TSTE19 Power Electronics

Lecture 3

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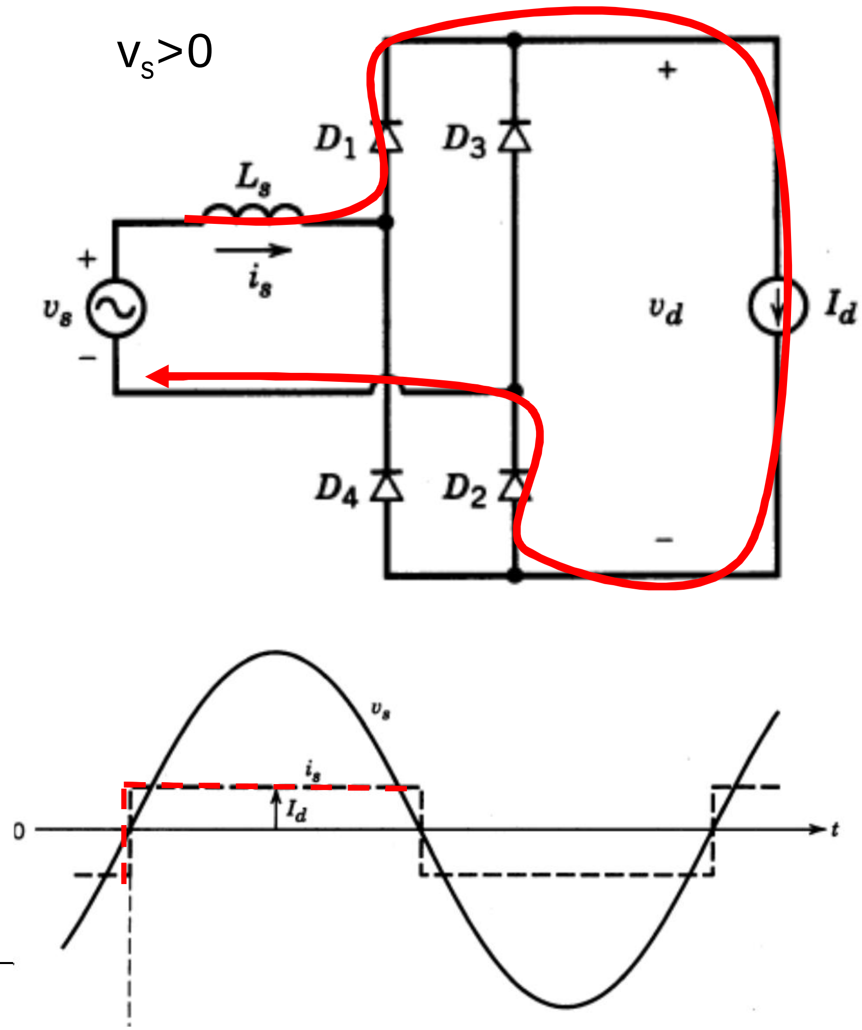
Outline

- Rectifiers
  - Current commutation
- Rectifiers, cont.
  - Three phase

Effect of L_s on current commutation

- Current commutation = current path changed from one diode to another
  - Commutation not instantaneous when L_s nonzero
  - Magnetic energy change
- Use simplified example
  - Output represented by constant dc current source

$v_s > 0$



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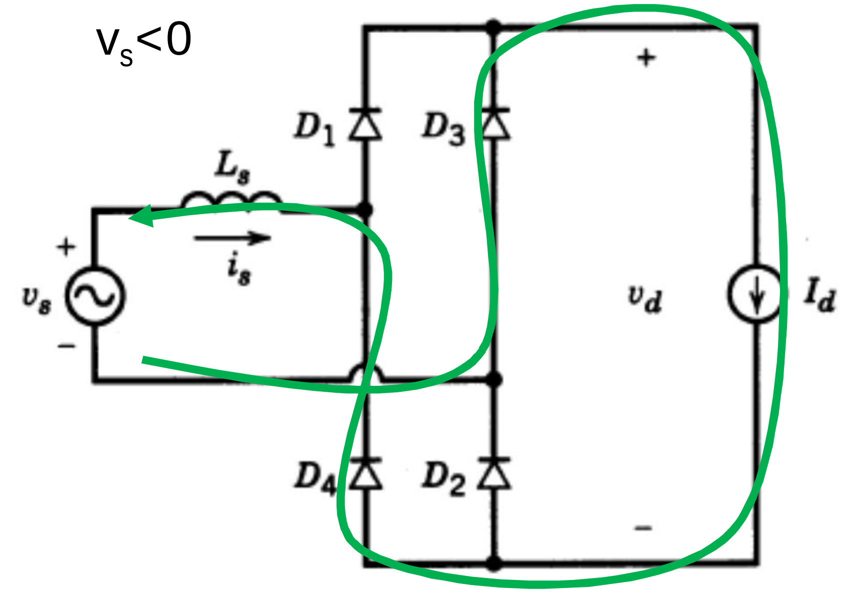
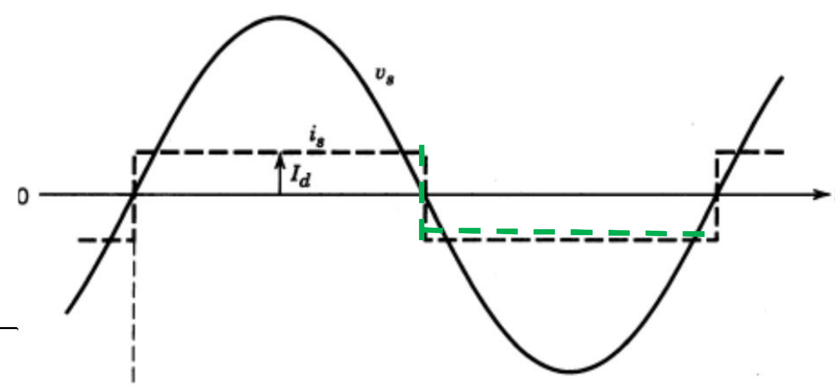
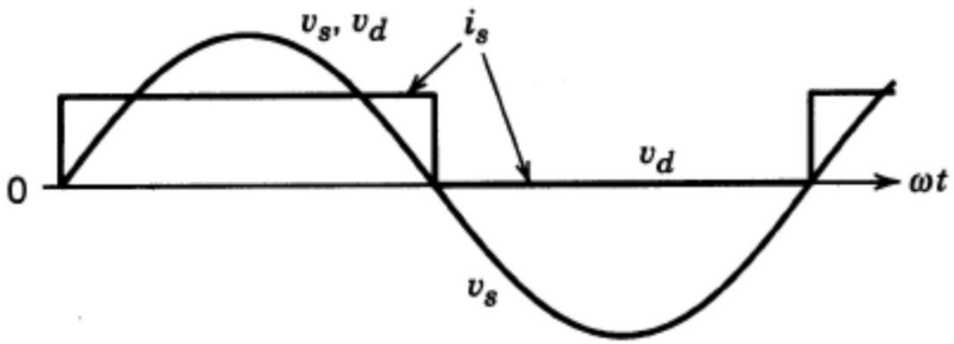
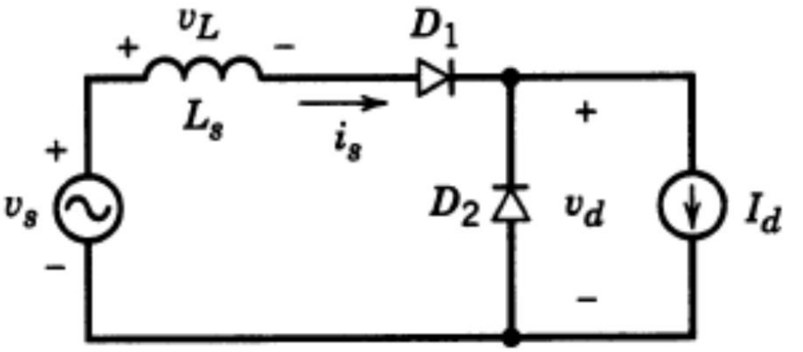




Source inductance effects, cont

- Waveform if L=0

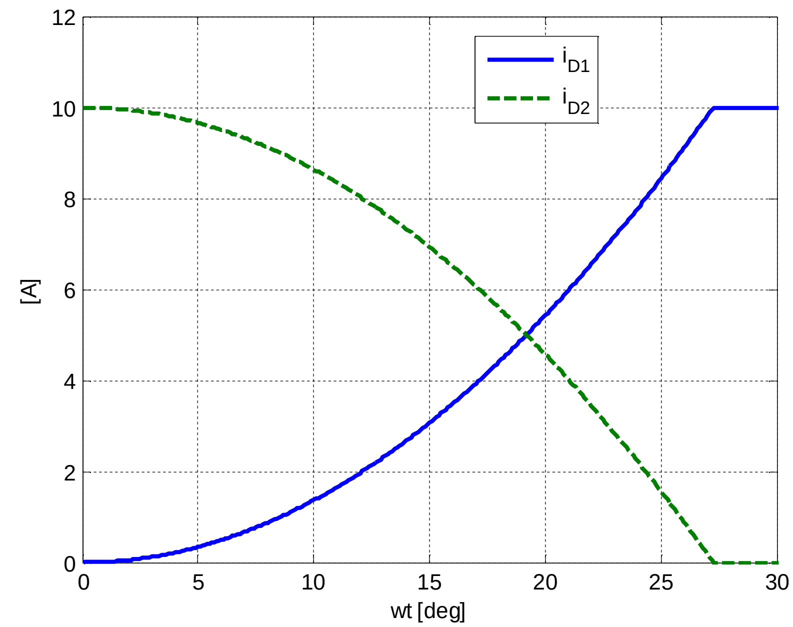


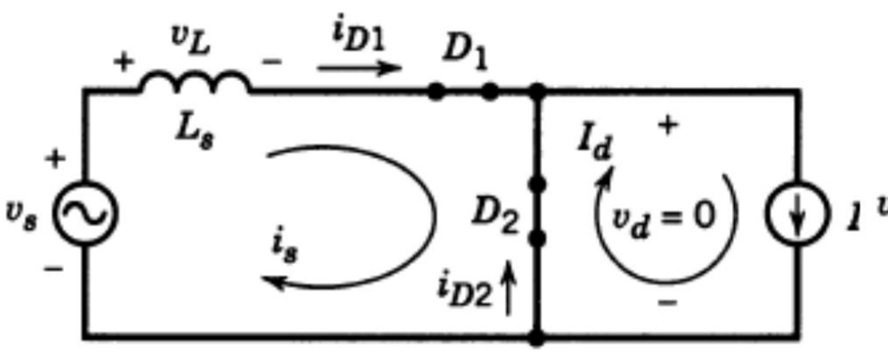


- Prior to $\omega t = 0$, v_s is negative, current flow through D2
  - $v_d = 0$, $i_s = 0$

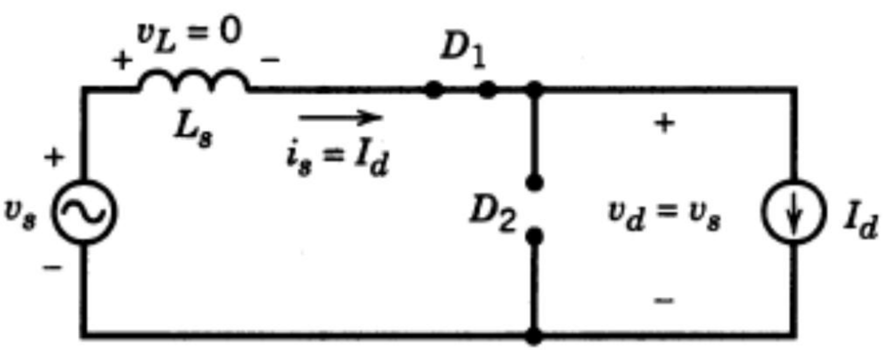
Current commutation

- During commutation ($\omega t > 0$)
  - v_s positive, D1 turns on
  - $i_{D1} = i_s$
  - $i_{D2} = I_d - i_s$
  - $i_{D1} + i_{D2} = I_d$
  - D2 stops conducting when $i_{D2} = 0$





Valid for $0 < i_s < I_d$



After commutation completed

Commutation current

- Commutation current
  - Temporary current contribution related to energy transfer

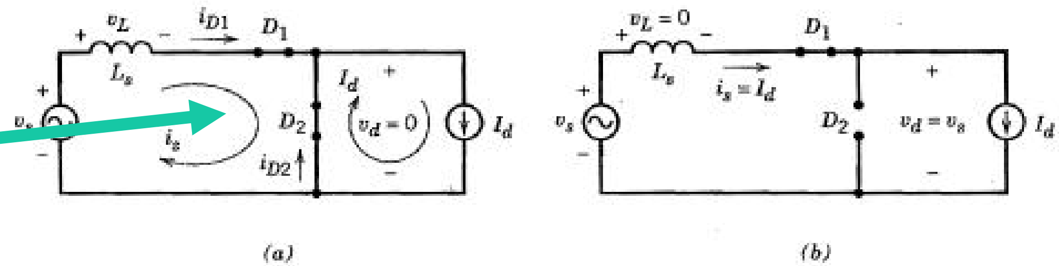


Figure 5-12 (*a*) Circuit during the commutation. (*b*) Circuit after the current commutation is completed.

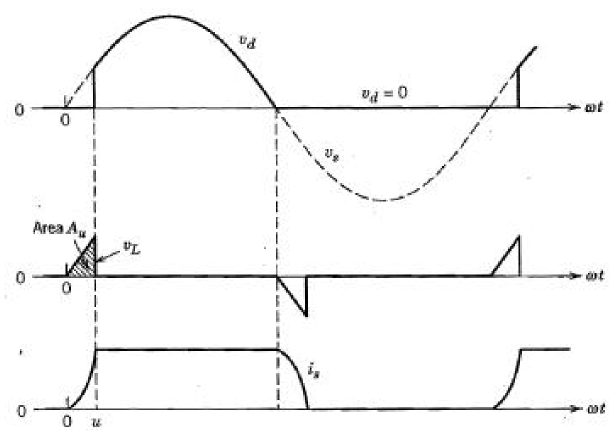
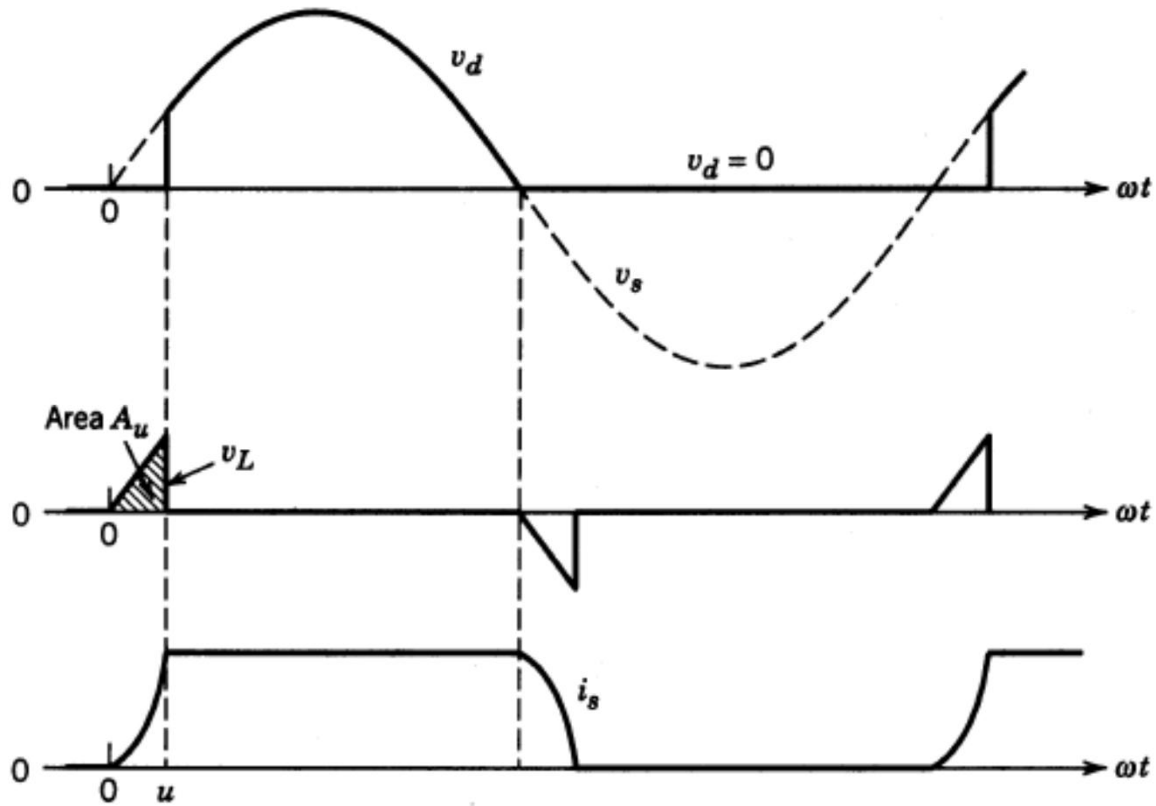


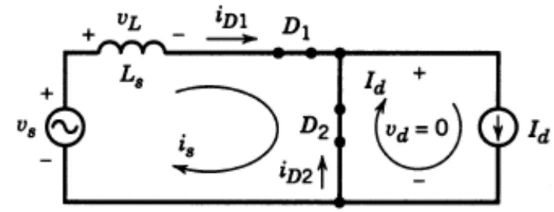
Figure 5-13 Waveforms in the basic circuit of Fig. 5-11. Note that a large value of L_s is used to clearly show the commutation interval.

Current commutation waveforms

- Large L_s used to clearly show effect
- Time for commutation depend on L_s size and current change in L_s



Current commutation time



- i_s through inductor starts at zero, end at I_d when ωt=u

$$v_L = \sqrt{2}V_s \sin\omega t = L_s \frac{di_s}{dt} = \omega L_s \frac{di_s}{d(\omega t)} \quad 0 < \omega t < u$$

$$\sqrt{2}V_s \sin\omega t\, d(\omega t) = \omega L_s di_s$$

- Integrate both sides, left is area A_u (voltage * angle)

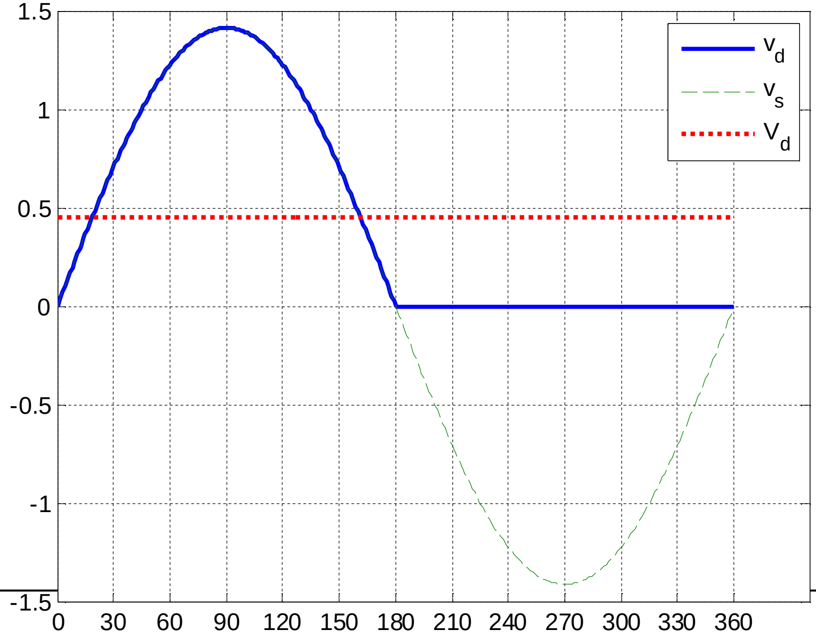
$$A_u = \int_0^u \sqrt{2}V_s \sin\omega t\, d(\omega t) = \sqrt{2}V_s(1 - \cos u) = \omega L_s \int_0^{I_d} di_s = \omega L_s I_d$$

- Commutation angle can be calculated

$$\cos u = 1 - \frac{\omega L_s I_d}{\sqrt{2}V_s}$$

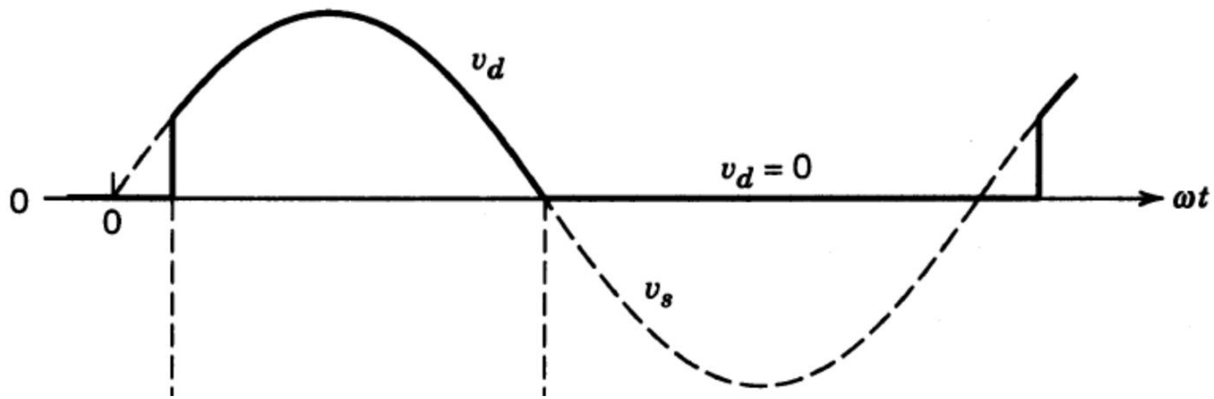
Half-wave rectifier output voltage

- V_{do} = Ideal average voltage of half-wave rectified voltage (effect of the commutation inductance L_s neglected)
  - $V_{d0} = \frac{1}{2\pi}\int_0^{\pi}\sqrt{2}V_s \sin(\omega t)\, d\omega t = \frac{\sqrt{2}V_s}{2\pi}[-\cos(\omega t)]_0^{\pi} = \frac{2\sqrt{2}V_s}{2\pi}$
  - $V_{d0} \approx 0.45V_s$



Output voltage incl commutation voltage drop

- $V_d = V_{d0} - \Delta V_d = V_{d0} - \frac{A_u}{2\pi} = 0.45V_s - \frac{\omega L_s}{2\pi} I_d$
- Commutation voltage drop appears as a resistance to the dc-side current. $R_{comm} = \frac{\omega L_s}{2\pi}$



Commutation conclusions

- Conduction:
  - Magnetic energy is stored related to the inductance of the conduction path
- Commutation
  - Transfer of current between two paths:
  - ⇒Stored magnetic energy needs to be transfered!
  - Output voltage reduction proportional to I_d and L_s

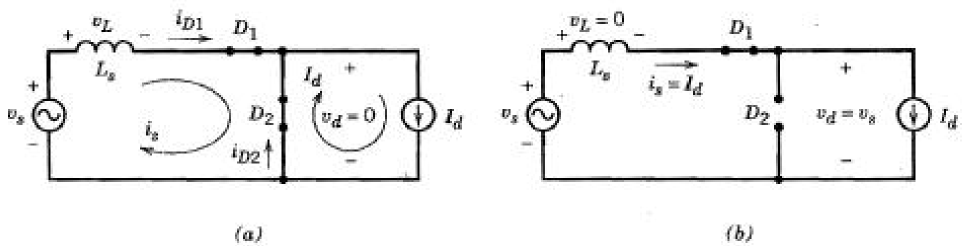


Figure 5-12 (*a*) Circuit during the commutation. (*b*) Circuit after the current commutation is completed.

Exercise 5-5

Consider the basic commutation circuit of Fig. *5-11a* with I_d = 10 A.

a) With V_s=120 V at 60 Hz and L_s = 0, calculate V_d and the average power P_d

b) With V_s=120 V at 60 Hz and L_s = 5 mH, calculate *u*, V_d , and P_d

c) With data as i b) calculate *u*, V_d , and P_d with I_d = 20 A

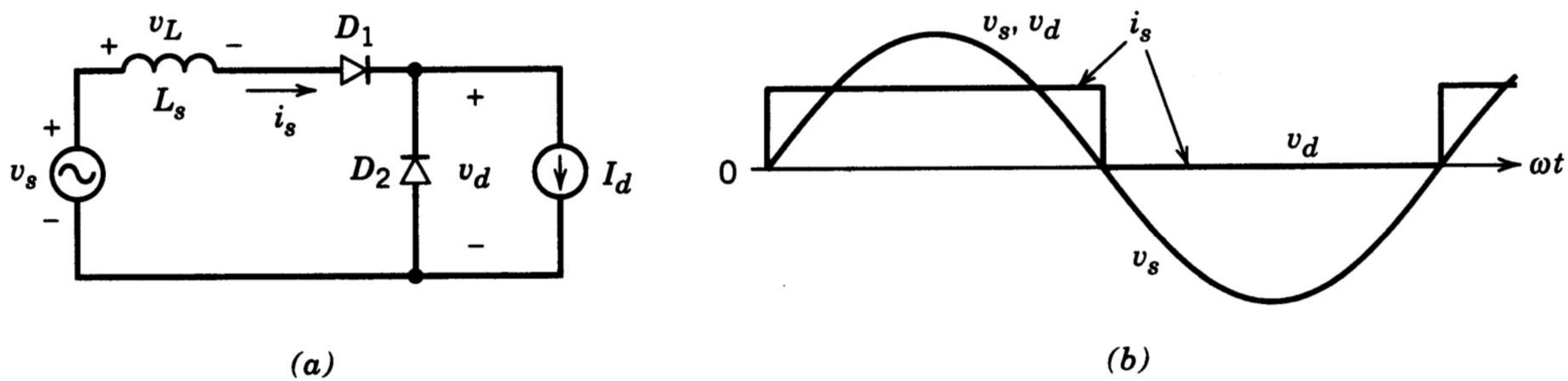
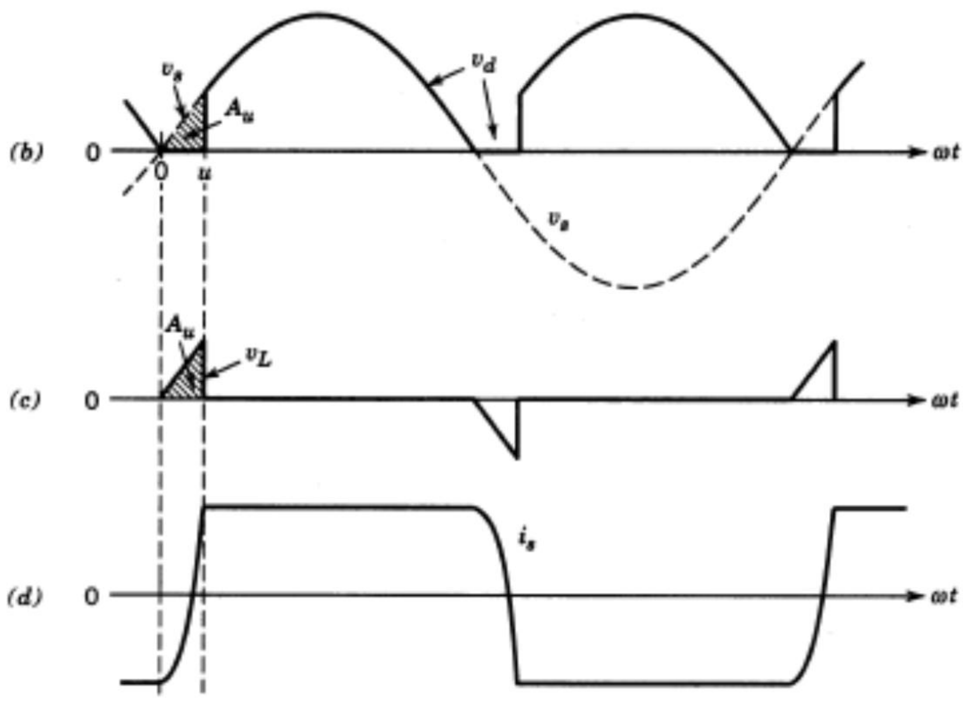
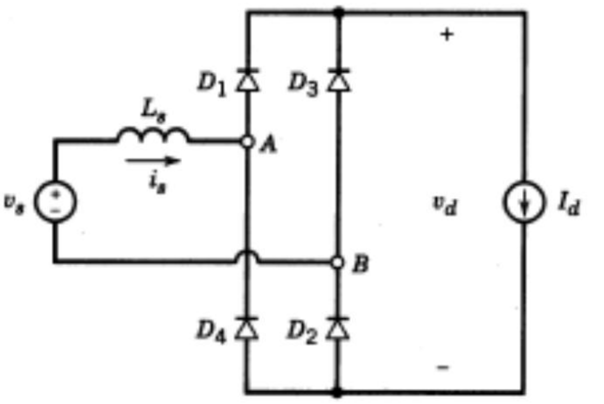


Figure 5-11 Basic circuit to illustrate current commutation. Waveforms assume $L_s = 0$.

Current commutation in full-bridge

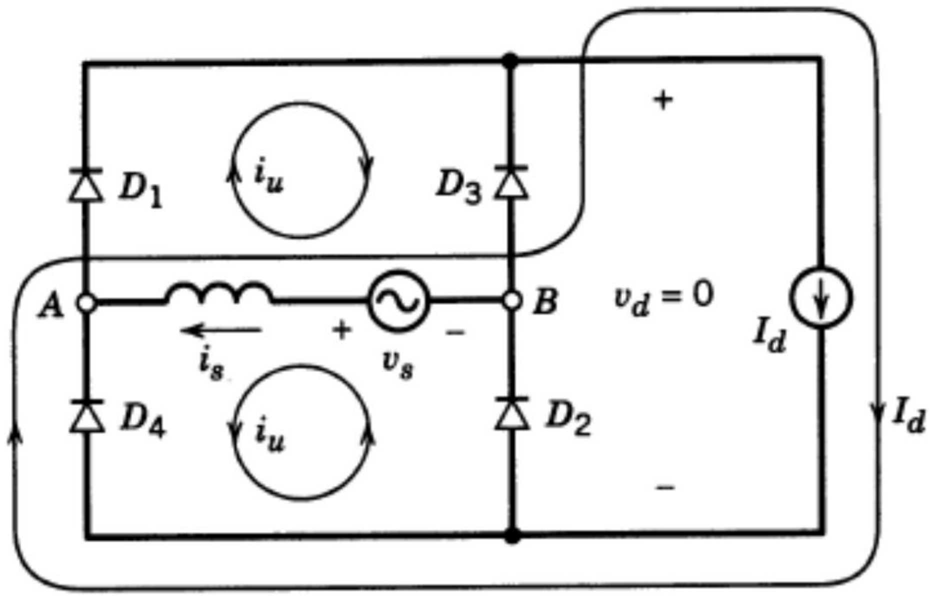
- Same principle for area A_u due to L_s





Rectifier during current commutation

- v_s negative before t = 0
  - D3 and D4 conducting
  - $i_s = -I_d$
- v_s positive
  - D1 and D2 starts conducting (Short circuit path through D3 and D4)
- i_u are commutation currents
- $v_d = 0$ during commutation



Valid for $-I_d < i_s < I_d$

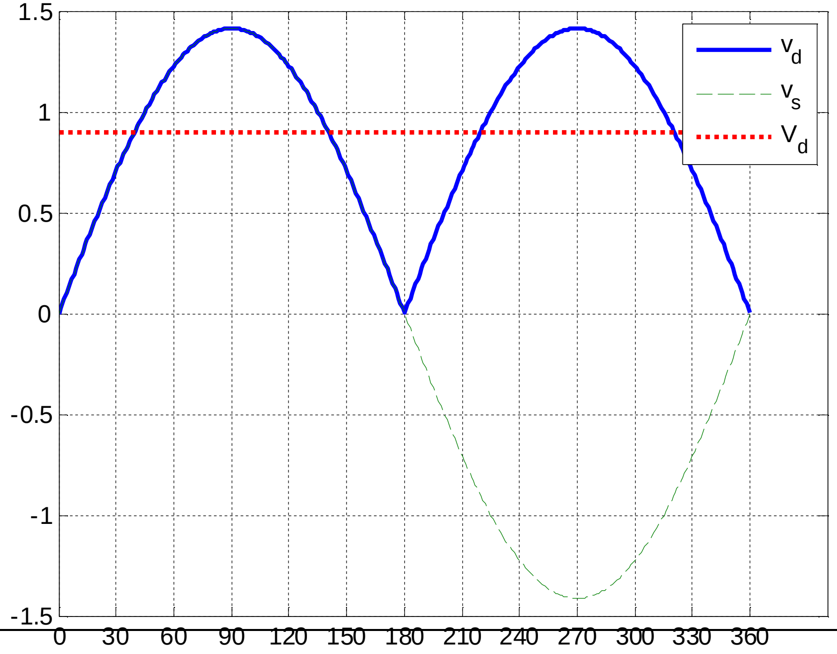
Current commutation angle

- i_s change is double that of previous example (from $-I_d$ to I_d)

$$\cos u = 1 - \frac{2\omega L_s I_d}{\sqrt{2} V_s}$$

Full-bridge rectifier output voltage

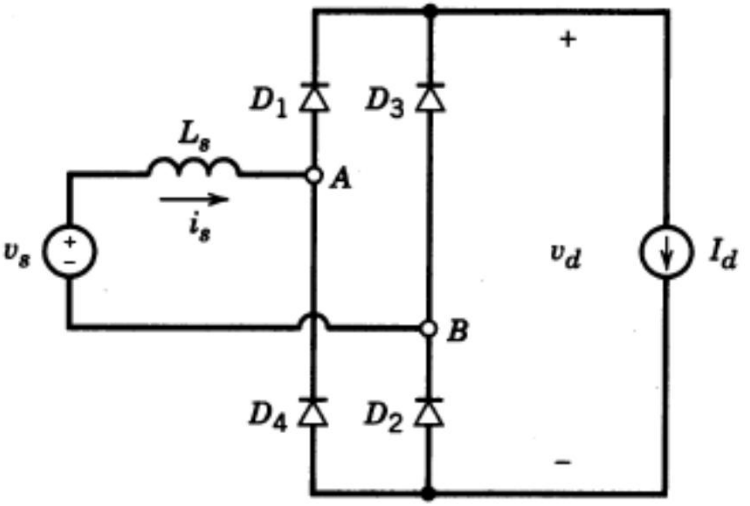
- V_{do} = average voltage of full wave rectified voltage (effect of the commutation inductance L_s neglected)
  - $V_{d0} = \frac{1}{\pi}\int_0^{\pi} \sqrt{2}V_s \sin(\omega t)\, d\omega t = \frac{\sqrt{2}V_s}{\pi}[-\cos(\omega t)]_0^{\pi} = \frac{2\sqrt{2}V_s}{\pi}$
  - $V_{d0} \approx 0.9V_s$



Exercise 5-8

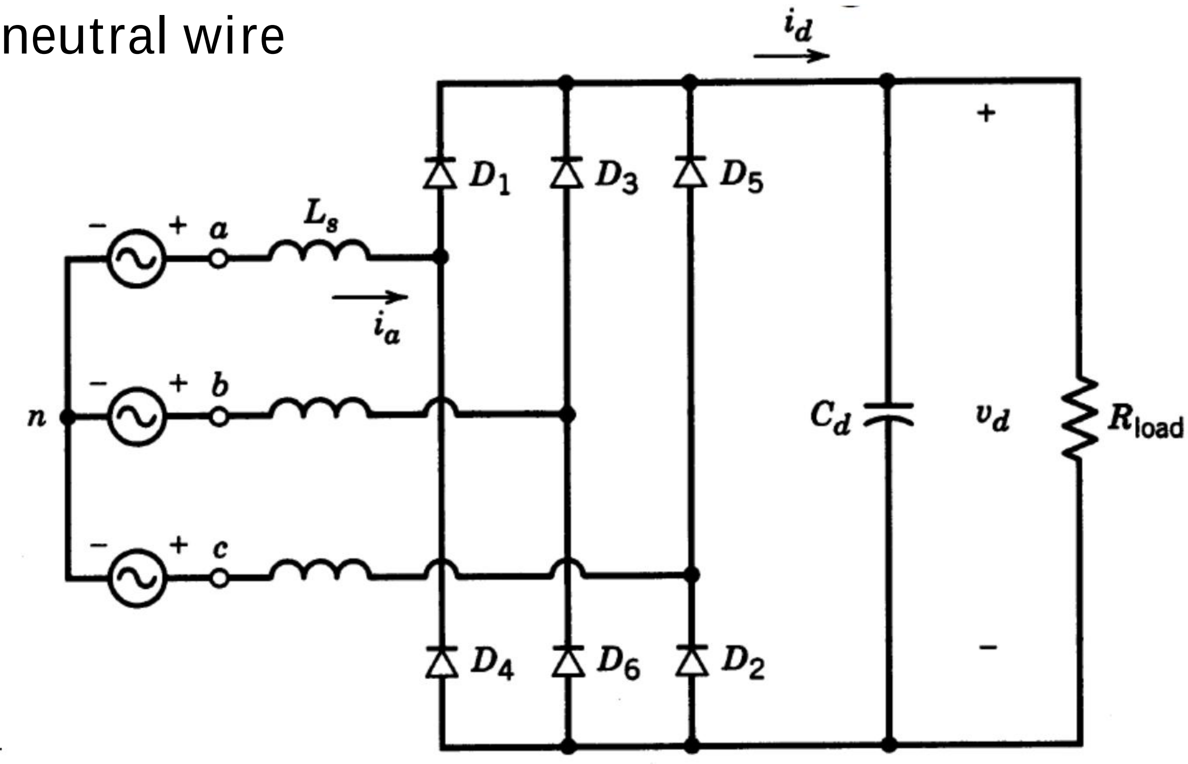
In the single-phase rectifier circuit shown in Fig. *5-14a*, V_s = 120 V at 60 Hz, L_s = 1 mH, and I_d = 10 A.

1. Calculate *u*, V_d, and P_d
2. What is the percentage voltage drop in V_d due to L_s?



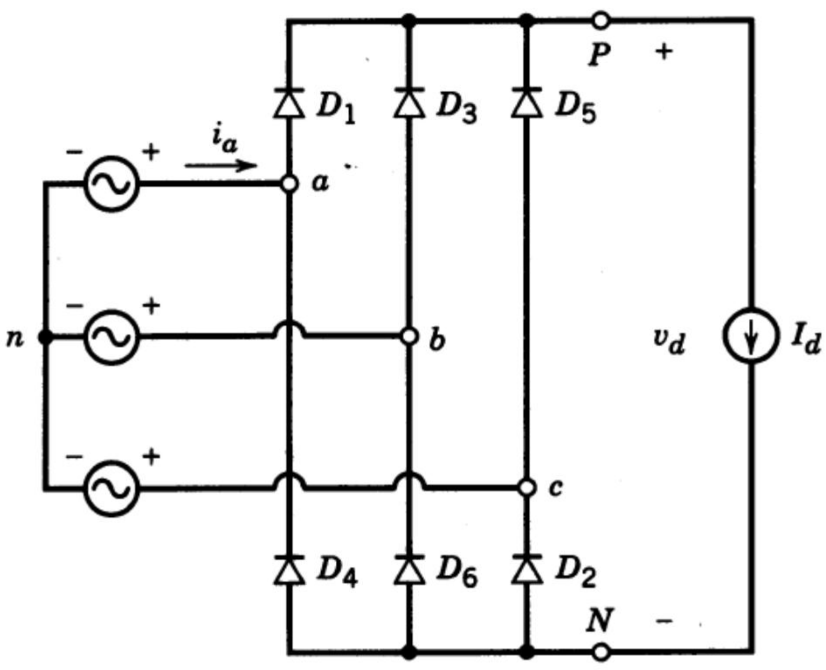
3-phase full-bridge rectifier, general view

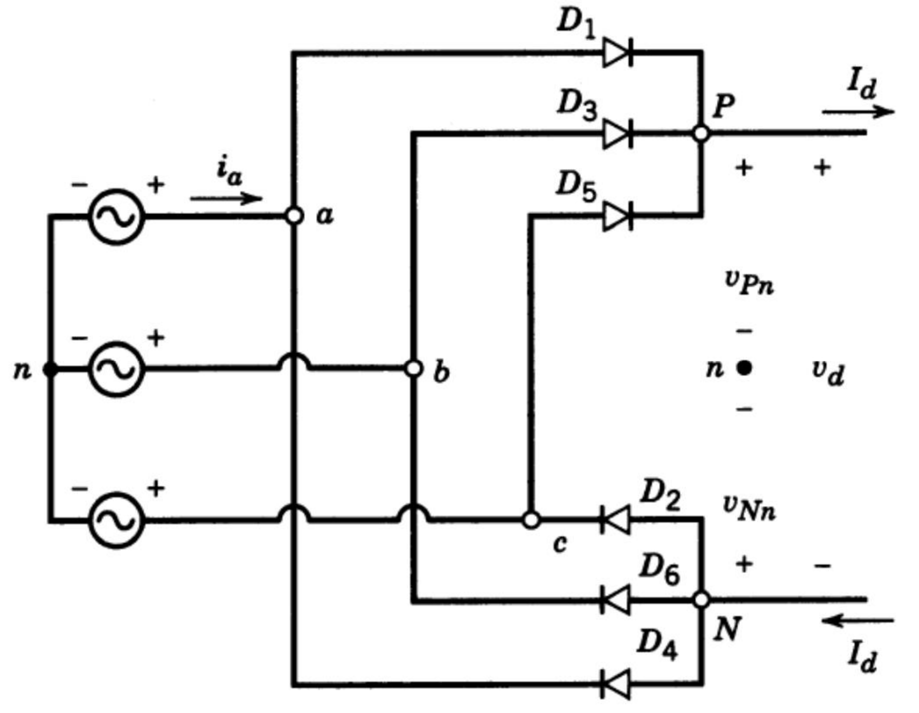
- Less ripple on output
- Handles higher power
- No current in neutral wire



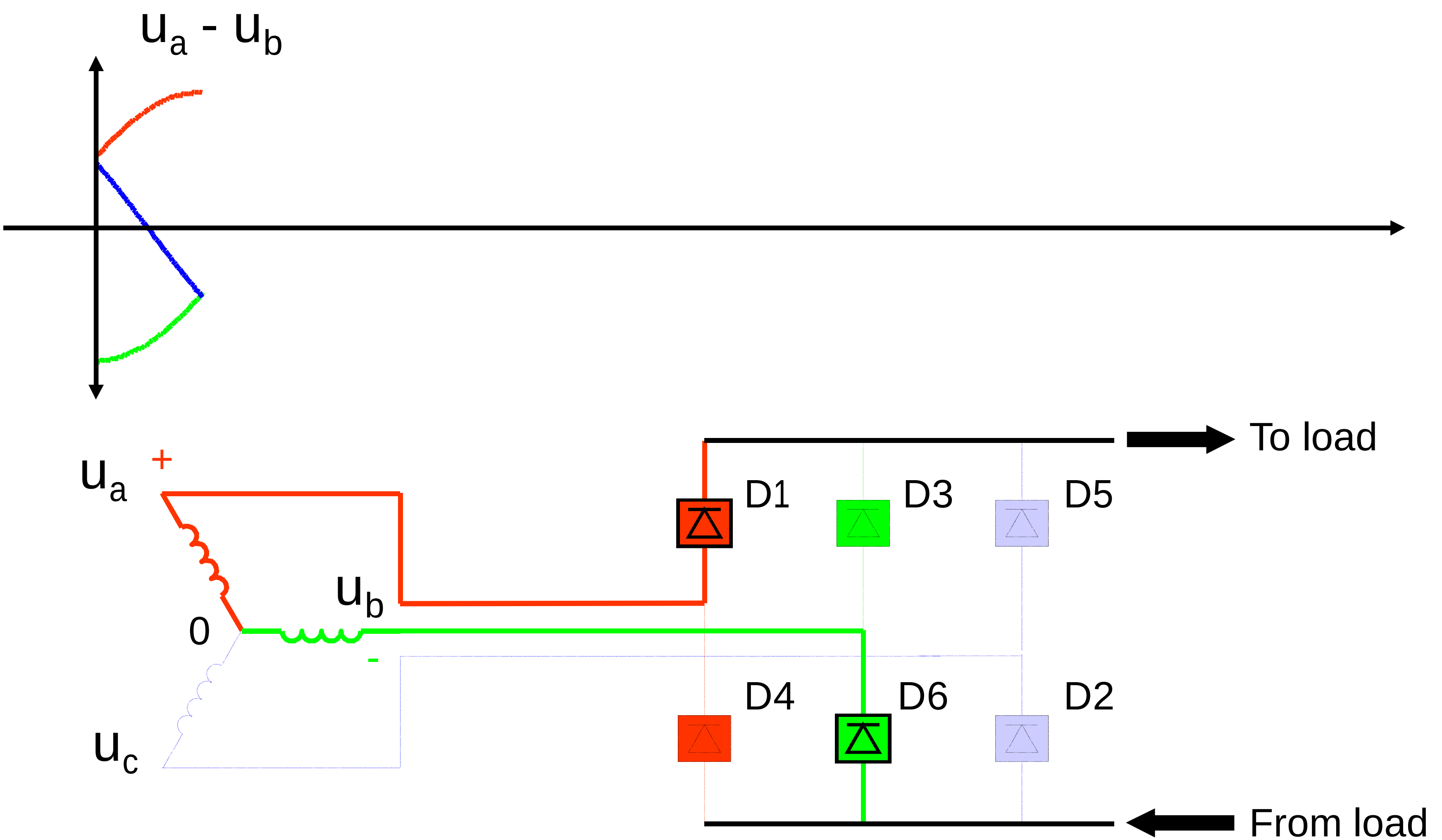
3-phase full bridge rectifiers, L = 0

- One diode in each group is conducting at any time



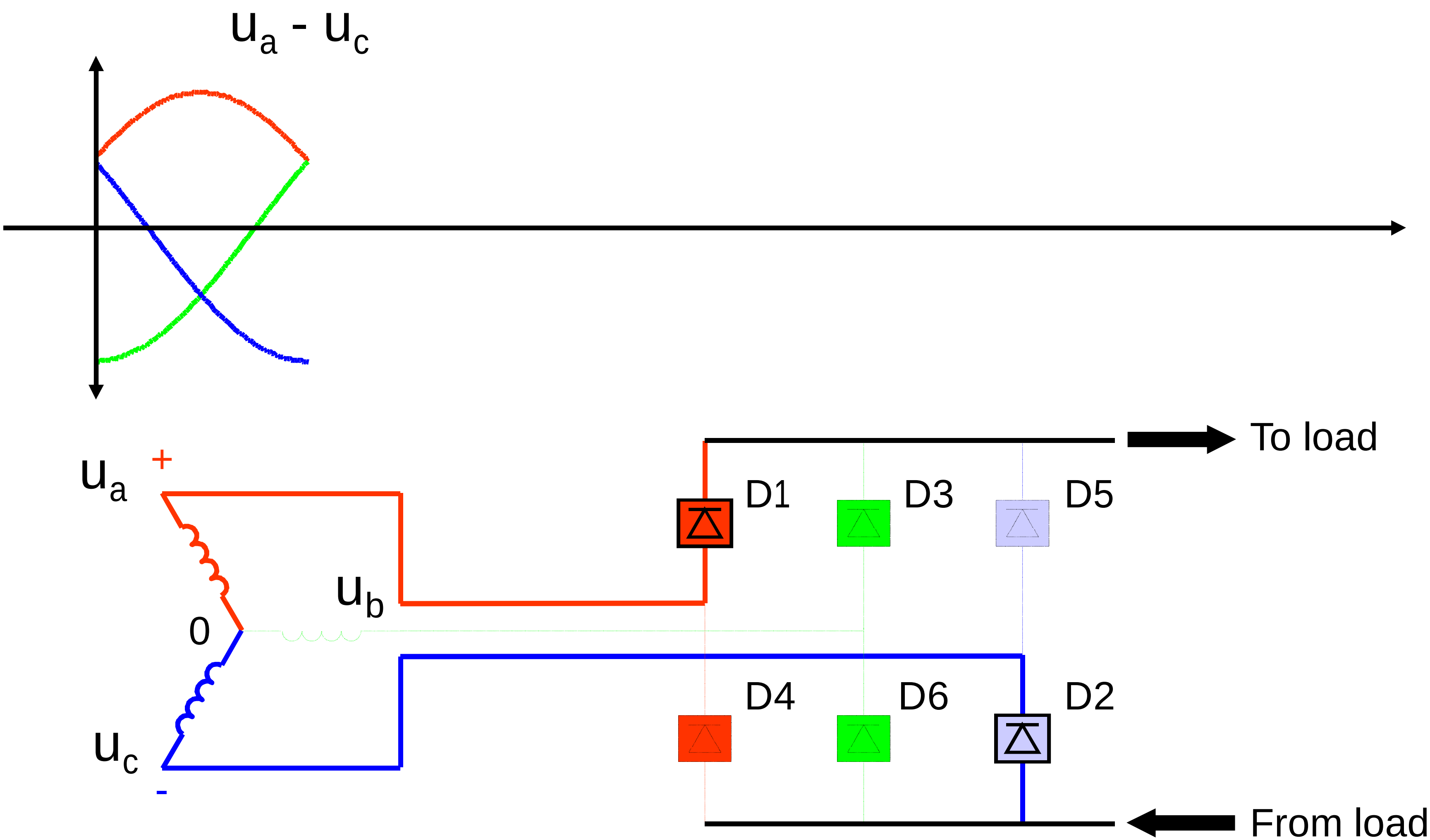


Diode rectifier



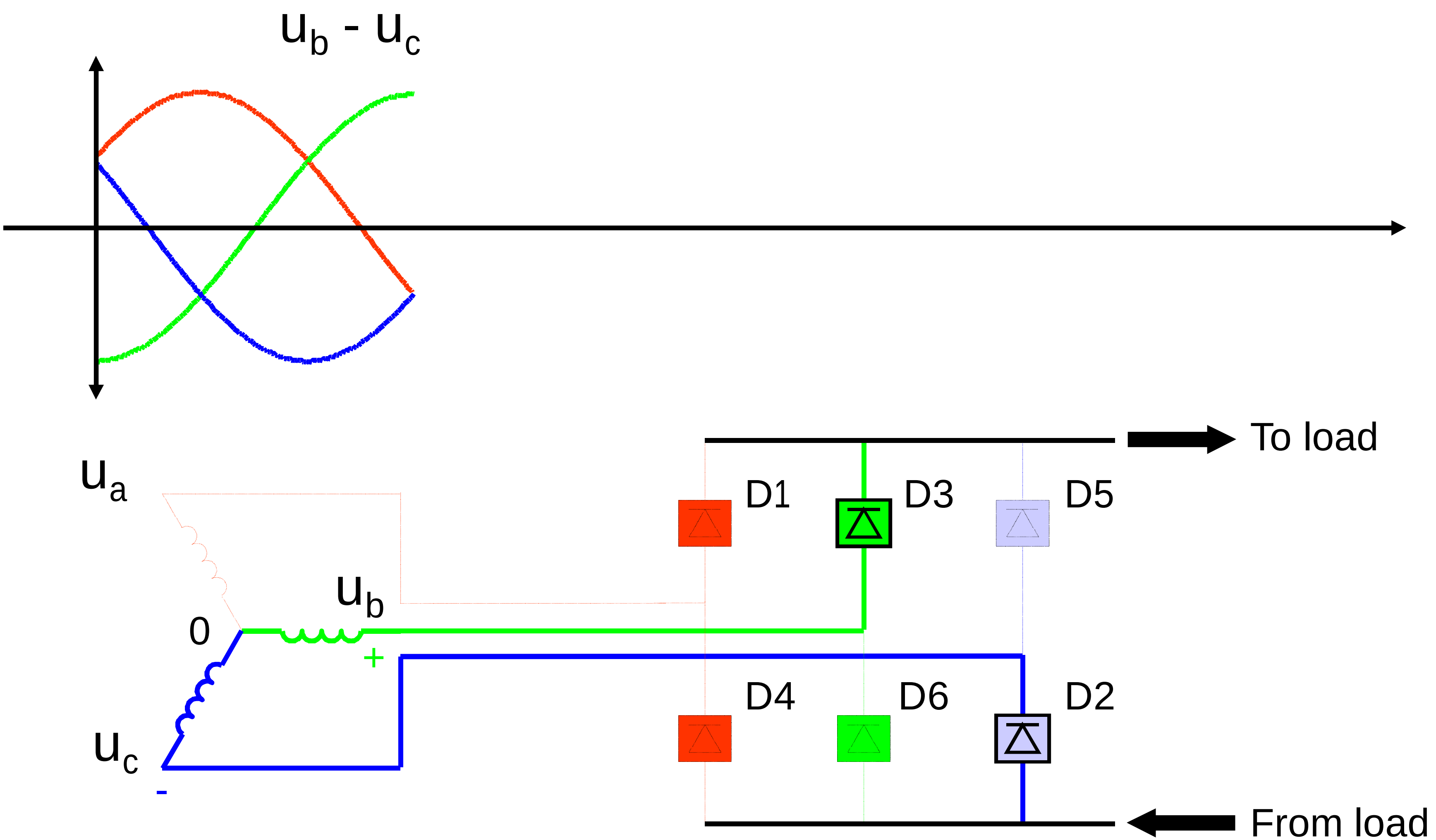
6-pulse Graetz rectifier bridge

Diode rectifier



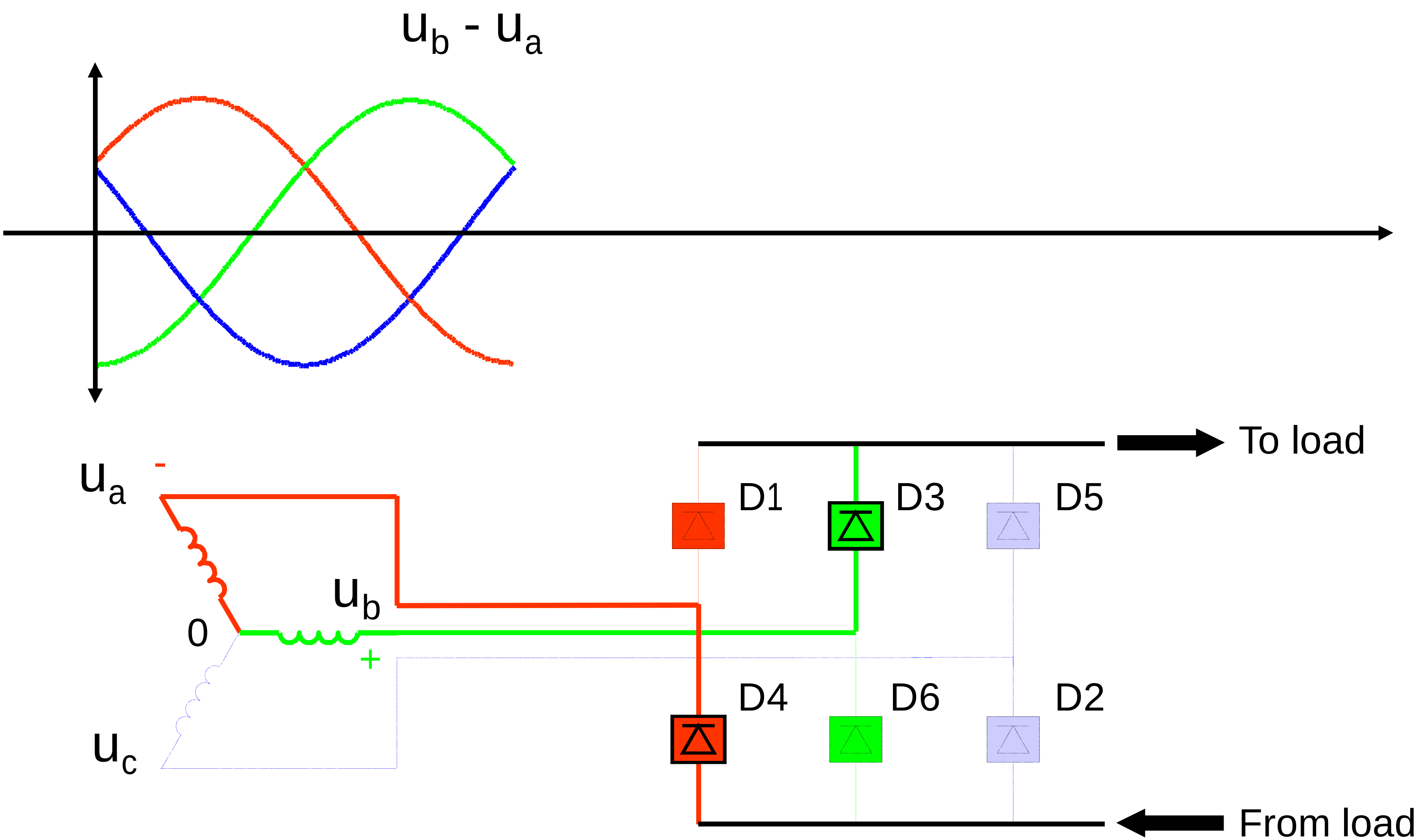
6-pulse Graetz rectifier bridge

Diode rectifier



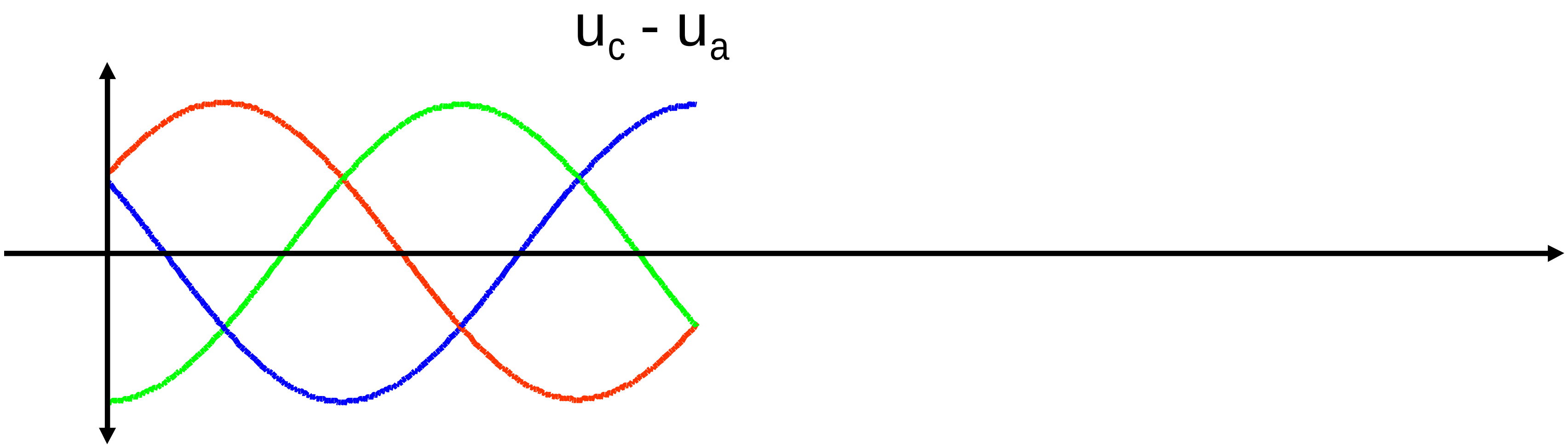
6-pulse Graetz rectifier bridge

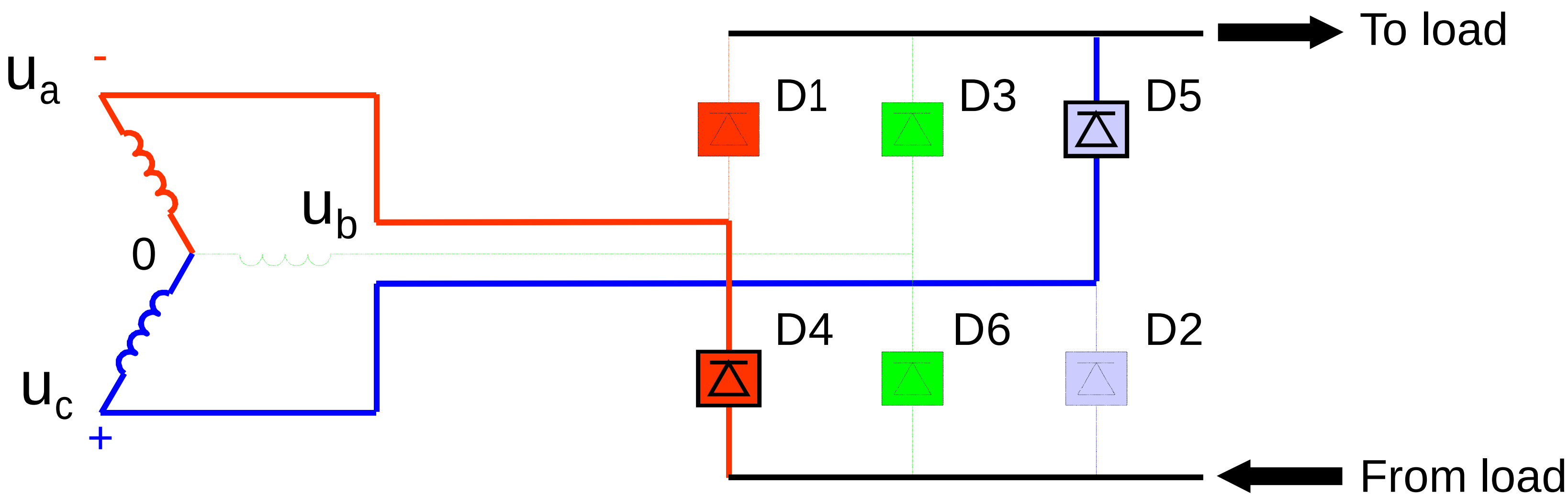
Diode rectifier



6-pulse Graetz rectifier bridge

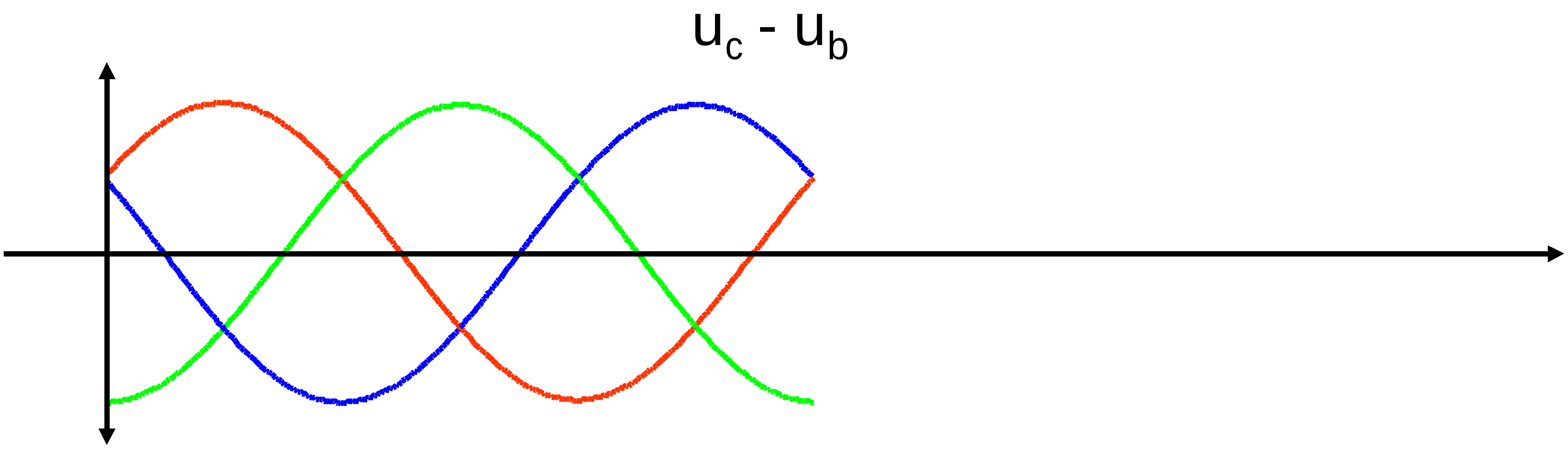
Diode rectifier

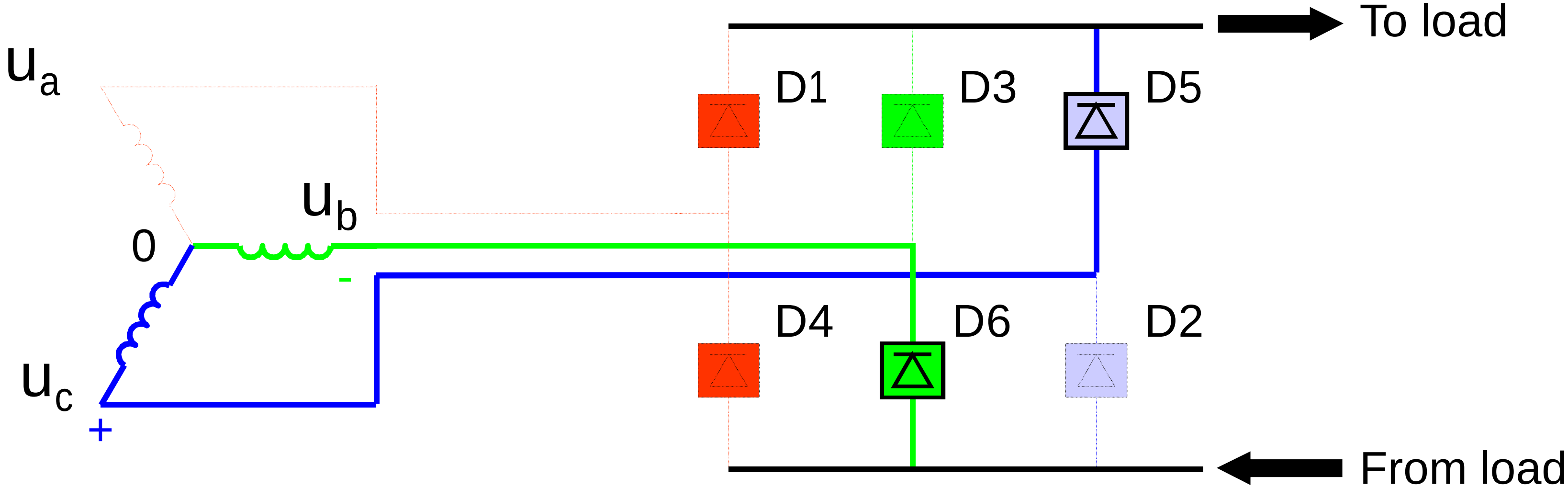




6-pulse Graetz rectifier bridge

Diode rectifier





6-pulse Graetz rectifier bridge

3-phase full bridge rectifier waveforms

- Every diode conducts 1/3 of the cycle
- Output waveform contains 6 segments

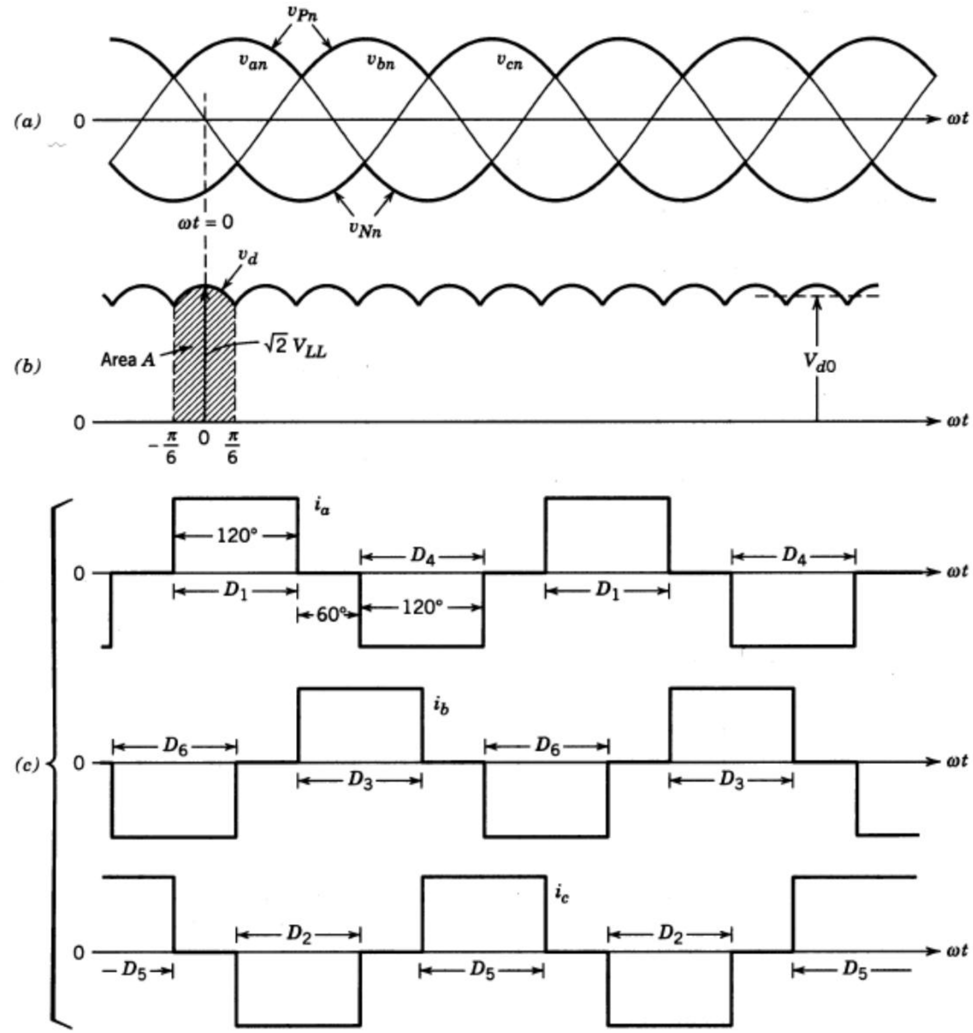
$$v_d = v_{P_n} - v_{N_n}$$

- Instantaneous current commutation due to L = 0

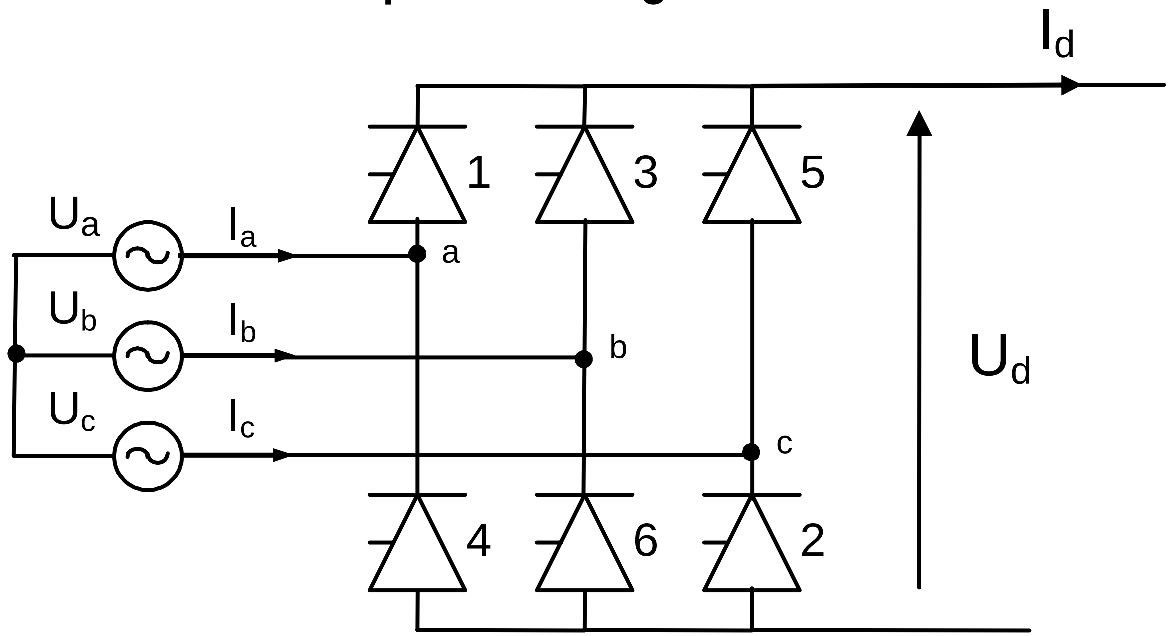
$$v_{d_{max}} = \sqrt{2}V_{LL}$$

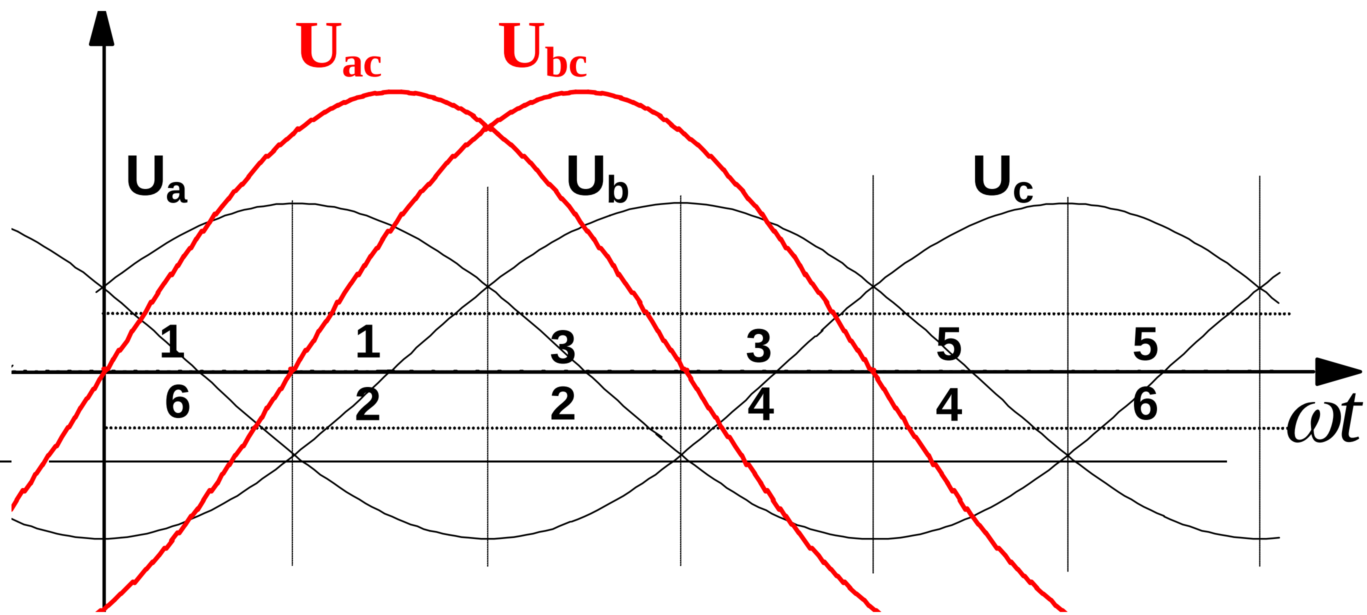
$$v_{do} = \frac{1}{\pi/3}\int_{-\pi/6}^{\pi/6} \sqrt{2}\,V_{LL}\cos\omega t\,d(\omega t)$$

$$= 1.35V_{LL}$$



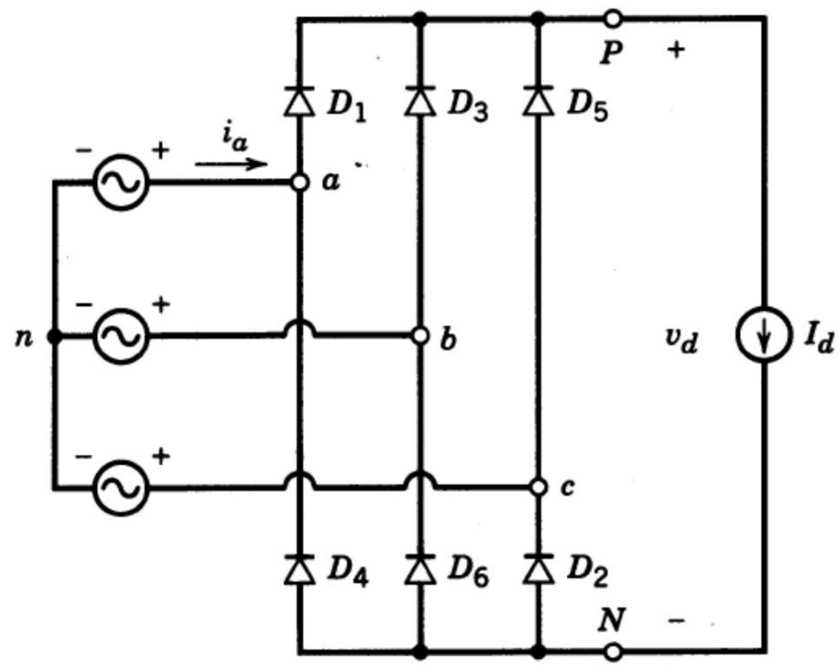
Principles of AC/DC conversion, 6-pulse bridge





Exercise 3-100

- In the ideal three-phase rectifier circuit, *construct the wave forms of diode D1 and D2 voltages and currents.*



Input line current 3ph rectifier

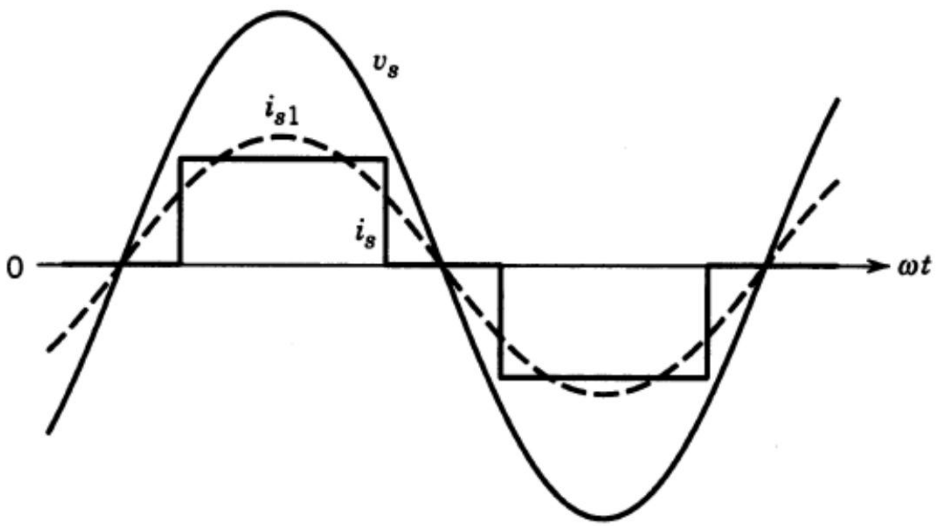
- No 3rd harmonic
- Compare with single phase PF = 0.9

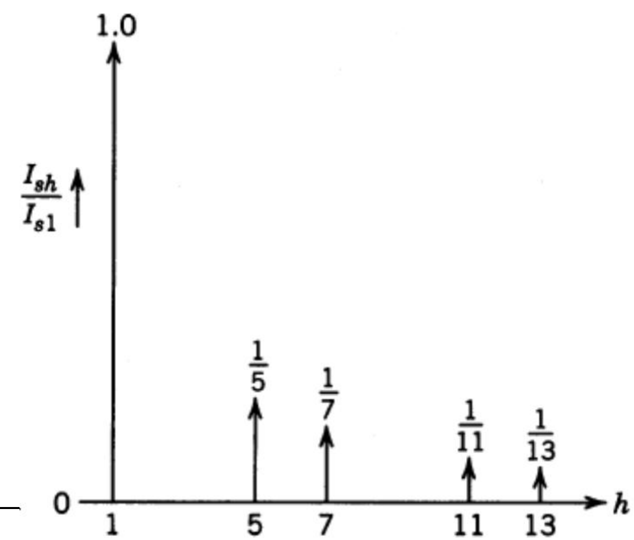
$$RMS\ current:\ I_s = \sqrt{\frac{2}{3}} \cdot I_d$$

$$Fundamental\ current:\ I_{s1} = \frac{1}{\pi}\sqrt{6}I_d = 0.78I_d$$

$$DPF = \cos\phi_1 = 1.0$$

$$PF = \frac{P}{S} = \frac{V_s I_{s1} \cos\phi_1}{V_s I_s} = \frac{I_{s1}}{I_s}\cos\phi_1 = \frac{3}{\pi} = 0.955$$





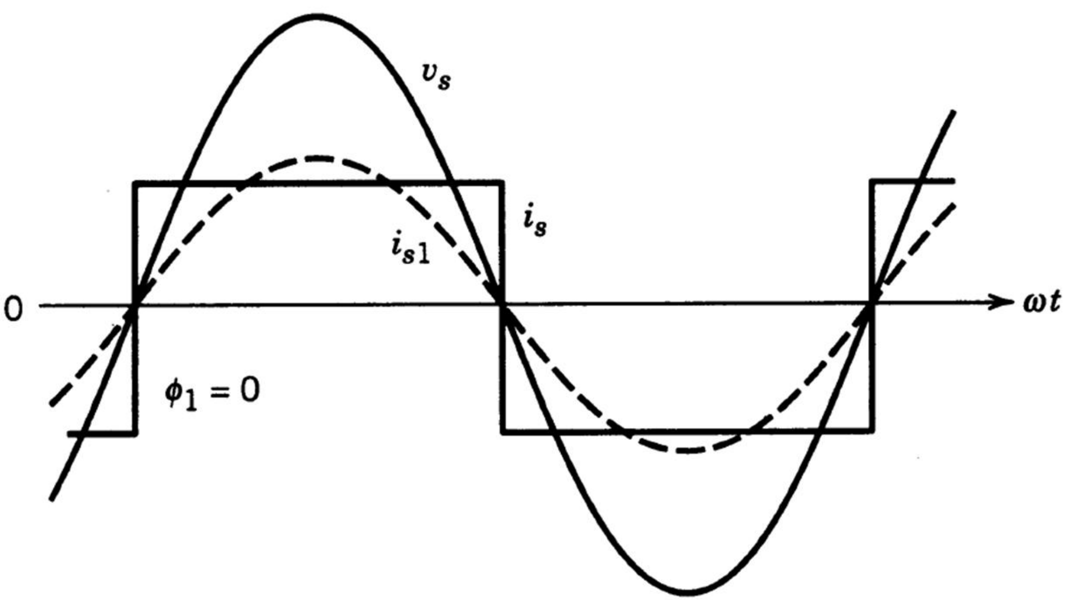
Single phase rectifier, input current

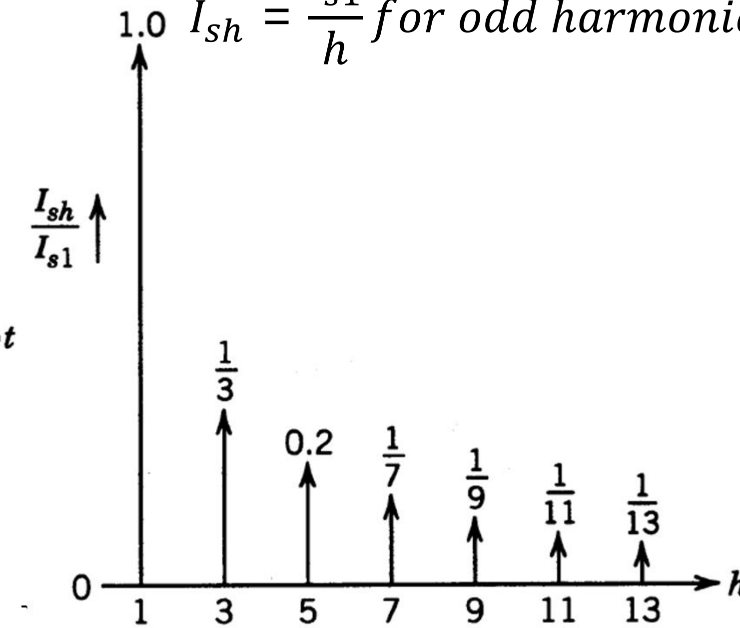
- Fourier analysis gives additional harmonic components
  - Remember calculation uses RMS of I_s, I_{s1} and I_d

$$I_{s1} = \frac{2}{\pi}\sqrt{2}I_d = 0.9I_d$$

$$I_{sh} = 0 \ for\ even\ harmonics$$

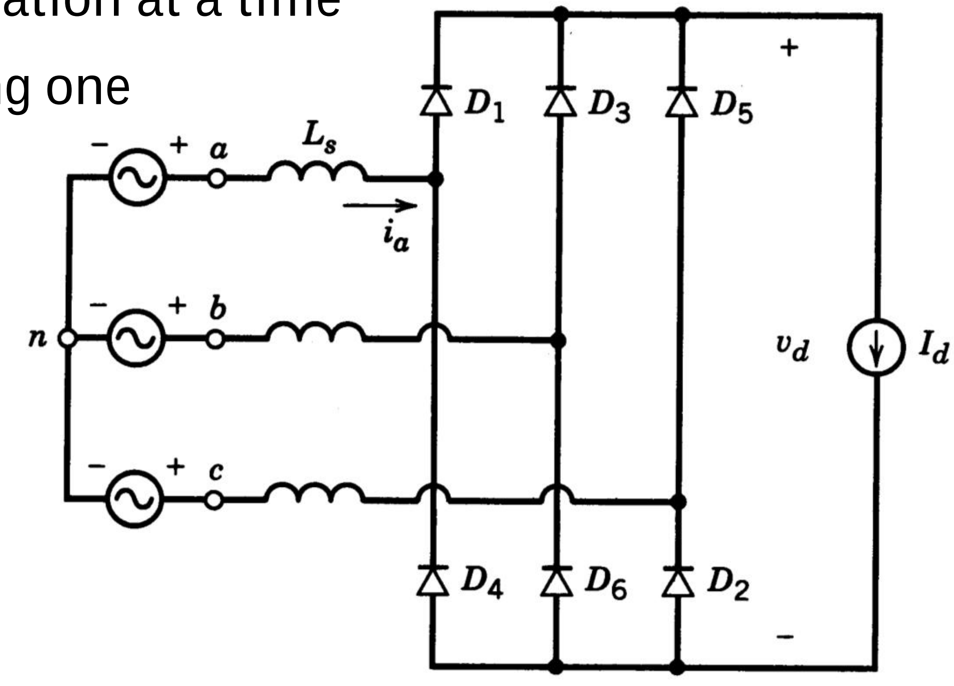
$$I_{sh} = \frac{I_{s1}}{h} for\ odd\ harmonics$$



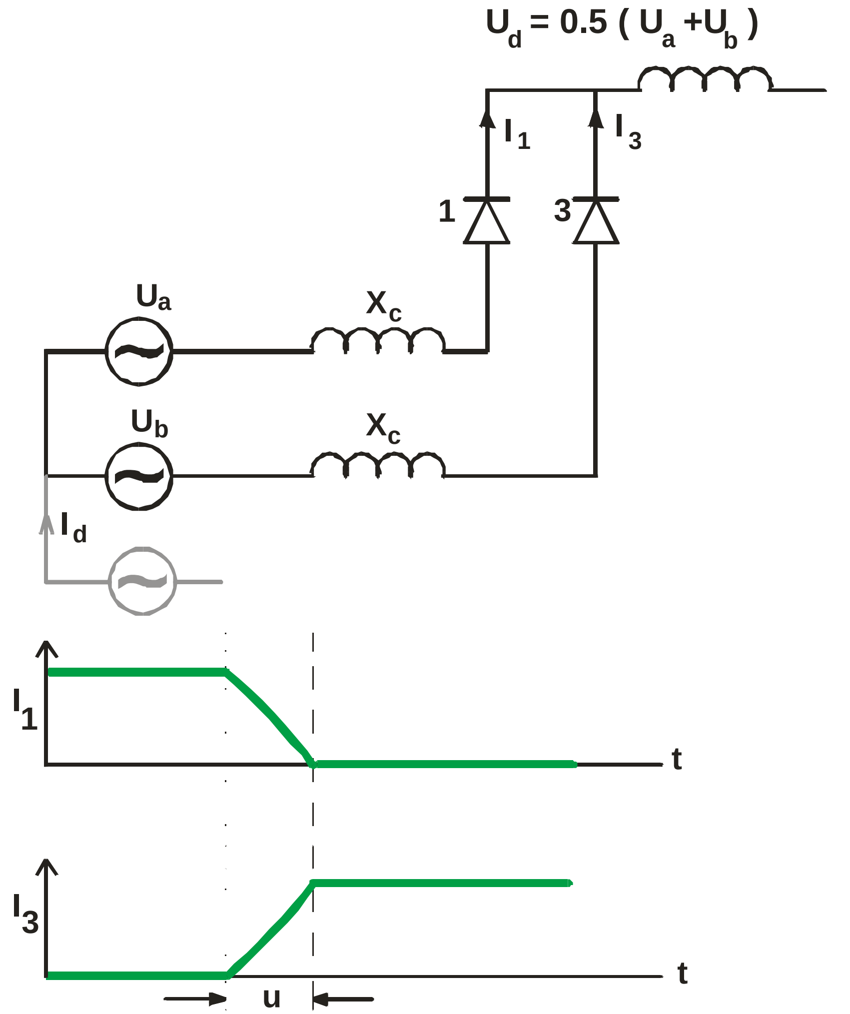


Source inductance effects, DC current load

- Source L not 0
- Only one current commutation at a time
  - 6 commutations during one line-frequency cycle



Transfer of current from valve 1 to valve 3



Current commutation

- Current commutation phase c -> phase a (D5 -> D1)
- A_u indicates the current commutation voltage drop

$$i_c + i_a = I_d$$

- A_u only half of area between v_a and v_c because of two inductances

$$A_u = \omega L_s \int_0^{I_d} di_u = \int_0^u \frac{v_{an} - v_{cn}}{2} d(\omega t) =$$

$$= \int_0^u \frac{\sqrt{2} v_{LL} \sin(\omega t)}{2} d(\omega t) = \frac{\sqrt{2} v_{LL} (1 - \cos(u))}{2}$$

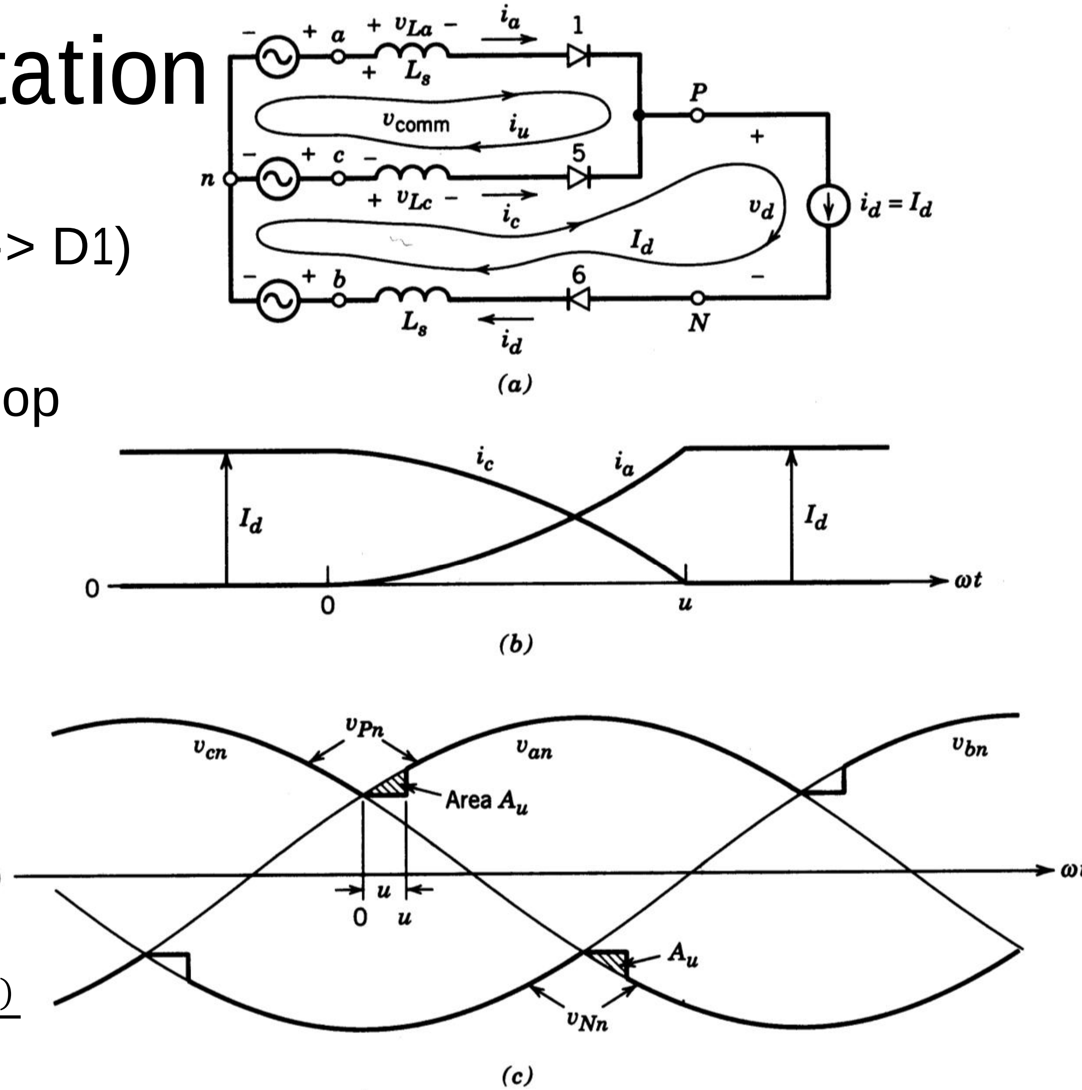


Figure 5-35 Current commutation process.

Effect of commutation inductance

$$A_u = \omega L_s \int_0^{I_d} di_u = \omega L_s I_d =$$

$$= \int_0^u \frac{v_{an} - v_{cn}}{2} d(\omega t) = \int_0^u \frac{\sqrt{2} v_{LL} \sin(\omega t)}{2} d(\omega t) = \frac{\sqrt{2} v_{LL}(1 - \cos(u))}{2}$$

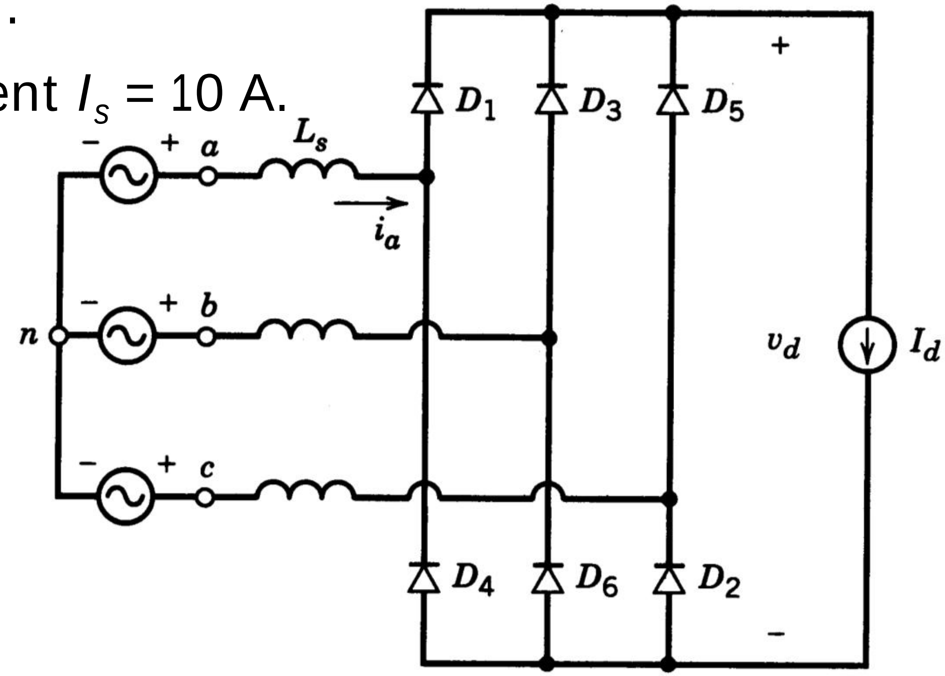
$$\Delta V_d = \frac{\omega L_s I_d}{\pi / 3} = \frac{3}{\pi} \omega L_s I_d$$

$$V_d = V_{d0} - \Delta V_d = 1.35 V_{LL} - \frac{3}{\pi} \omega L_s I_d$$

Exercise 3-101

A 3-ph rectifier feeding a constant current load has the following data:
V_{LL} = 400 V at 50 Hz, L_s = 7 mH.

The maximum ac-side rms current I_s = 10 A.



Calculate

a) Max dc-side current

b) Average dc-side voltage at max current

c) Max active power

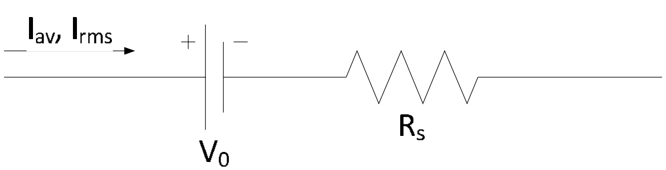
d) Diode average current

e) Diode rms current

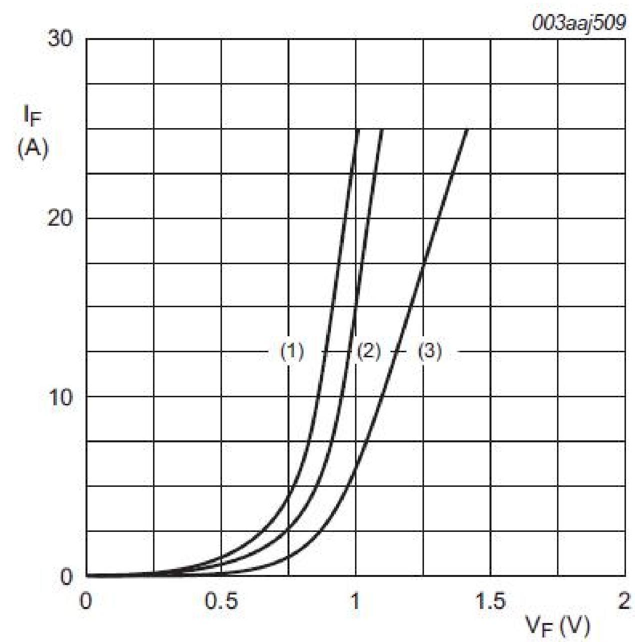
Exercise 3-102

Using results from exercise 3-101, calculate

- Diode conduction losses ($p_{D1}=\int u_{D1}\square iD_1$) using the diode BYW29E with V_0=0.79V, R_s = 0.013 ohm (T_j=25C)
- Use the diode on-state model below where i_D can be expressed with its average and rms current as calculated above



Diode on-state model



(1) T_j = 150 °C; typical values;

(2) T_j = 150 °C; maximum values;

(3) T_j = 25 °C; maximum values;

V_O = 0.791 V; R_S = 0.013 Ω

Inrush current

- LC-circuit fed by voltage step
  - Worst case when input voltage at maximum when applied

$$v_d = 2\sqrt{2}V_s \text{ (single phase)}$$
$$v_d = 2\sqrt{2}V_{LL} \text{ (three phase)}$$

  - Peek voltage twice the input voltage step
- DC circuit needs to support twice the peak input voltage!
- Alternative: limit current, using resistor. Short resistor after start using thyristor

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