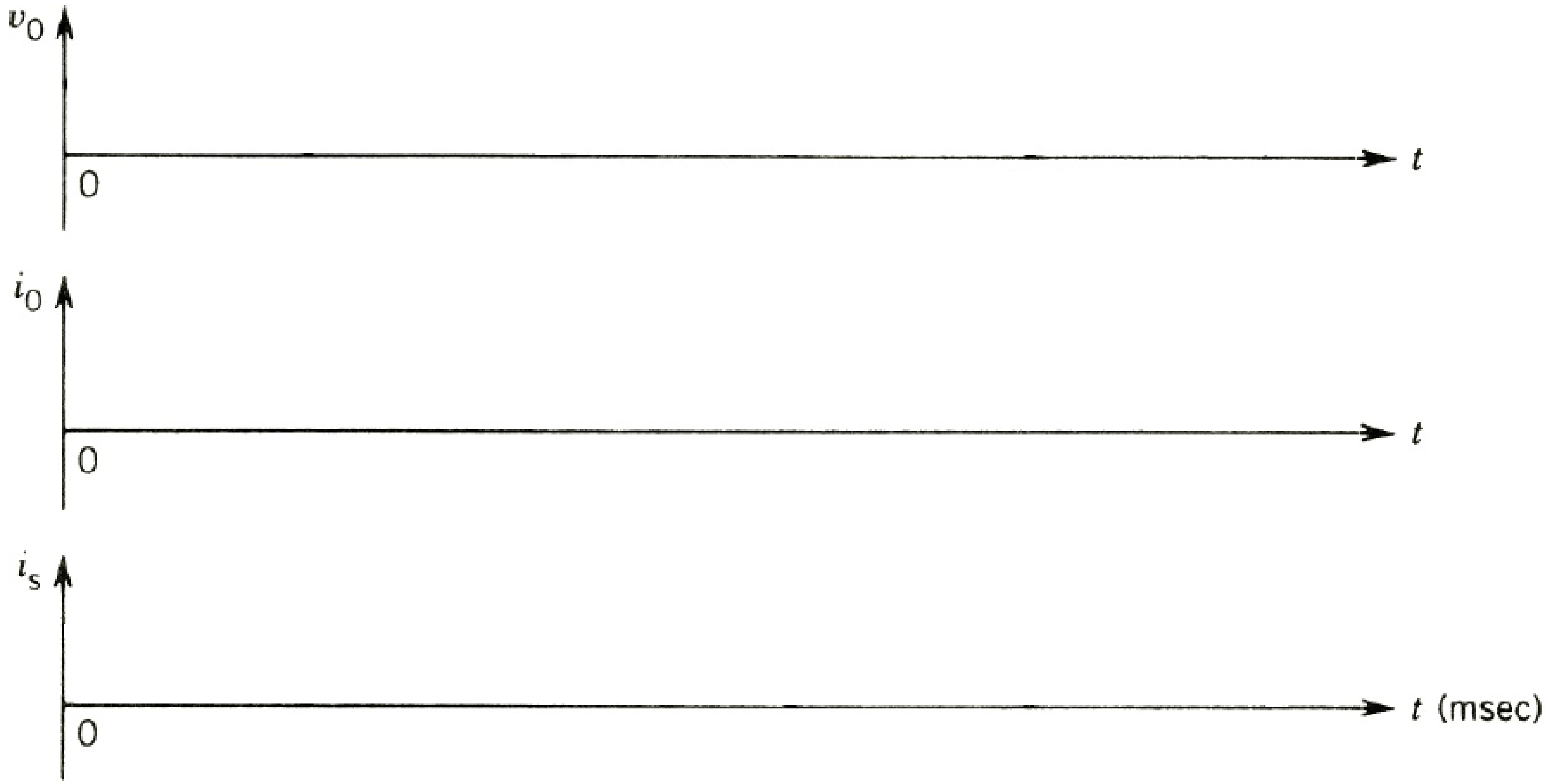
A step-up converter is used to control a motor during regenerative braking mode. The motor consists of voltage constant of 0.3 V/rpm and DC bus voltage of 600 V. When the motor is at 800 rpm, it draws average motor current of 300 A.

(a) Draw the waveforms of output voltage, output current and supply current.

(b) Find the duty ratio of the converter.

(c) Find the power fed back to the supply.

Concept Check 4.4



Concept Check 4.4

Concept Check 4.4

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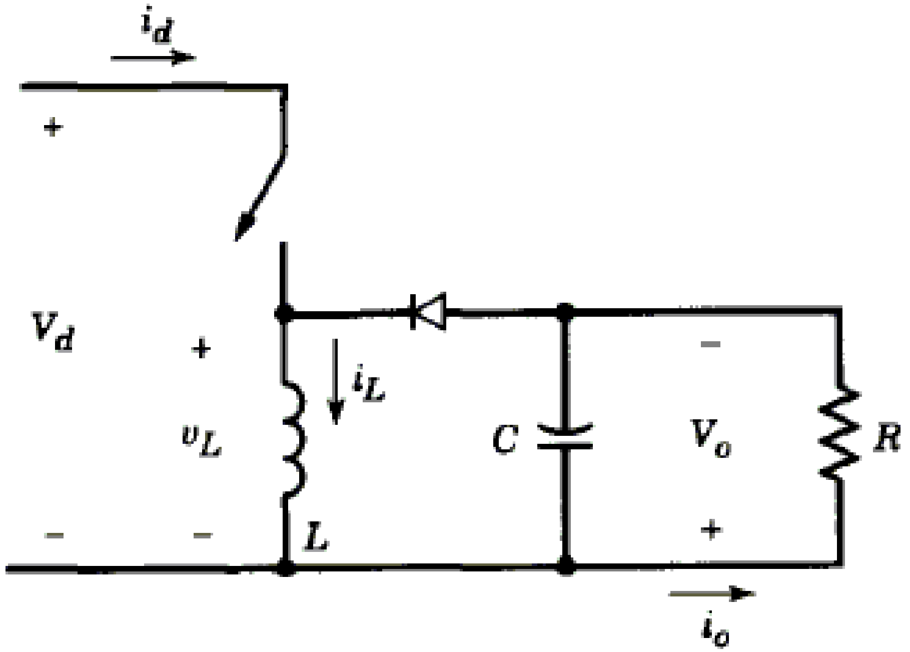
4.7 Buck-Boost Converter



- A buck-boost converter is able to produce an output voltage higher or lower than its input with the polarity reversed
- When switch is closed, input provides energy to inductor and diode is reversed biased
- When the switch is open, the stored energy is transferred to the output
- No energy is supplied by the input during this interval

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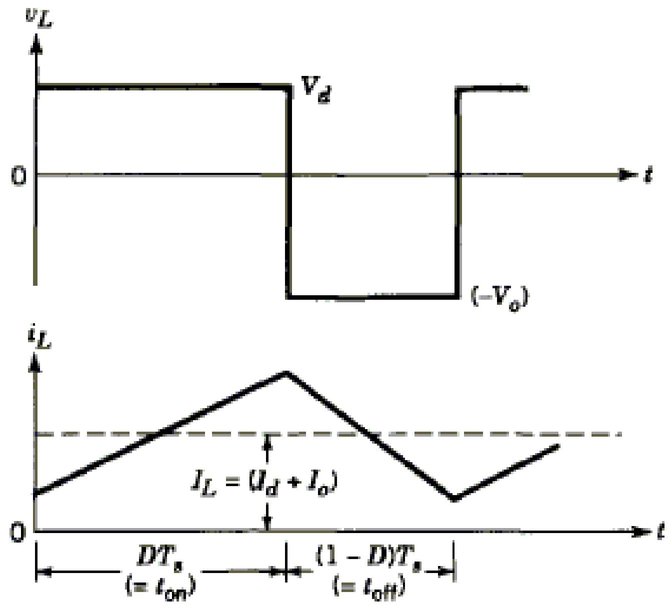
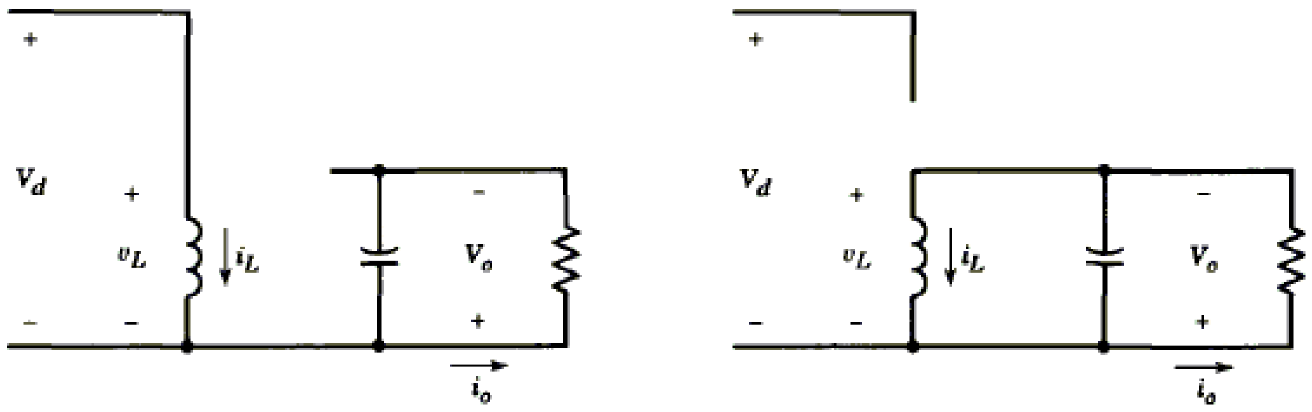
4.7 Buck-Boost Converter

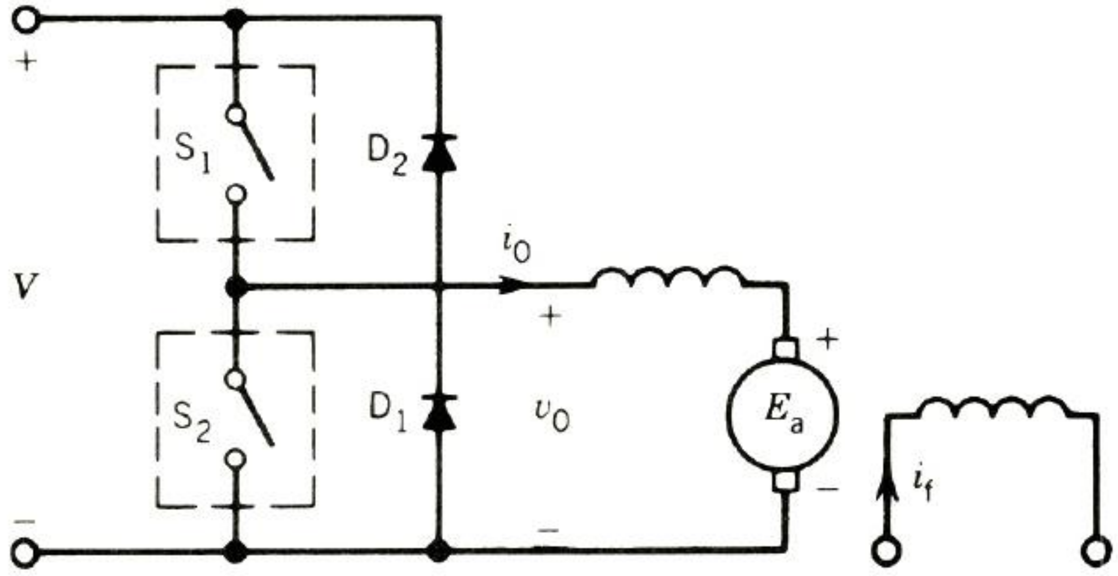
- Relation between output and input

$$\frac{V_o}{V_d} = \frac{D}{1 - D}$$





4.8 Two-Quadrant Chopper



- Two-quadrant chopper is formed by combination of buck and boost converters
- If S_1 and D_1 are operated, the system will operate as a buck converter and the DC machine as a motor
- If S_2 and D_2 are operated, the system will operate as a boost converter and the DC machine as a generator

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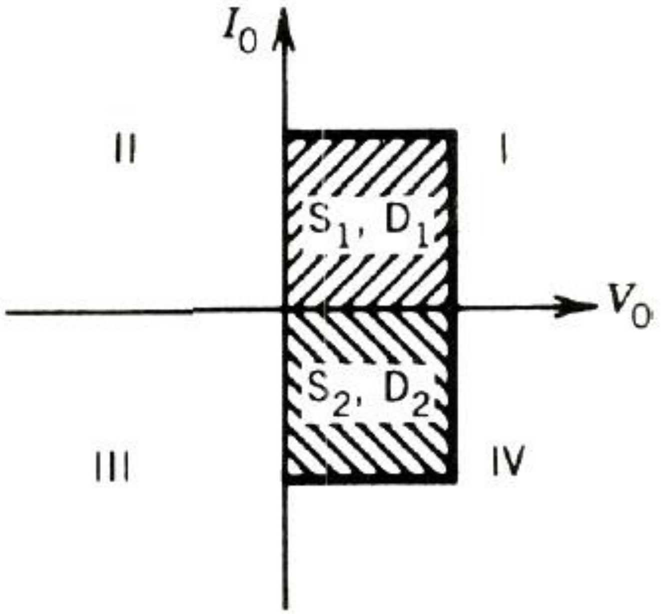
4.8 Two-Quadrant Chopper



- When the chopper is as a buck converter, its output voltage is either *V* or zero
- Its average voltage output is positive with output current flows in positive direction
- When the chopper is as a boost converter, its output voltage is either zero or *V*
- Its average voltage output is positive with output current flows in negative direction