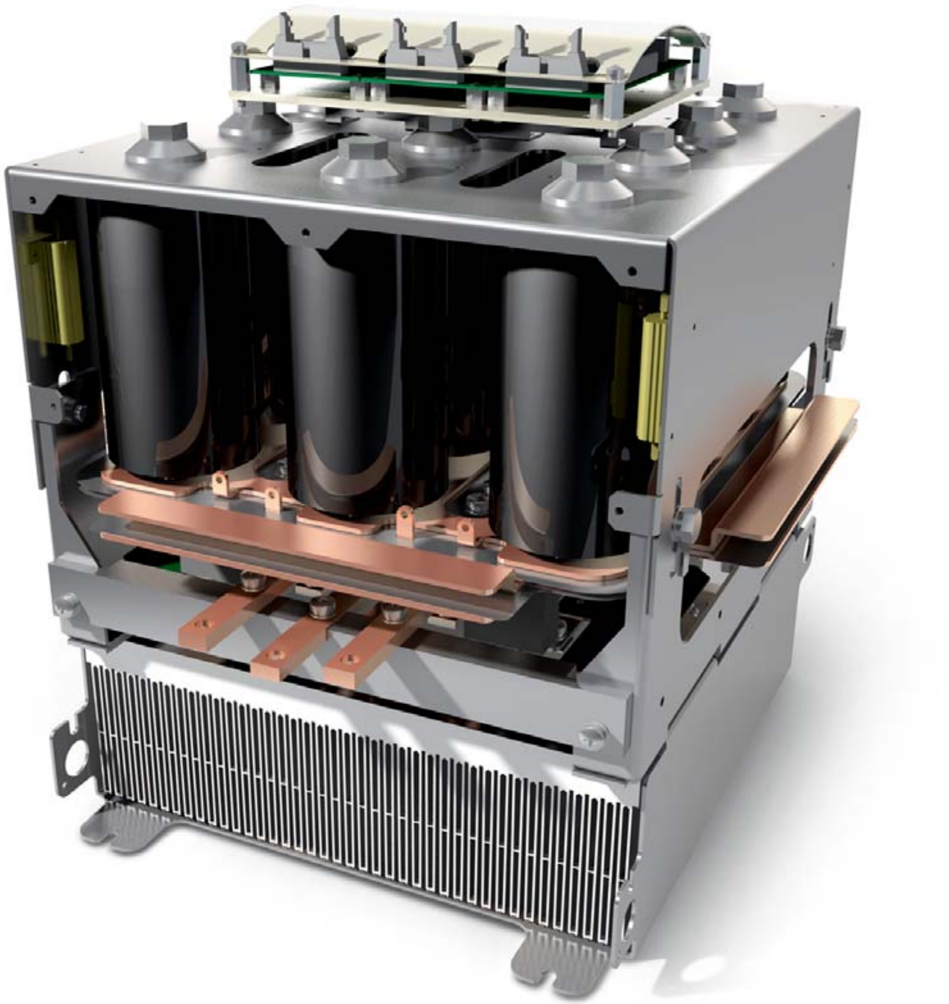
Diode and Thyristor based converters

= Line (or load) commutated converters



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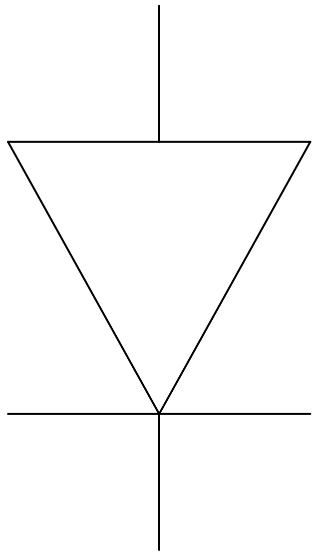
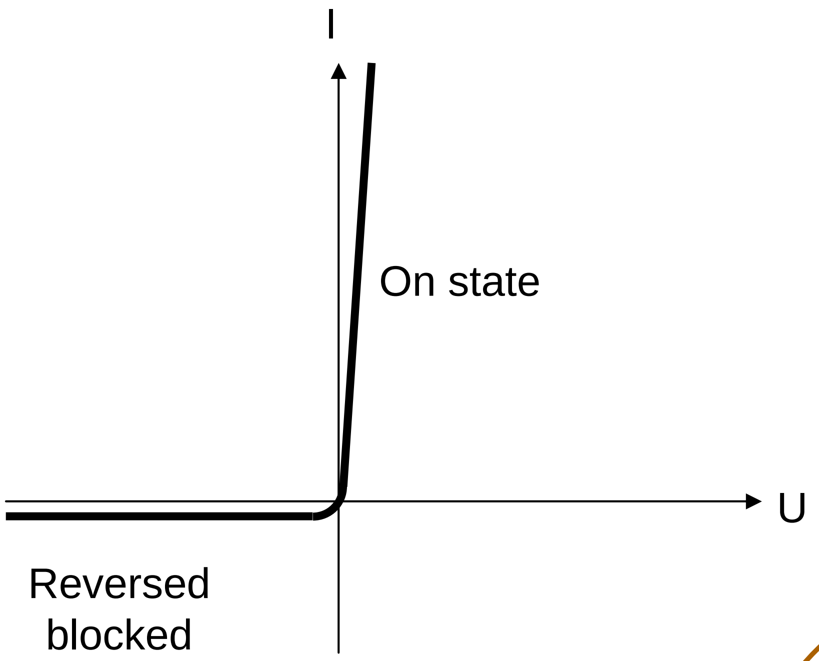
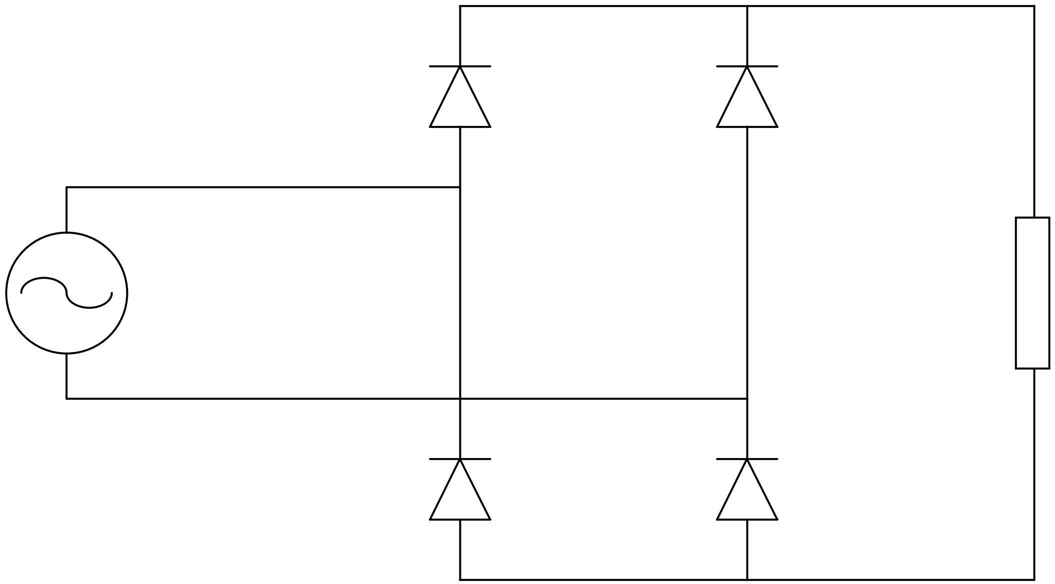
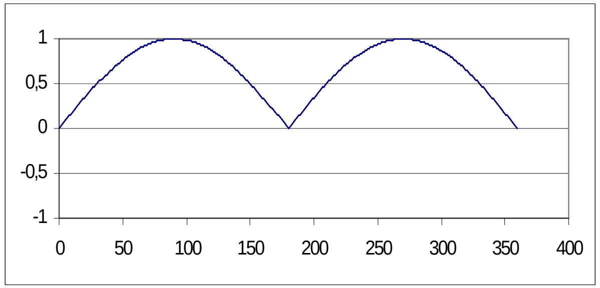
Diode



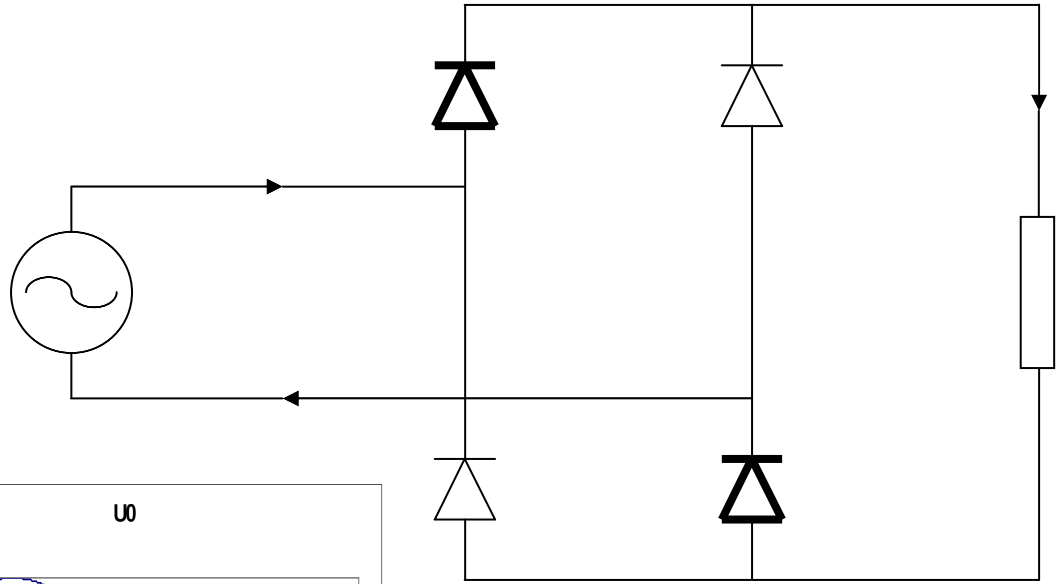


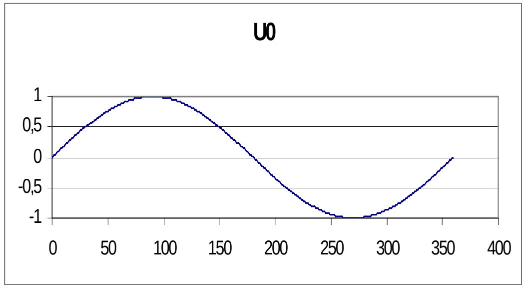
Single phase diode rectifier ideal

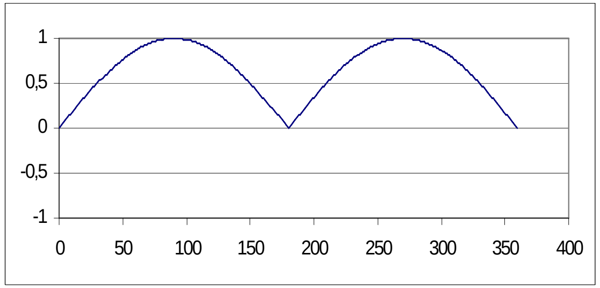




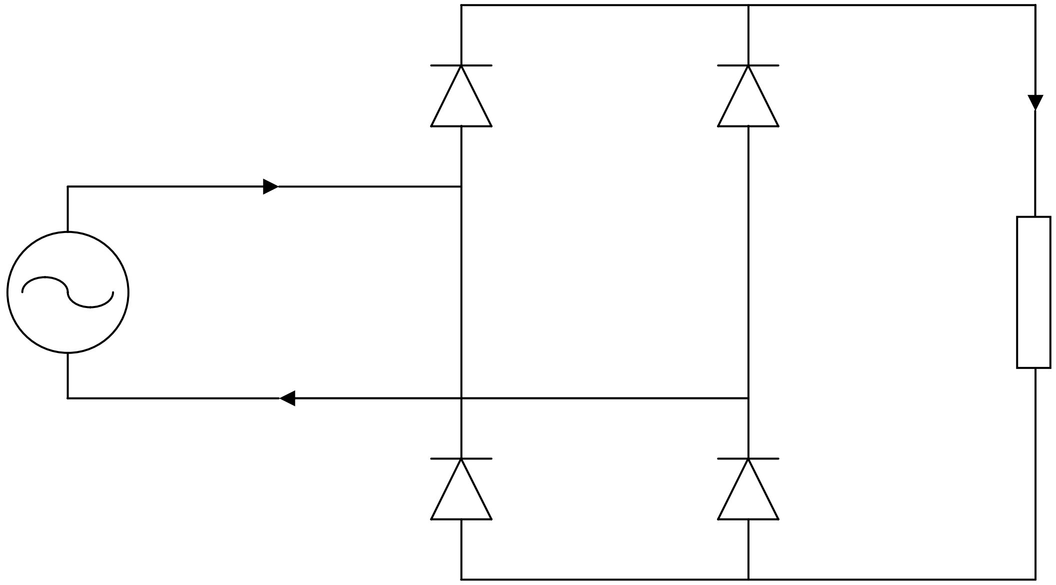
Single phase diode rectifier ideal

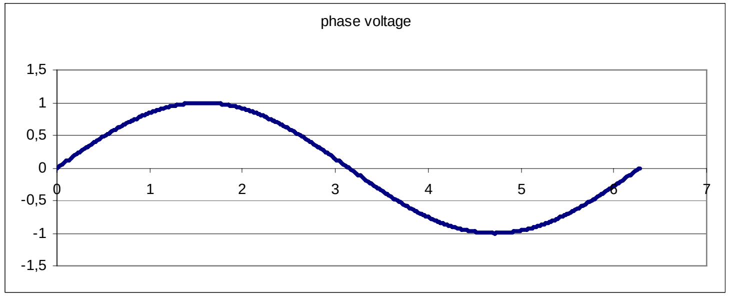


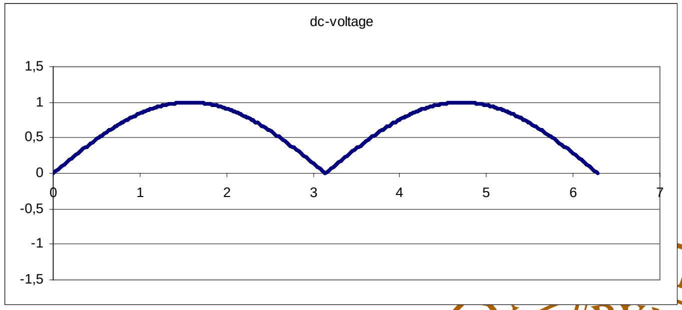




Single phase diode rectifier
AC-side and DC side voltage

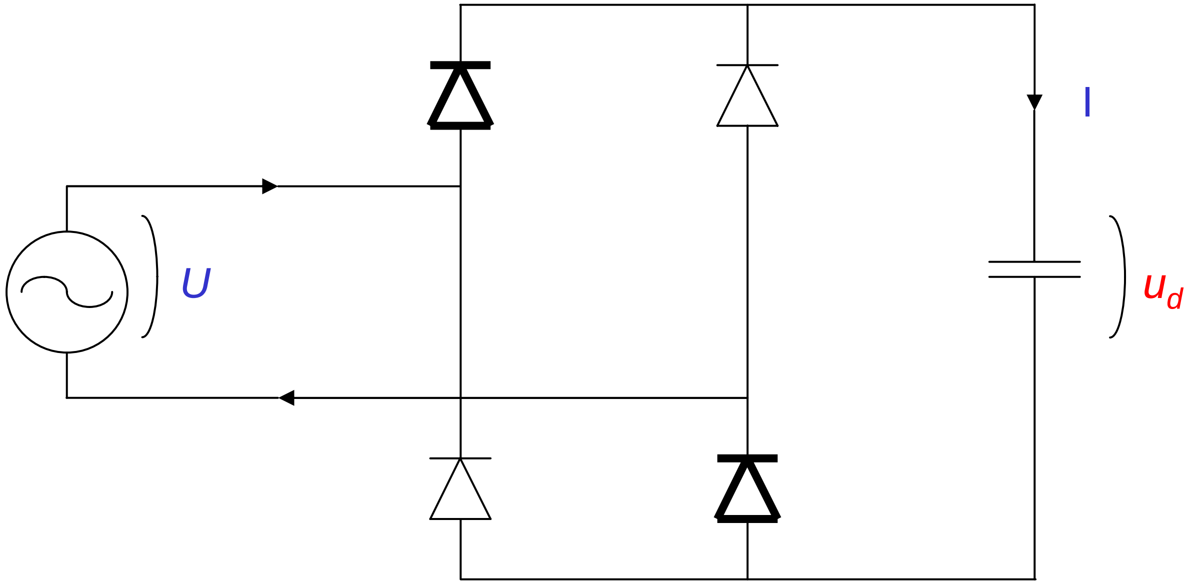


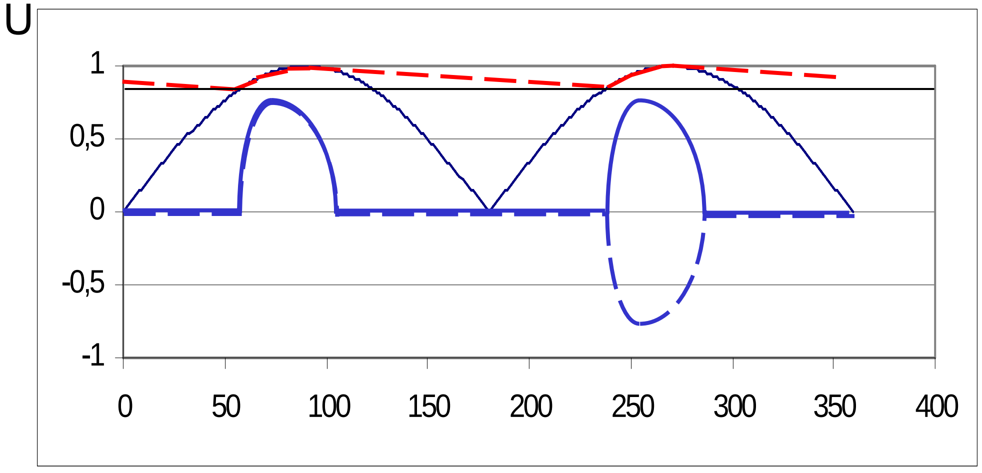




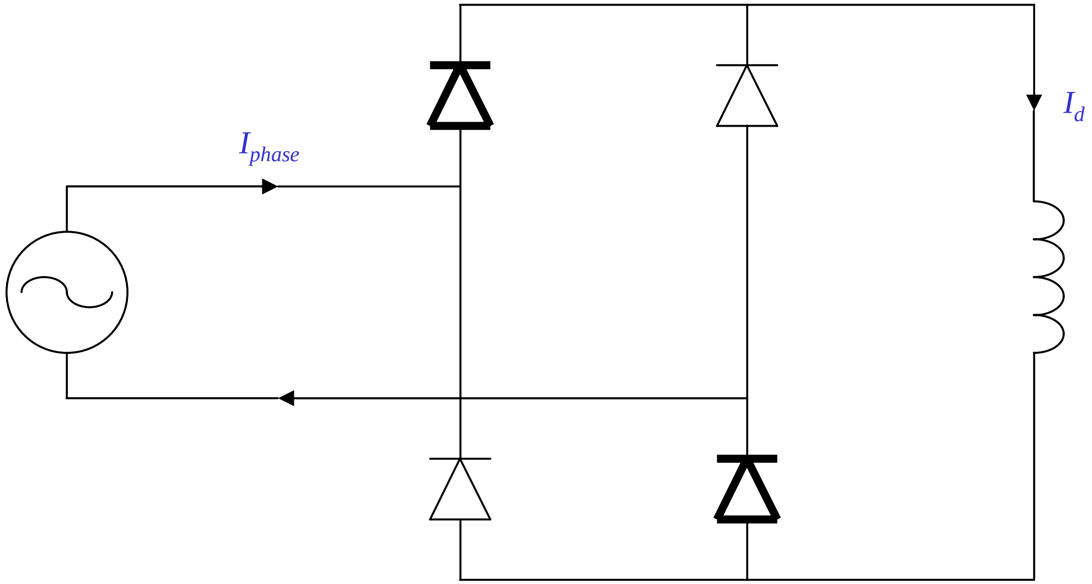
$$V_{dc} = \frac{1}{T/2} \int_{T/2} \hat{e}_{LN} \sin(\omega t)\, dt = \frac{\hat{e}_{LN}}{\pi} \int_{-\pi/2}^{\pi/2} \sin(\omega t)\, d(\omega t) = \frac{2}{\pi} \hat{e}_{LN} = \frac{2\sqrt{2}}{\pi} E_{LN}$$

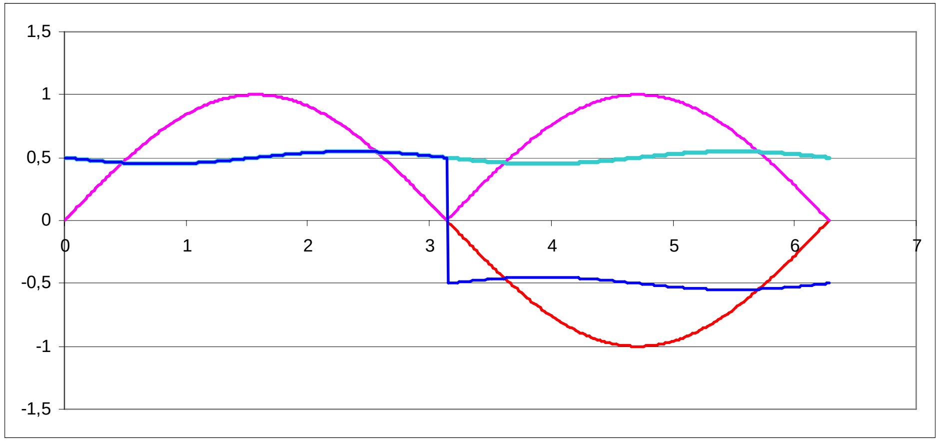
Single phase diode rectifier with capacitive load



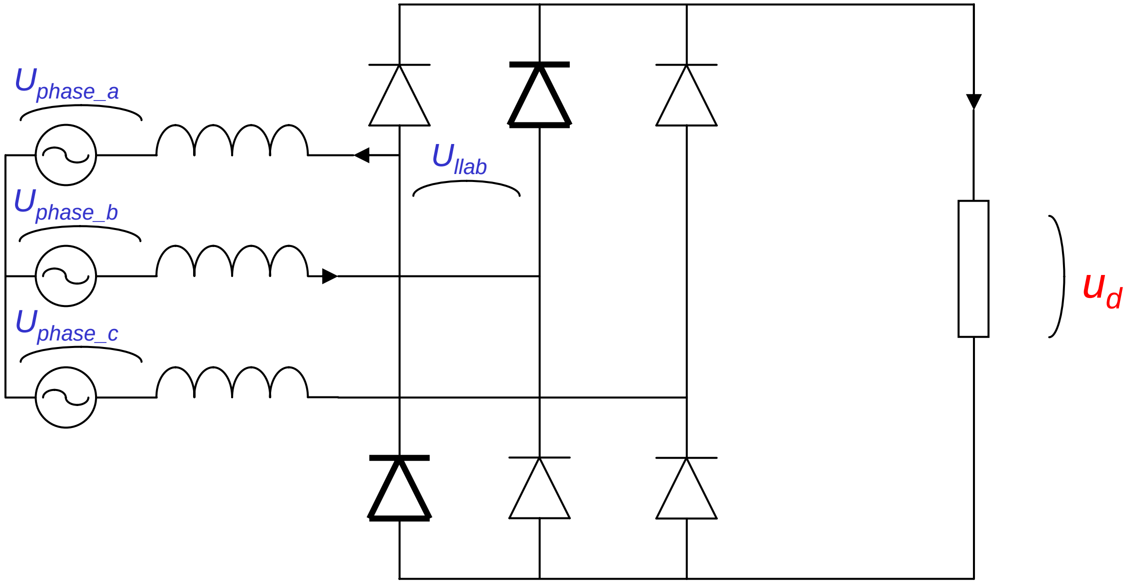


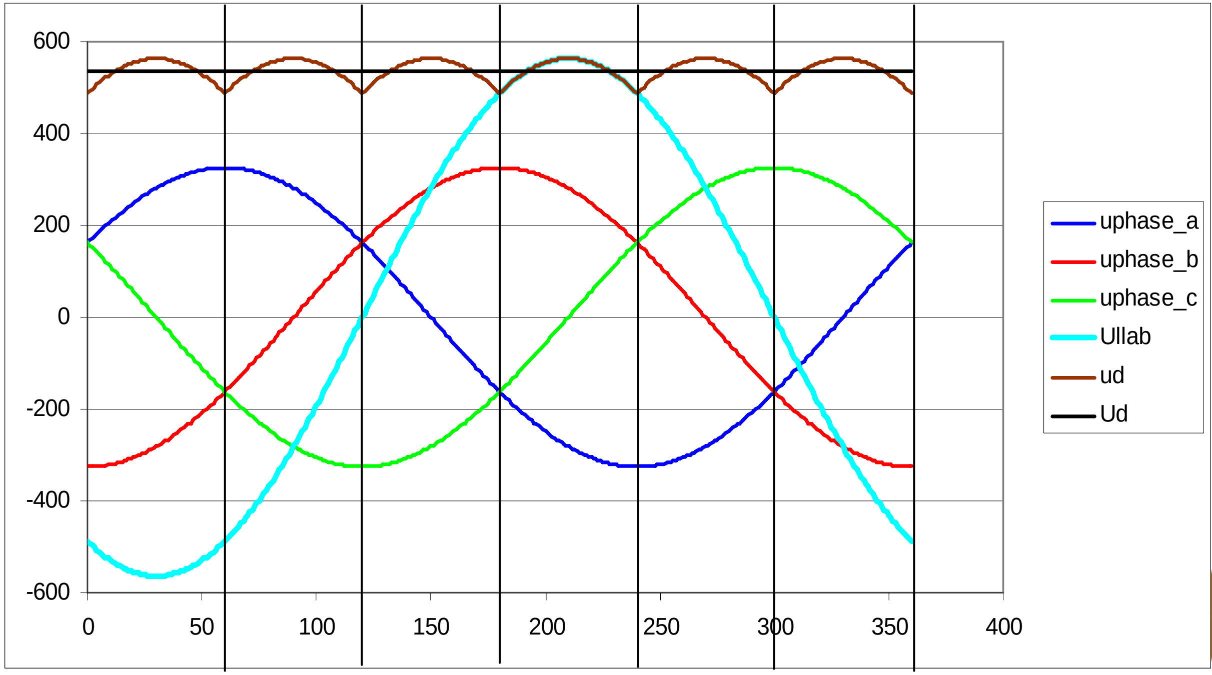
Single phase diode rectifier with inductive load



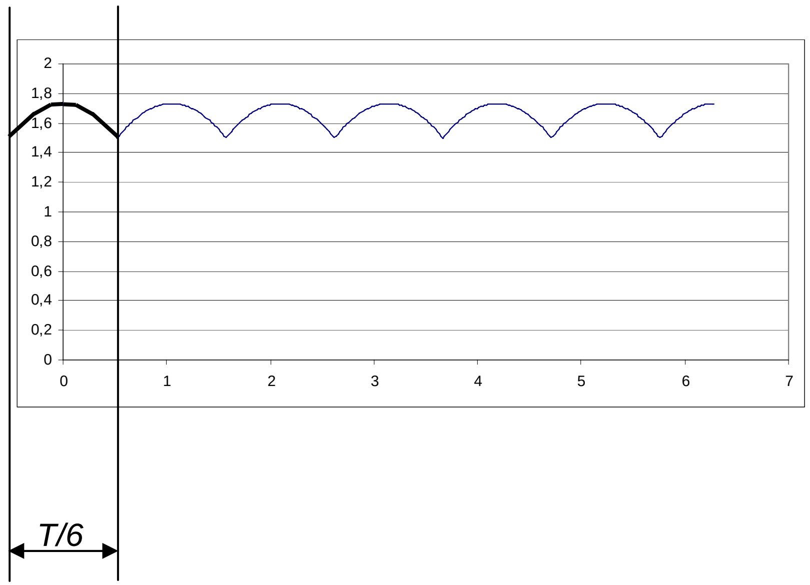


Three phase diode rectifier with resistive load



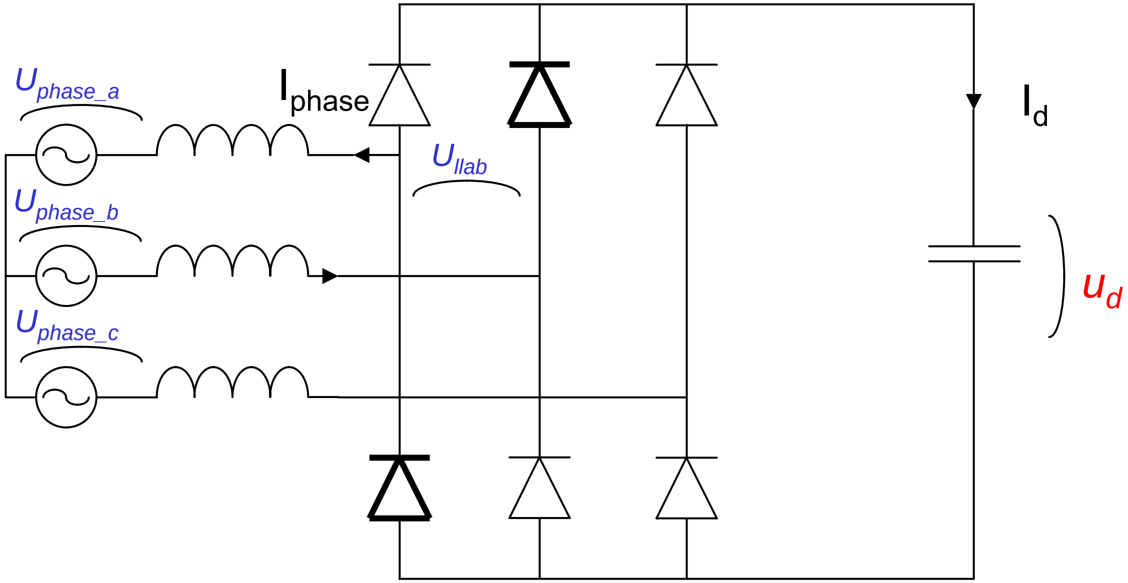


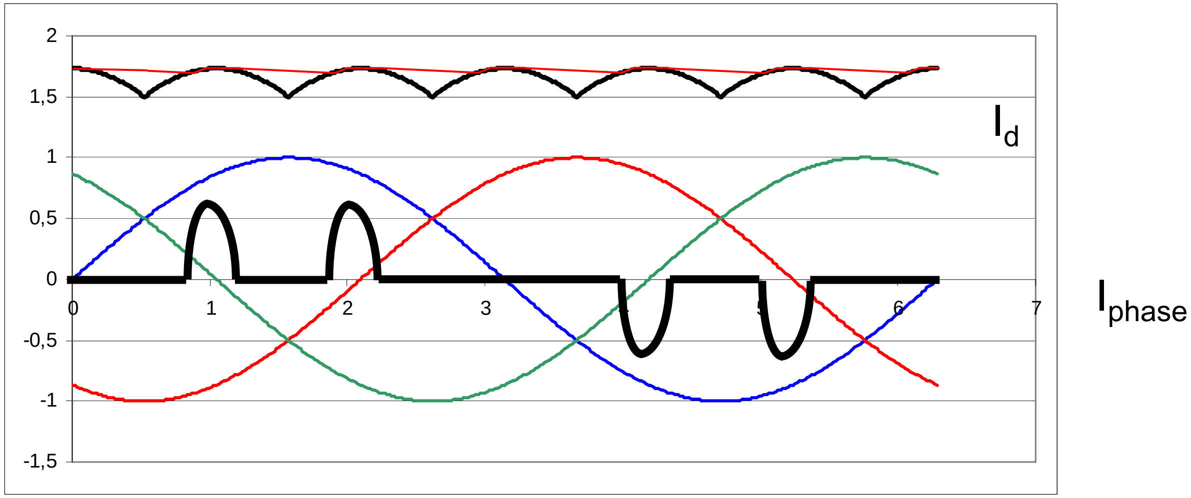
Three phase diode rectifier voltage



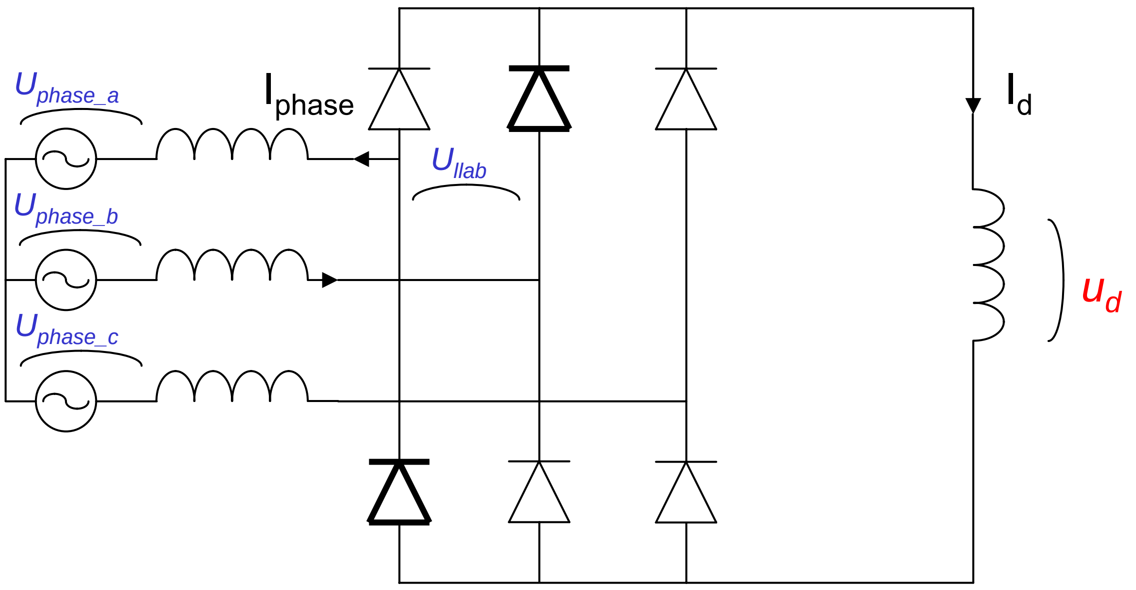
$$V_{dc} = \frac{\hat{e}_{LL}}{T/6} \int_{T/6} \cos(\omega t) dt = \frac{\hat{e}_{LL}}{\pi/3} \int_{-\pi/6}^{\pi/6} \cos(\omega t) d(\omega t) = \frac{3 \cdot \hat{e}_{LL}}{\pi} = \frac{3\sqrt{2} \cdot E_{LLeff}}{\pi} = \frac{3\sqrt{3} \cdot \hat{e}_{LN}}{\pi}$$

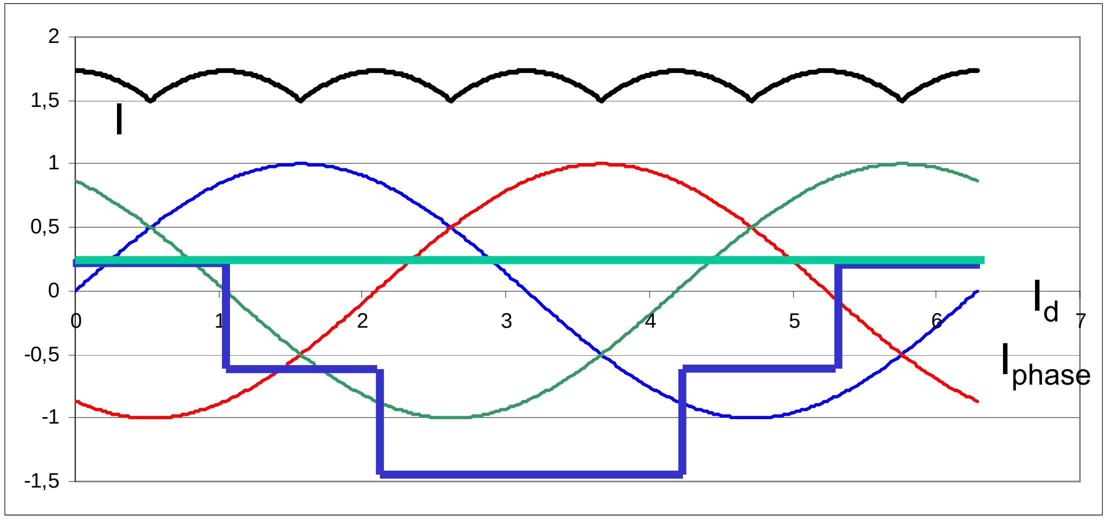
Three phase diode rectifier with capacitive load



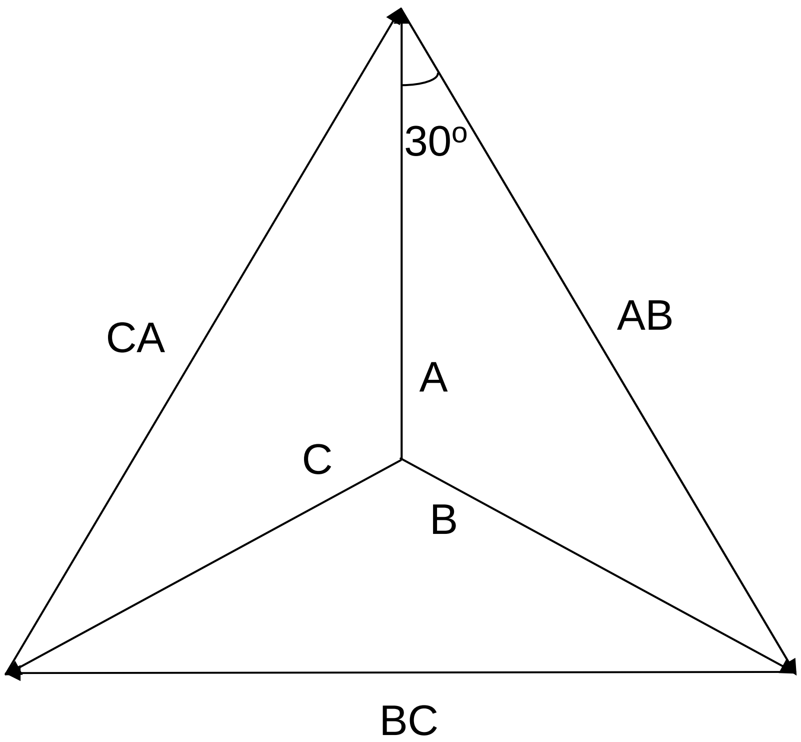


Three phase diode rectifier with inductive load

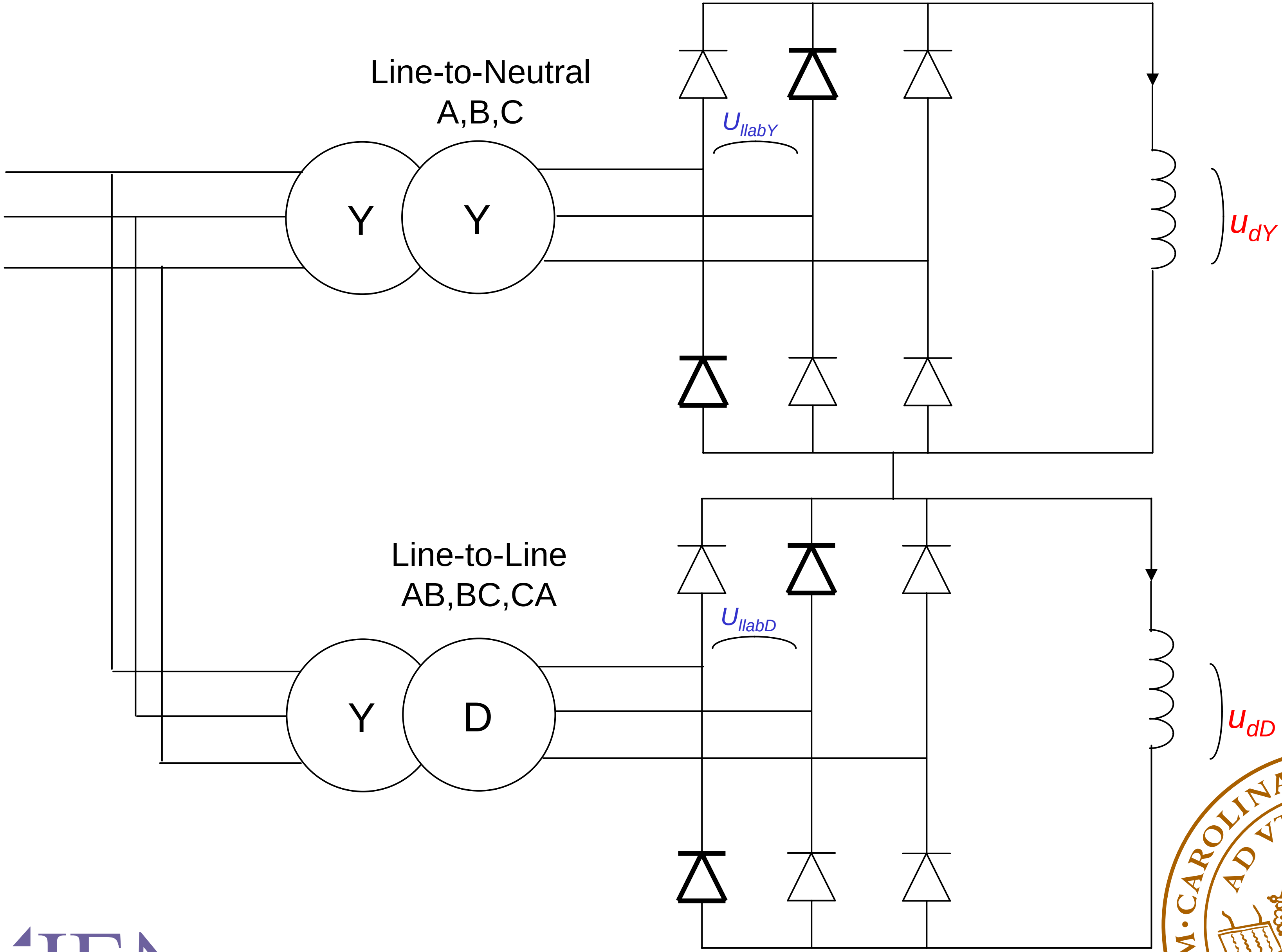




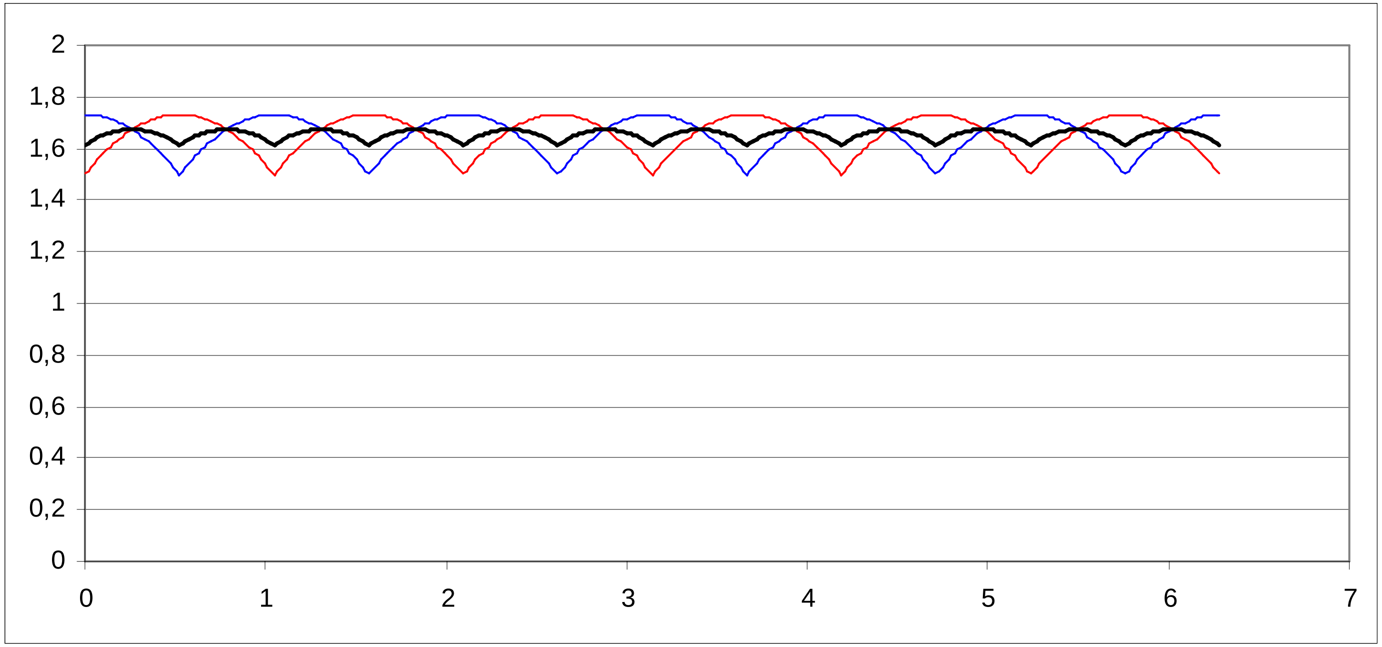
Three phase voltage phasors
Line-to-Neutral and Line-to-Line



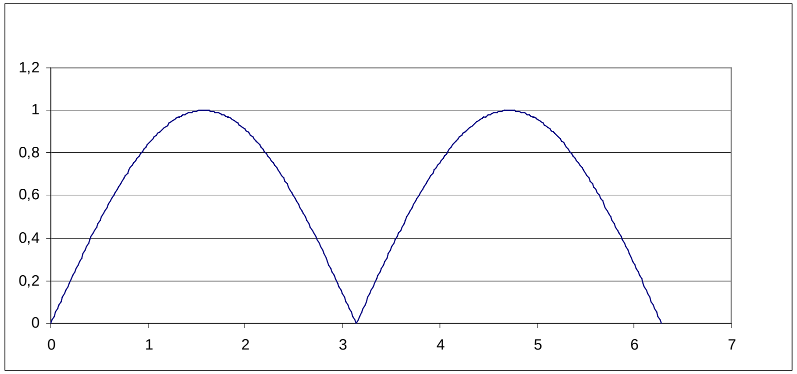
"Twelve pulse" rectifier

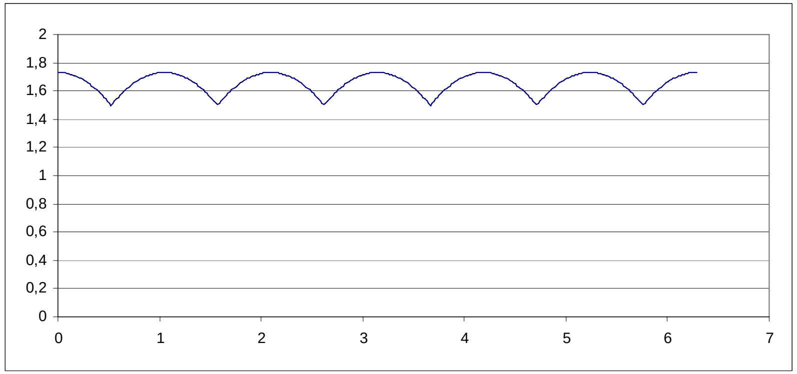


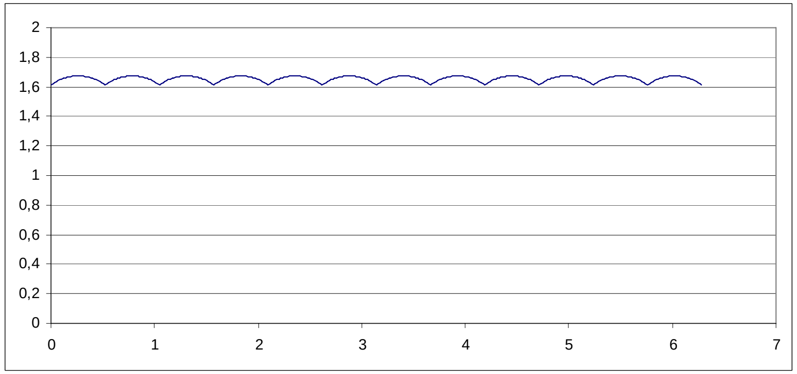
“Twelve pulse” rectifier



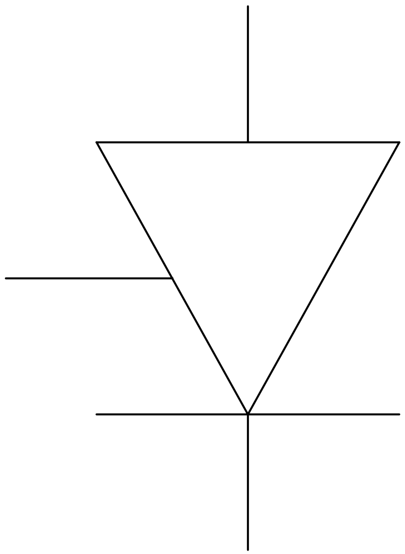
Ripple reduction

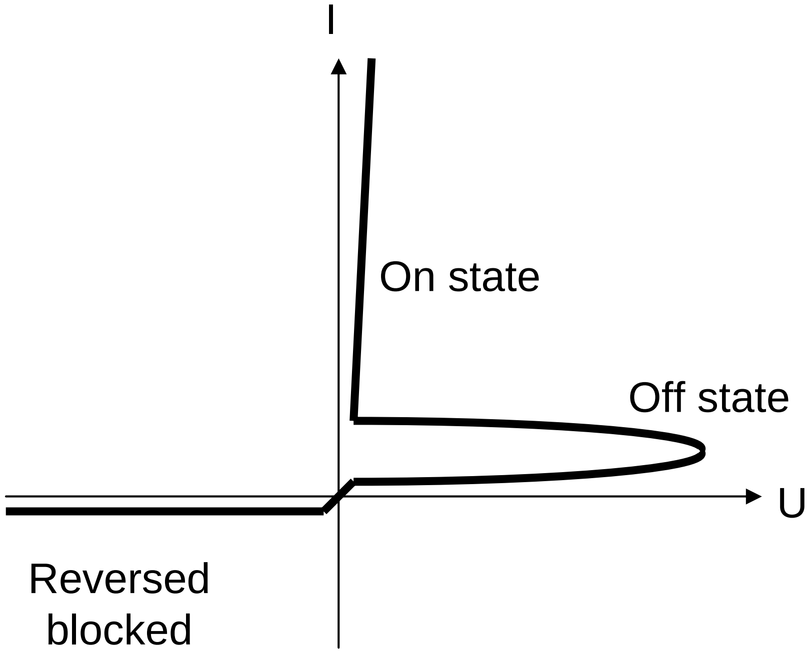




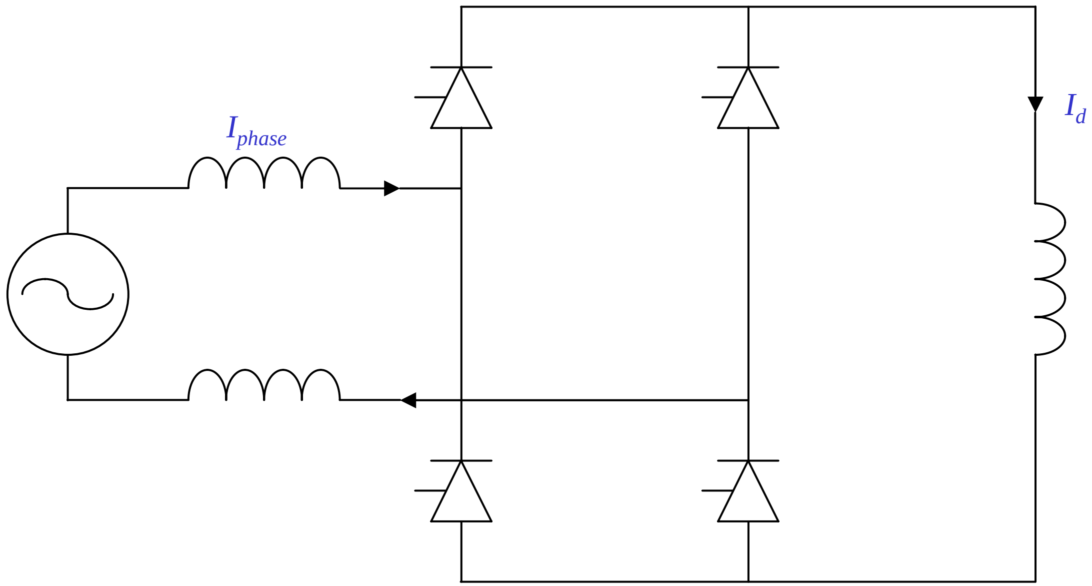


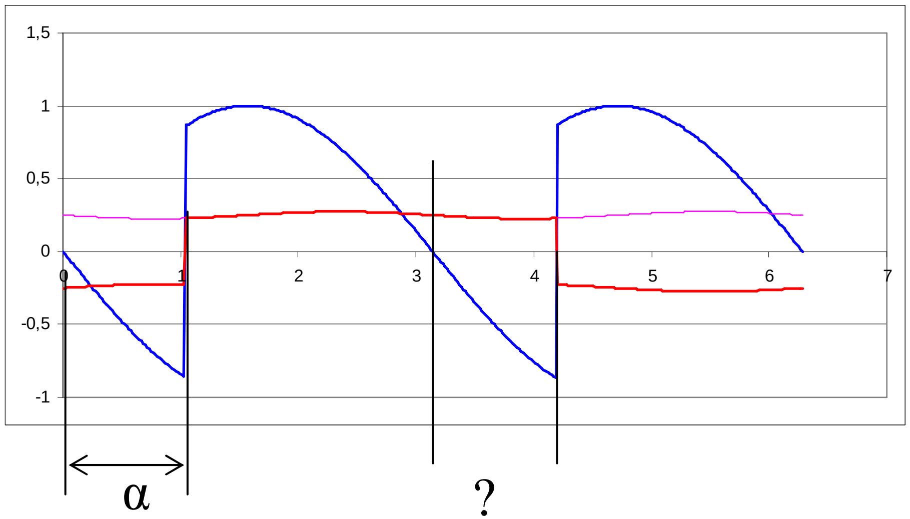
Thyristor





Single phase thyristor rectifier with inductive load

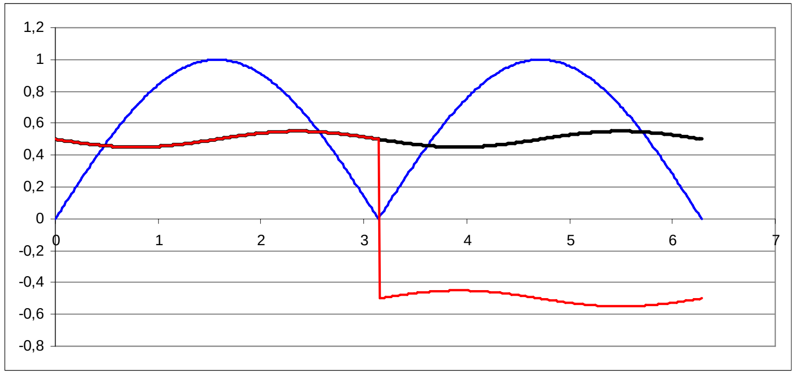




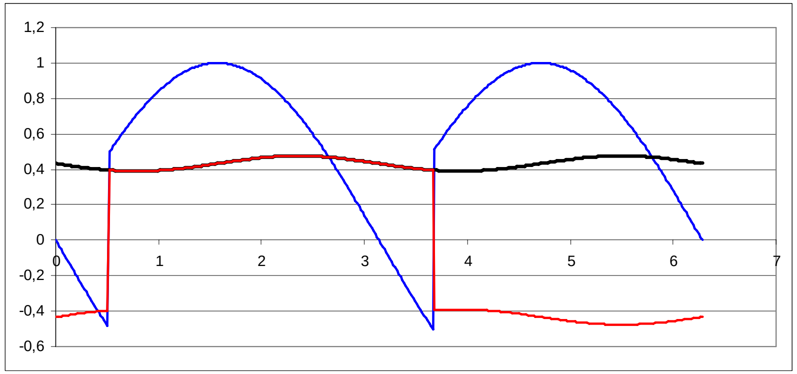
Single phase thyristor rectifier voltage

$$V_{dc} = \cos(\alpha)\cdot\frac{1}{T/2}\int_{T/2}\hat{e}_{LN}\sin(\omega t)\,dt = \cos(\alpha)\cdot\frac{\hat{e}_{LN}}{\pi}\int_{-\pi/2}^{\pi/2}\sin(\omega t)\,d(\omega t) = \cos(\alpha)\cdot\frac{2}{\pi}\hat{e}_{LN} = \cos(\alpha)\cdot\frac{2\sqrt{2}}{\pi}E_{LN} = V_{dc0}\cdot\cos(\alpha)$$

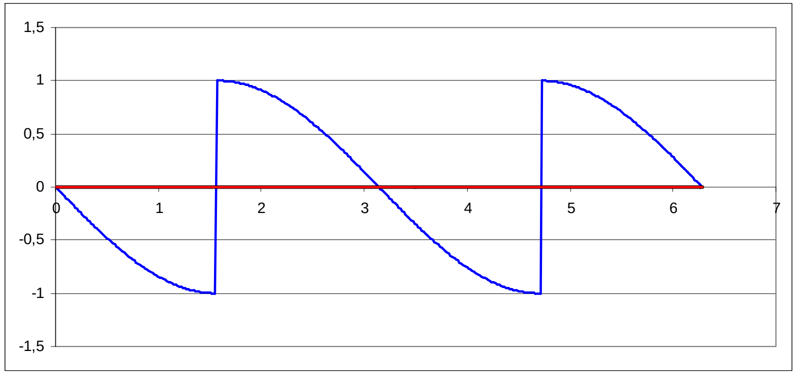
Single phase thyristor rectifier with inductive load
Different ignition angels



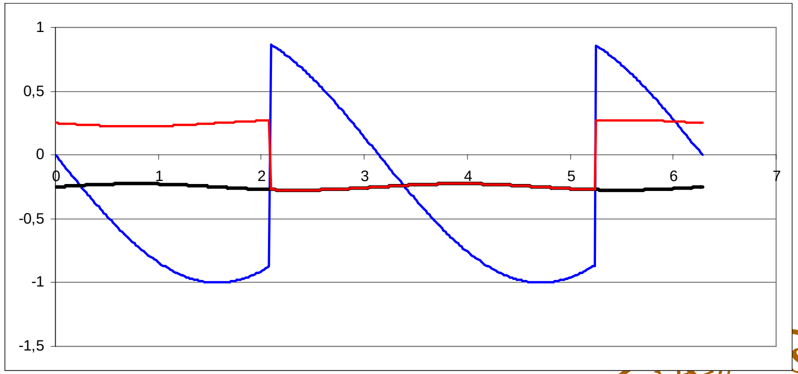
α=0º



α=30º



α=90º



α=120º

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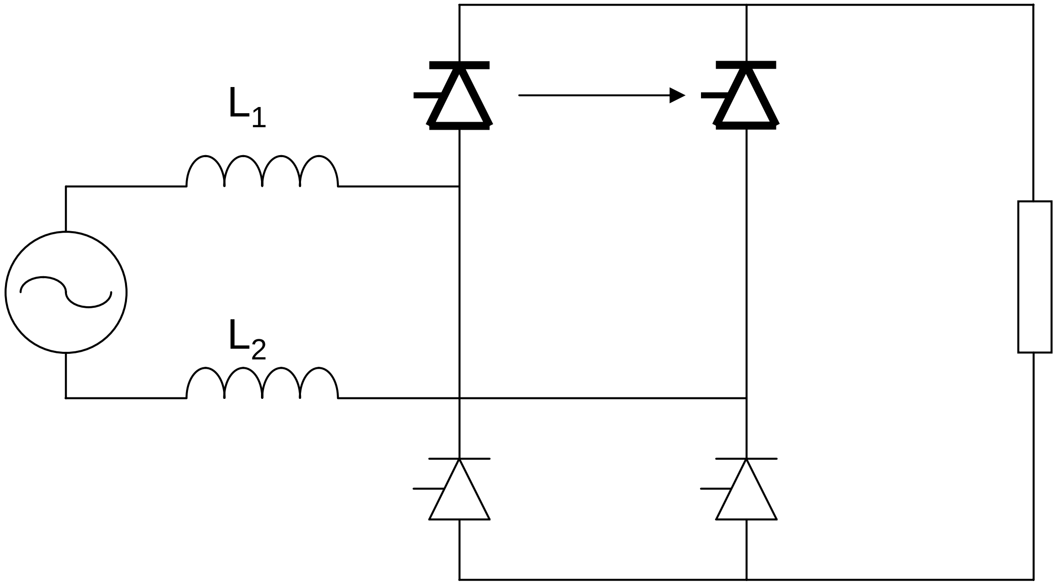
Commutation time in single phase thyristor rectifier with phase inductance

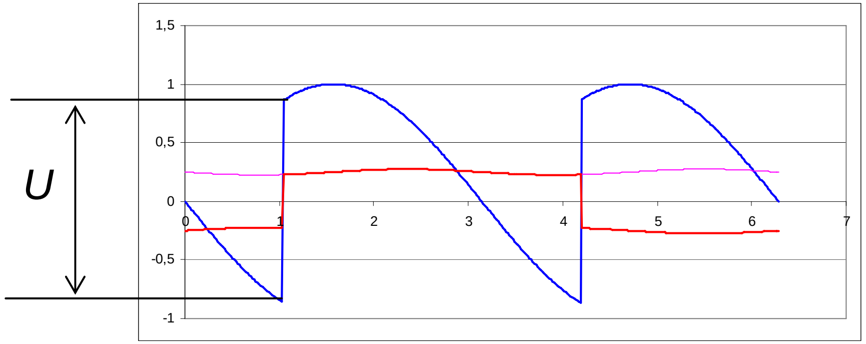


$$L = L_1 + L_2$$

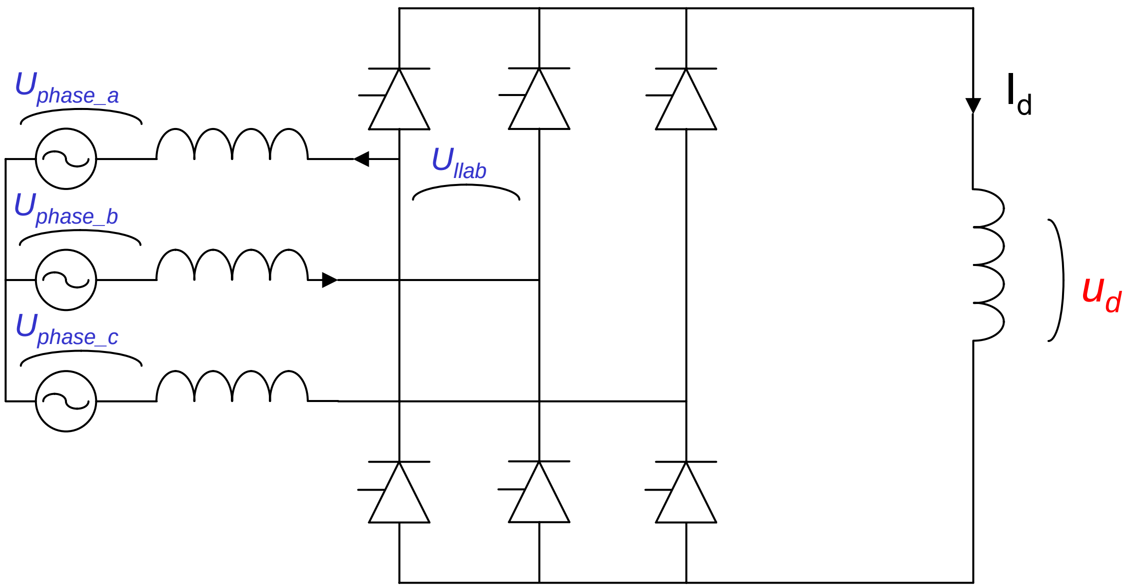
$$U = L \cdot \frac{di}{dt} \approx L \cdot \frac{\Delta i}{\Delta t}$$

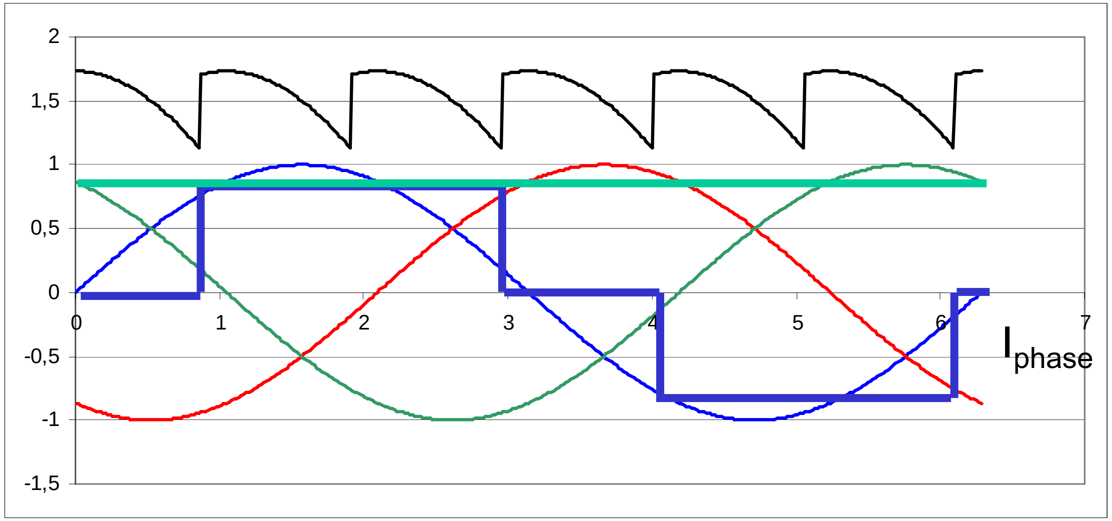
$$\Delta t = \frac{L \cdot \Delta i}{U}$$

The time can be very long with low voltage and high inductance



Three phase thyristor rectifier with inductive load

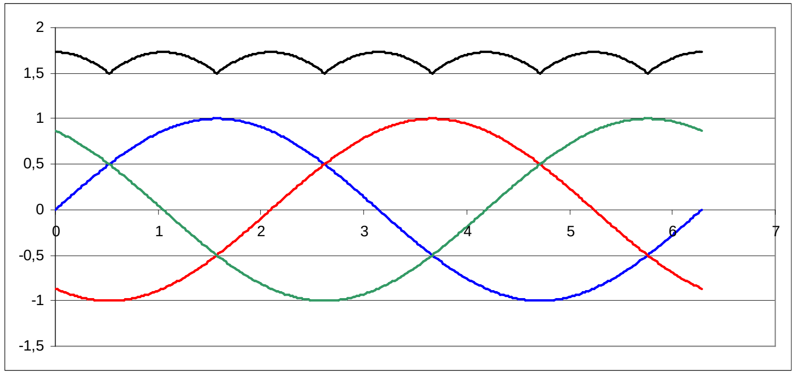




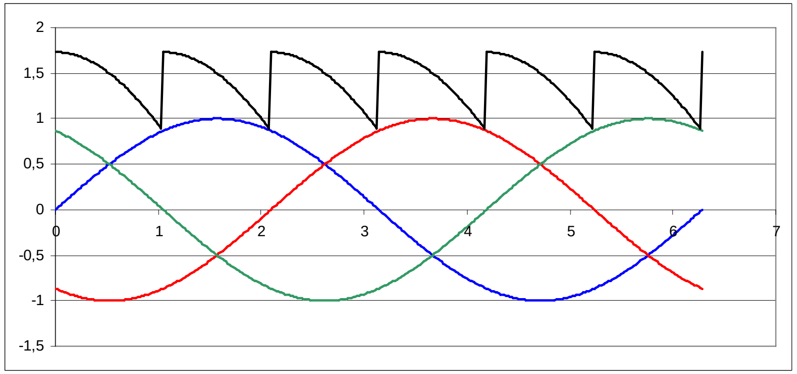
Three phase thyristor rectifier output voltage

$$V_{dc} = \cos(\alpha) \cdot \frac{\hat{e}_{LL}}{T/6} \int_{T/6} \cos(\omega t) dt = \cos(\alpha) \cdot \frac{\hat{e}_{LL}}{\pi/3} \int_{-\pi/6}^{\pi/6} \cos(\omega t) d(\omega t) = \cos(\alpha) \cdot \frac{3 \cdot \hat{e}_{LL}}{\pi} = \cos(\alpha) \cdot \frac{3\sqrt{2} \cdot E_{LLeff}}{\pi} = \cos(\alpha) \cdot \frac{3\sqrt{3} \cdot \hat{e}_{LN}}{\pi} = V_{dc0} \cdot \cos(\alpha)$$

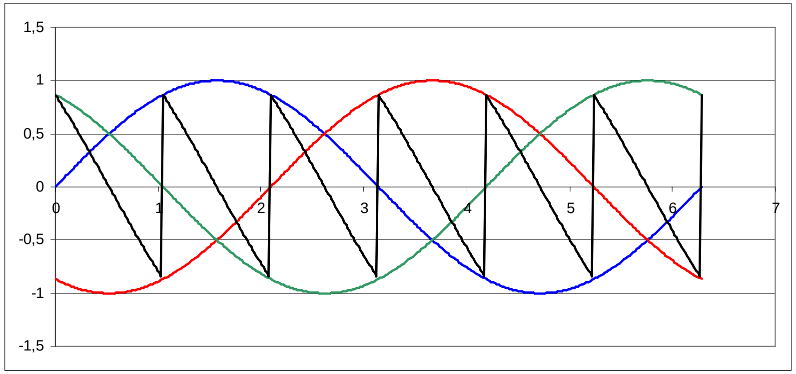
Three phase thyristor rectifier with inductive load
Different ignition angels



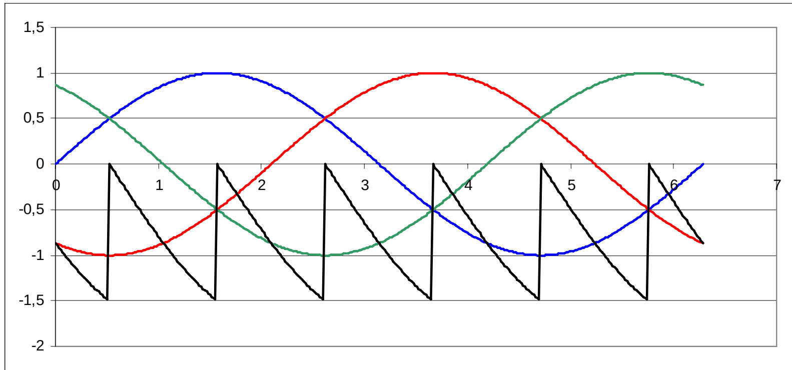
α=0°



α=30°

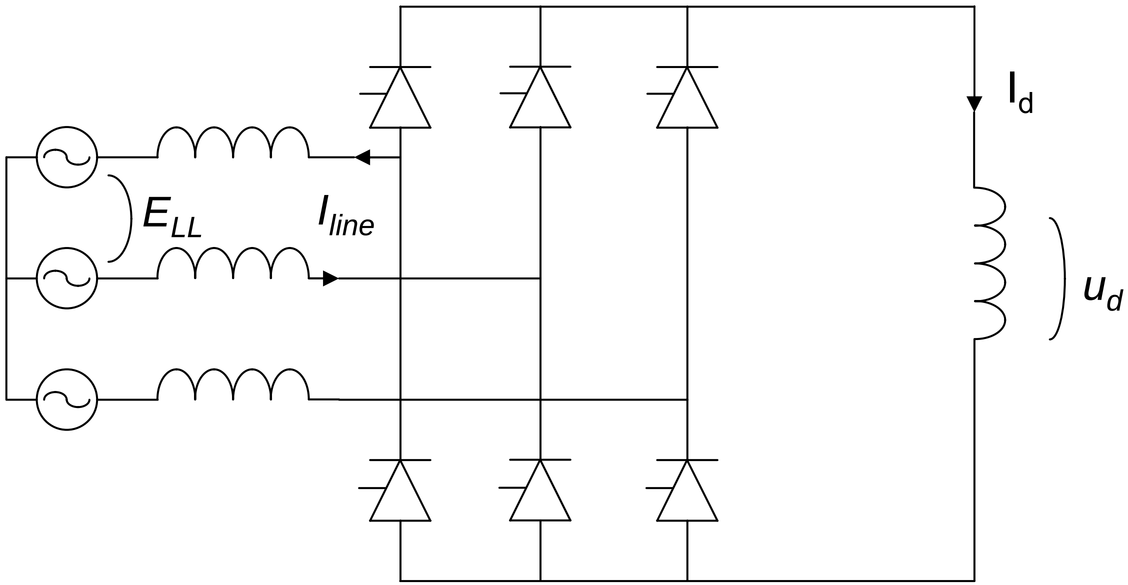


α=90°



α=120°

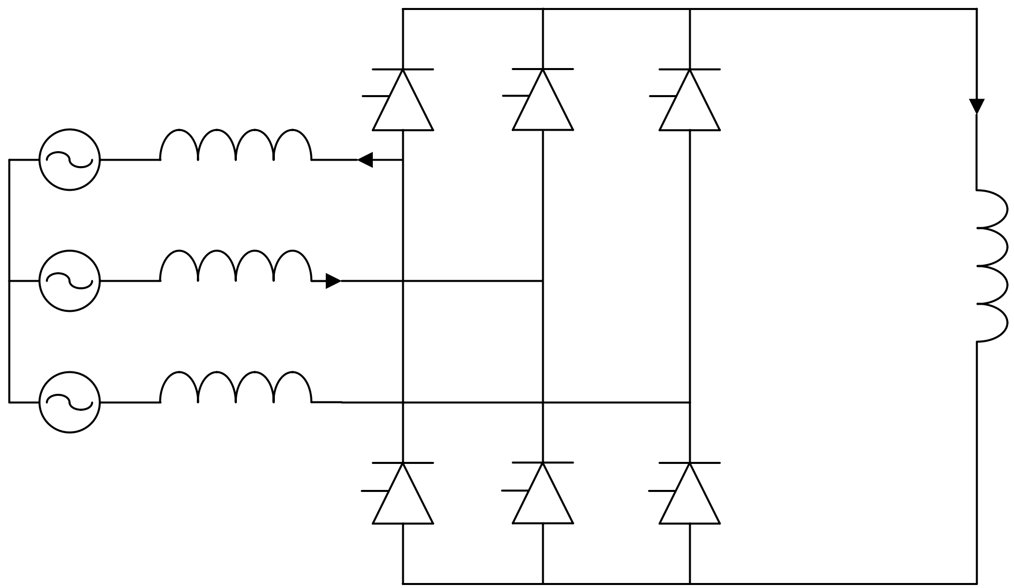
Three phase thyristor rectifier with inductive load



Active power $$P = \sqrt{3} \cdot E_{LL} \cdot I_{Line} \cdot \cos(\alpha)$$

Reactive power $$Q = \sqrt{3} \cdot E_{LL} \cdot I_{Line} \cdot \sin(\alpha)$$

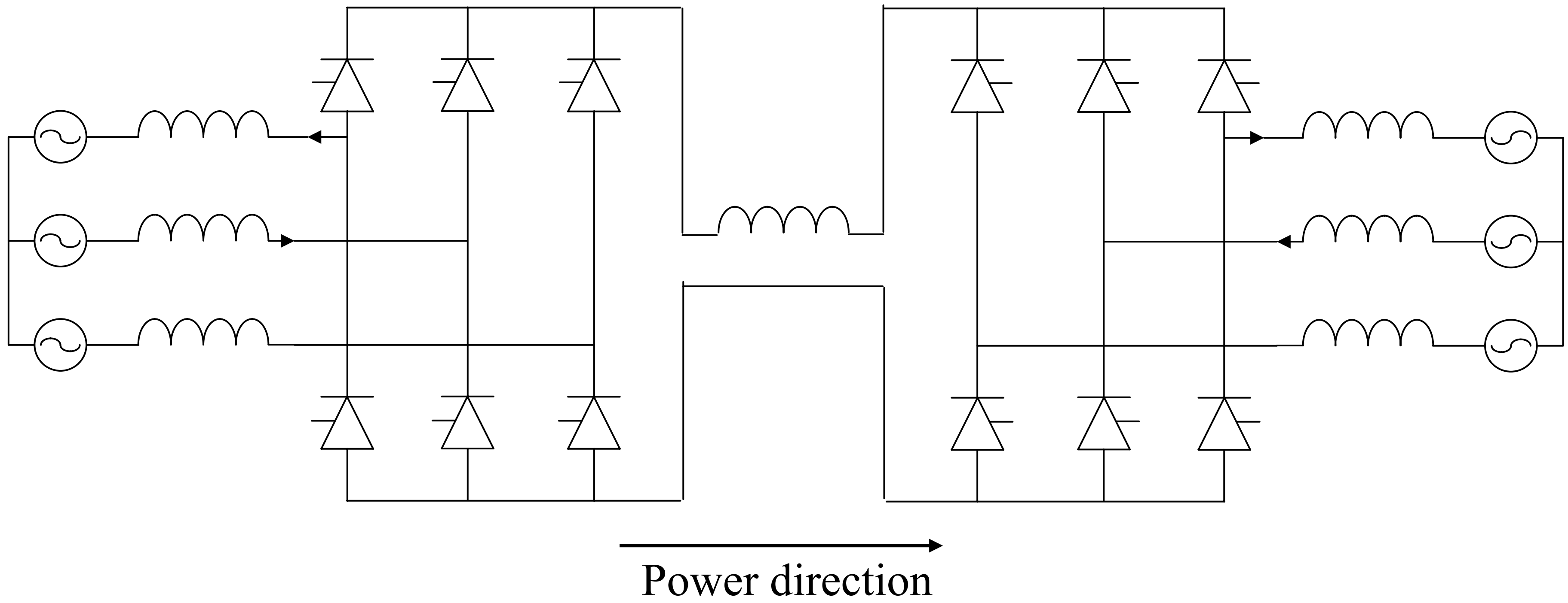
Three phase thyristor converter
Power direction



$0^o<\alpha<90^o$ Power direction from AC-side to DC-side

$90^o<\alpha<180^o$ Power direction from DC-side to AC-side

HVDC



$0^{o} < \alpha < 90^{o}$

$90^{o} < \alpha < 180^{o}$

HVDC

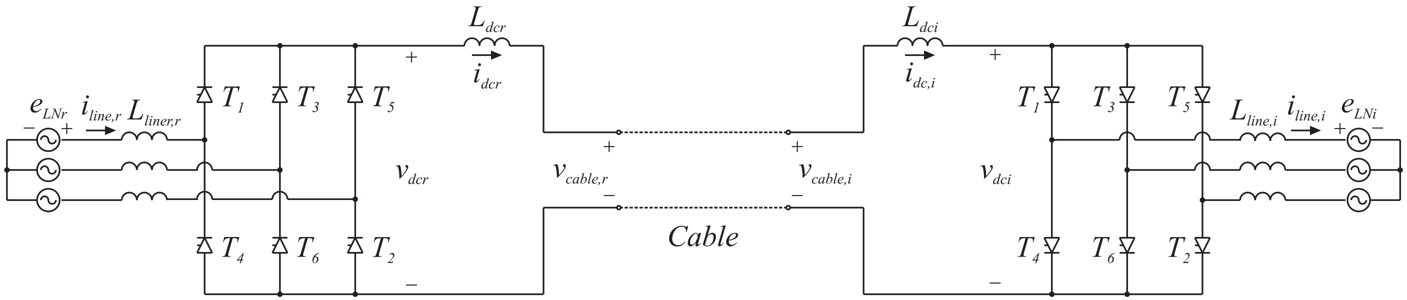


Figure 1.10: Principal schematic of a HVDC power transmission system.

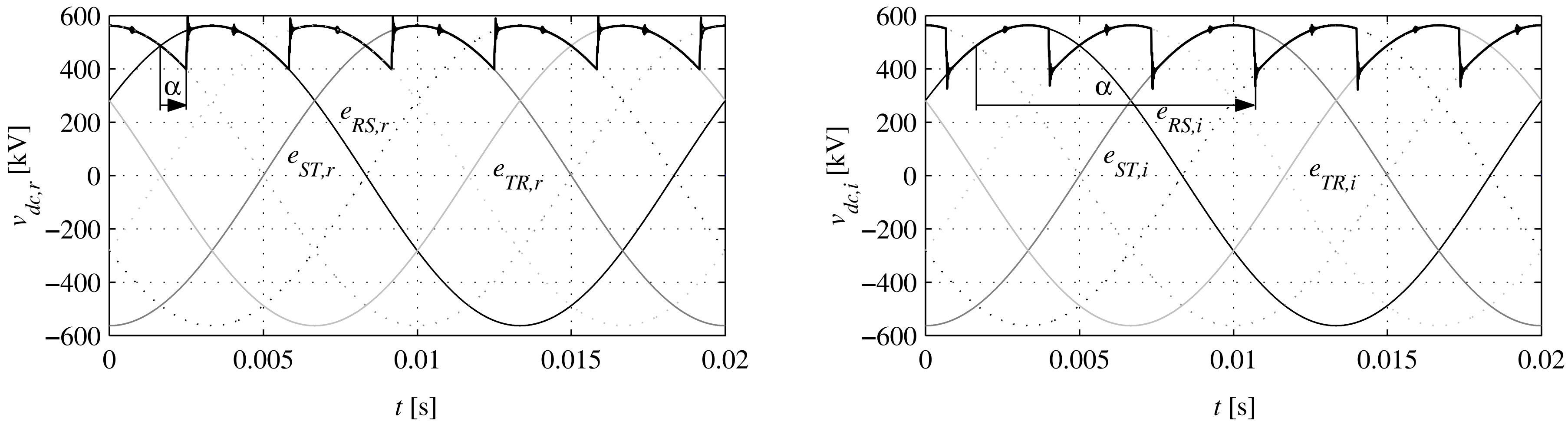


Figure 1.11: Line-to-line voltages, DC side voltage and control angles for the rectifier (left) and inverter (right) of an HVDC transmission system.

HVDC Converter Currents

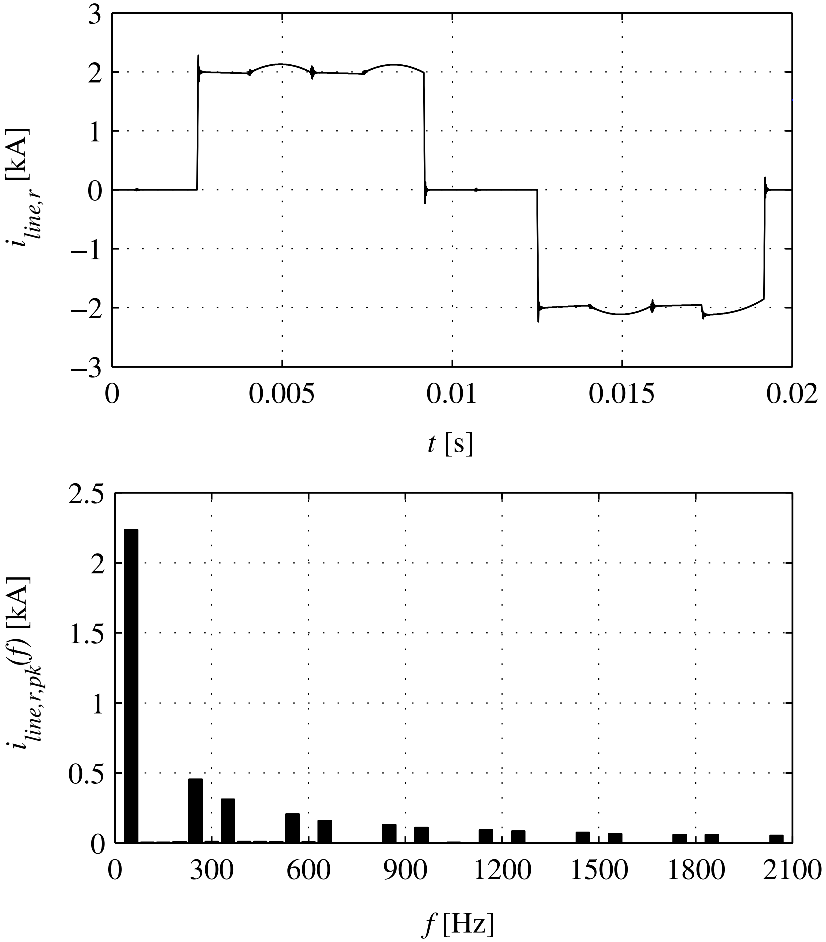


Figure 1.12: *R*-phase line current (top) and its spectrum (bottom) for the rectifier of an HVDC transmission system.

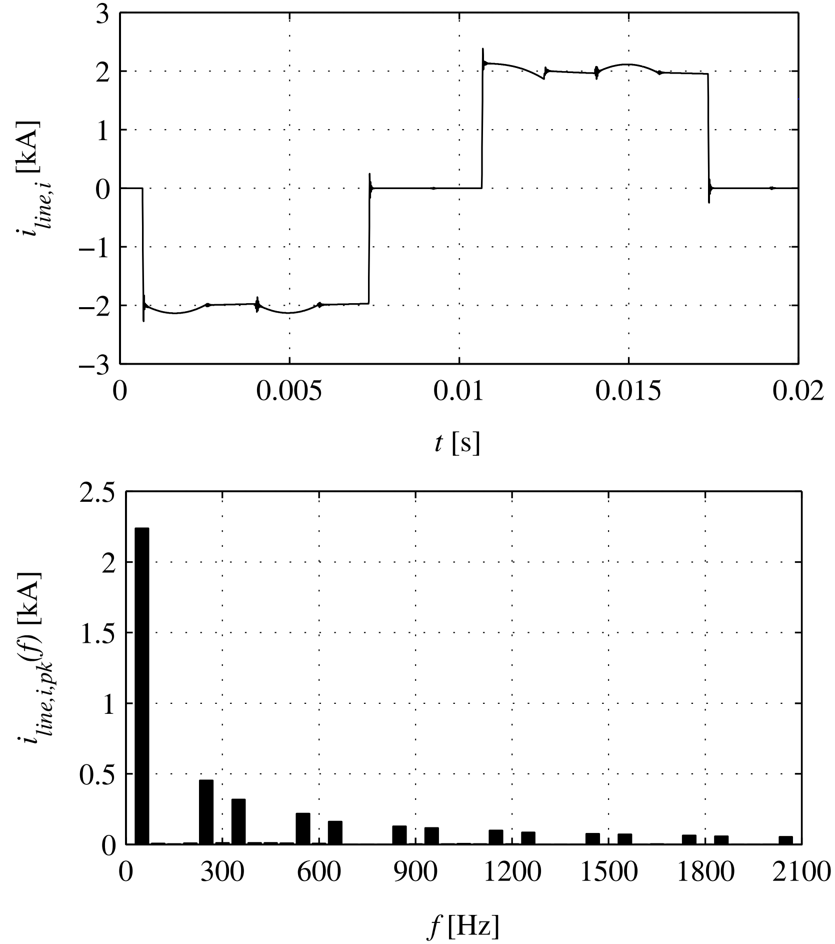


Figure 1.13: *R*-phase line current (top) and its spectrum (bottom) for the inverter of an HVDC transmission system.

Commutation Overlap

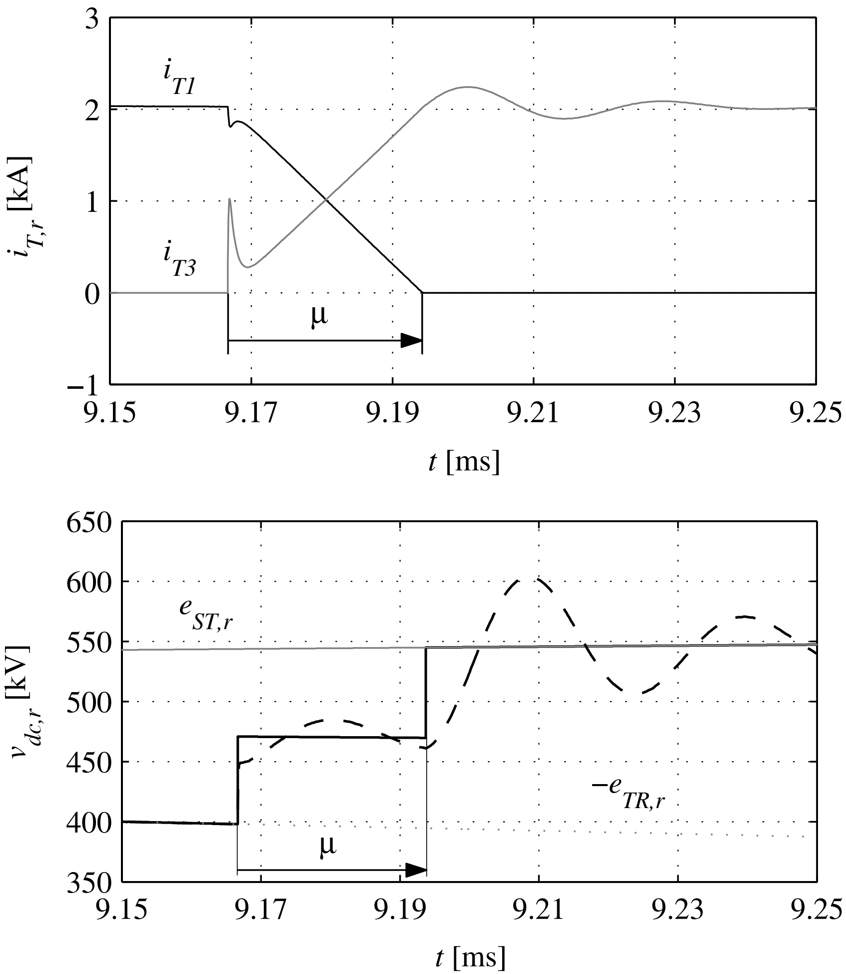


Figure 1.14: Commutation current (top) and voltage (bottom) for the rectifier.

The line inductance determines the commutation time, and therefore results in a loss of average voltage

$$V_{dcr} = V_{dc0} \cdot \cos(\alpha) - \Delta V_{dc} = V_{dc0} \cdot \cos(\alpha) - \frac{3}{\pi}\omega L_{line} I_{dc} =$$

$$= V_{dc0} \cdot \cos(\alpha) - \frac{3}{\pi} X_{line} I_{dc} = V_{dc0} \cdot \cos(\alpha) - R_{dcr} I_{dc}$$

Practical HVDC installations

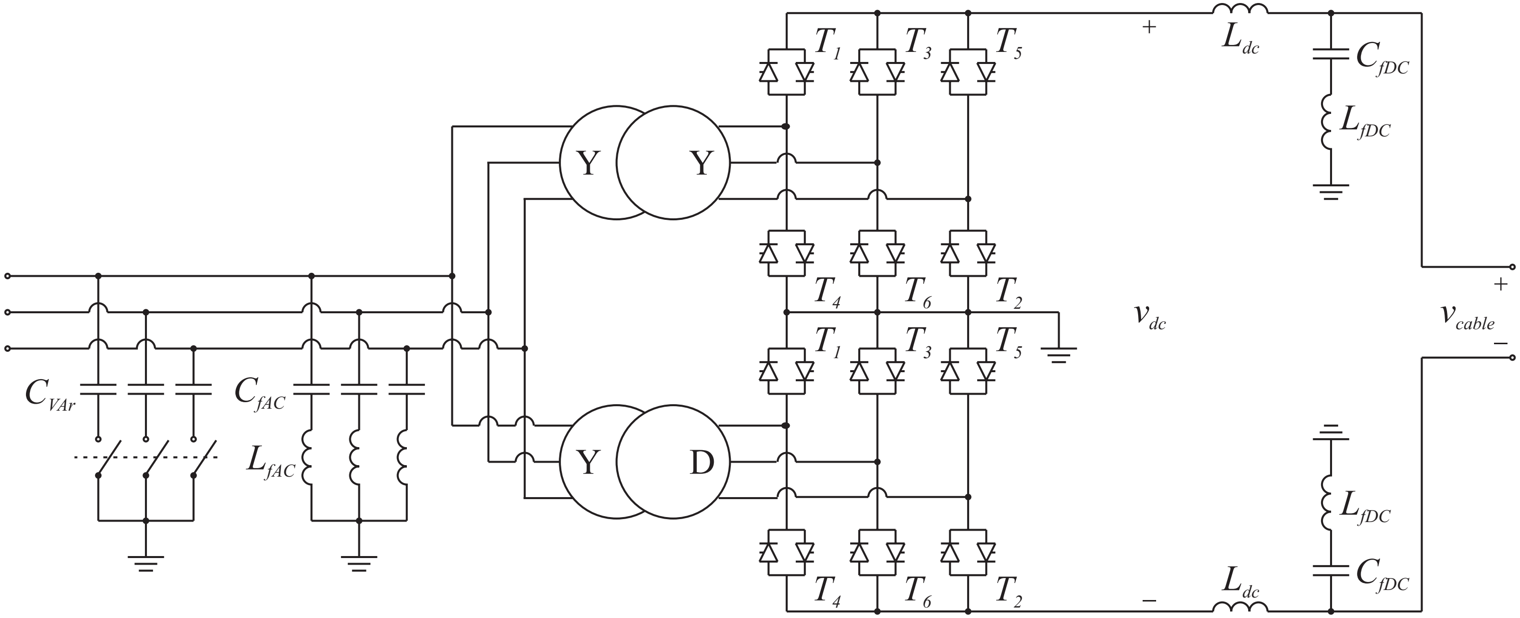


Figure 1.15: Realistic schematic of an HVDC power station.

The Buck Converter (Step-Down Converter)

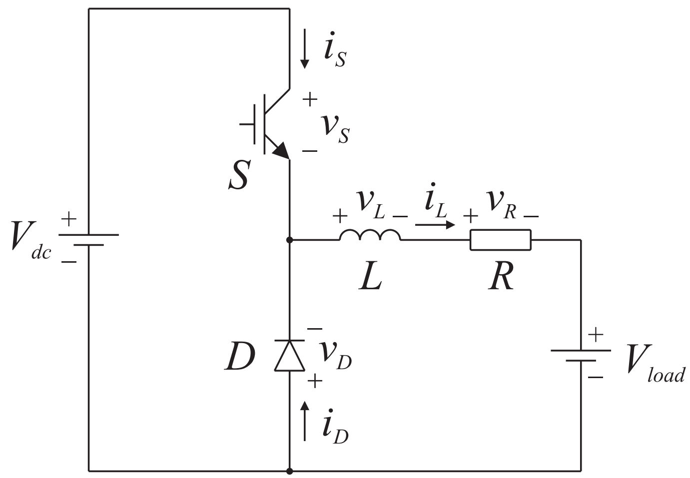


Figure 1.16: Buck converter.

S ”on”

$$V_{dc} - V_{load} = v_L = L\frac{di_L}{dt} \Rightarrow \Delta i_L = \frac{V_{dc} - V_{load}}{L} \cdot DT_{sw}$$

S ”off”

$$-V_{load} = v_L = L\frac{di_L}{dt} \Rightarrow \Delta i_L = -\frac{V_{load}}{L} \cdot (1-D)T_{sw}$$

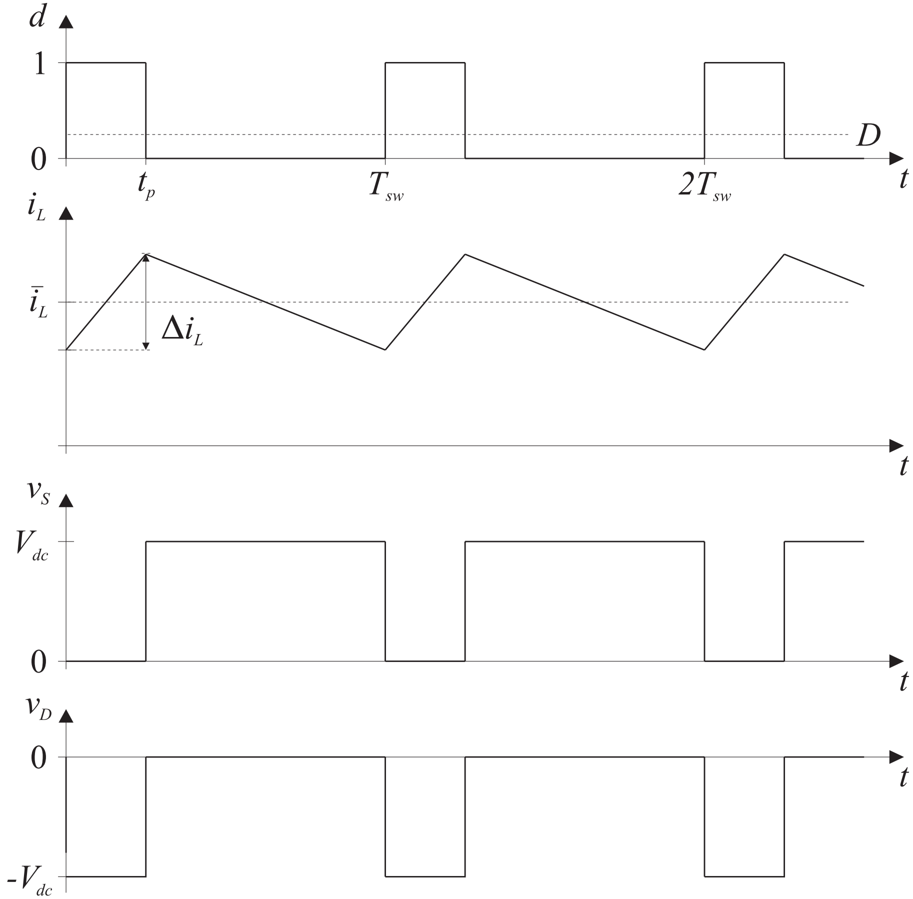


Figure 1.17: Ideal waveforms of the Buck converter.

The Boost Converter (Step-Up Converter)

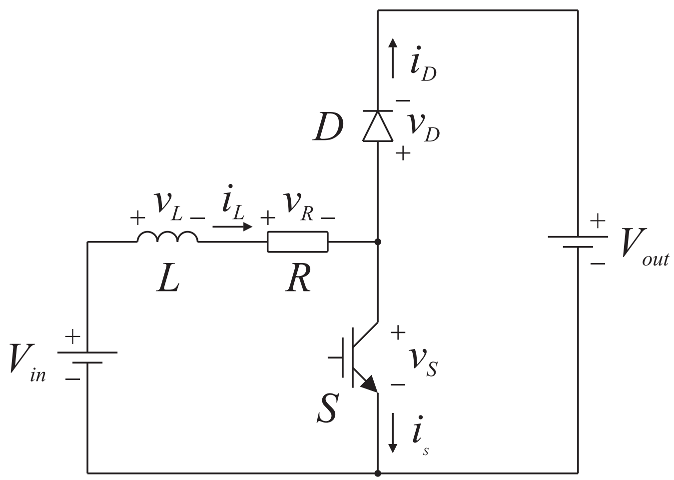


Figure 1.18: Boost converter.

S "on"

$$L\frac{di_L}{dt} = v_L = V_{in} - v_S \approx V_{in} \quad \Rightarrow \quad \Delta i_L = \frac{V_{in}}{L} \cdot DT_{sw}$$

S "off"

$$L\frac{di_L}{dt} = v_L = V_{in} - v_D - V_{out} \approx V_{in} - V_{out} \quad \Rightarrow$$

$$\Delta i_L = \frac{V_{in} - V_{out}}{L} \cdot (1-D)T_{sw}$$

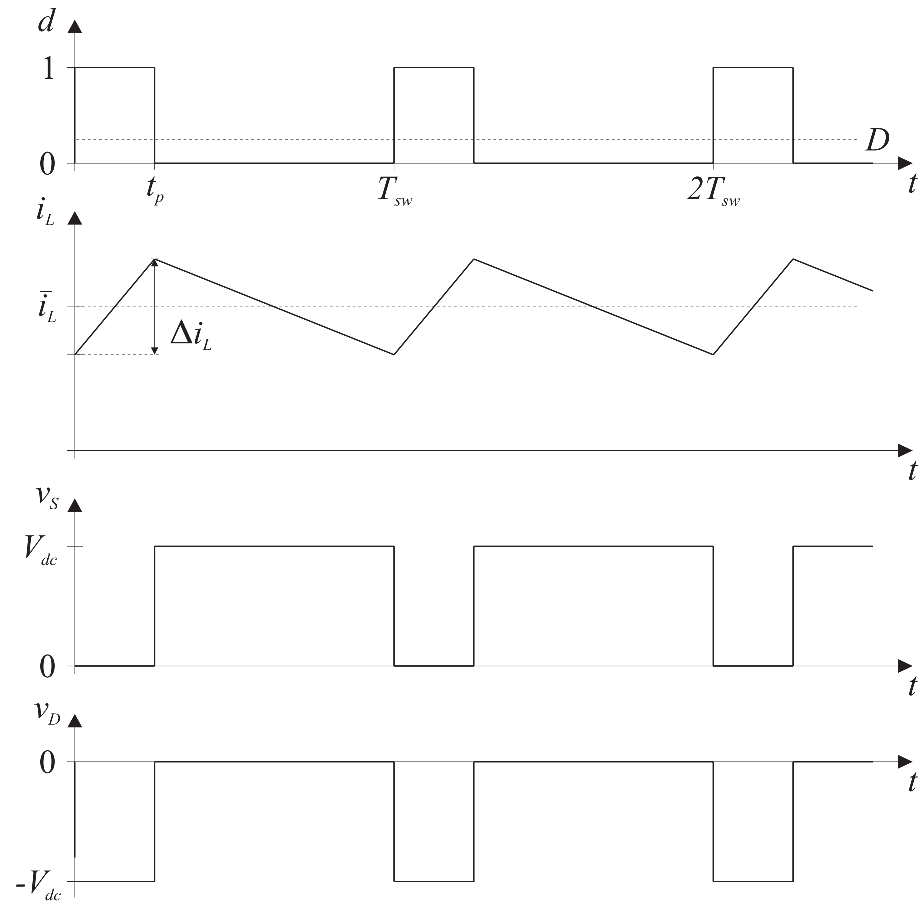


Figure 1.17: Ideal waveforms of the Boost converter. Replace V_{dc} and V_{load} of the Buck converter with V_{out} and V_{in}

The Buck-Boost Converter (Half-Bridge)

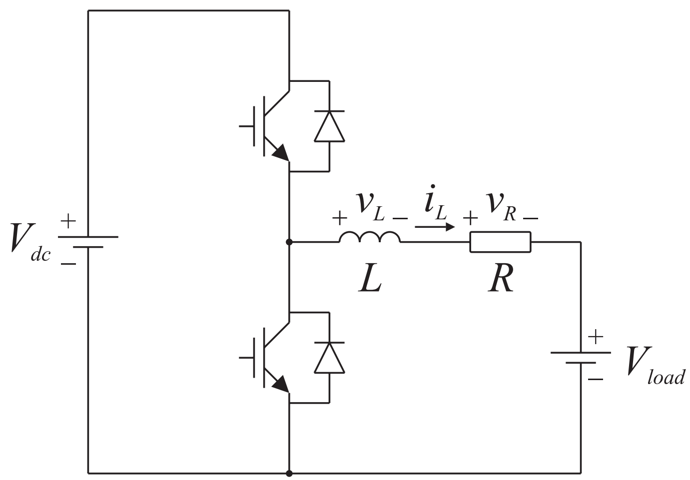


Figure 1.19: Buck-boost converter.

S "on"

$$V_{dc} - V_{load} = v_L = L\frac{di_L}{dt} \;\Rightarrow\; \Delta i_L = \frac{V_{dc} - V_{load}}{L} \cdot DT_{sw}$$

S "off"

$$-V_{load} = v_L = L\frac{di_L}{dt} \;\Rightarrow\; \Delta i_L = -\frac{V_{load}}{L} \cdot (1 - D)T_{sw}$$

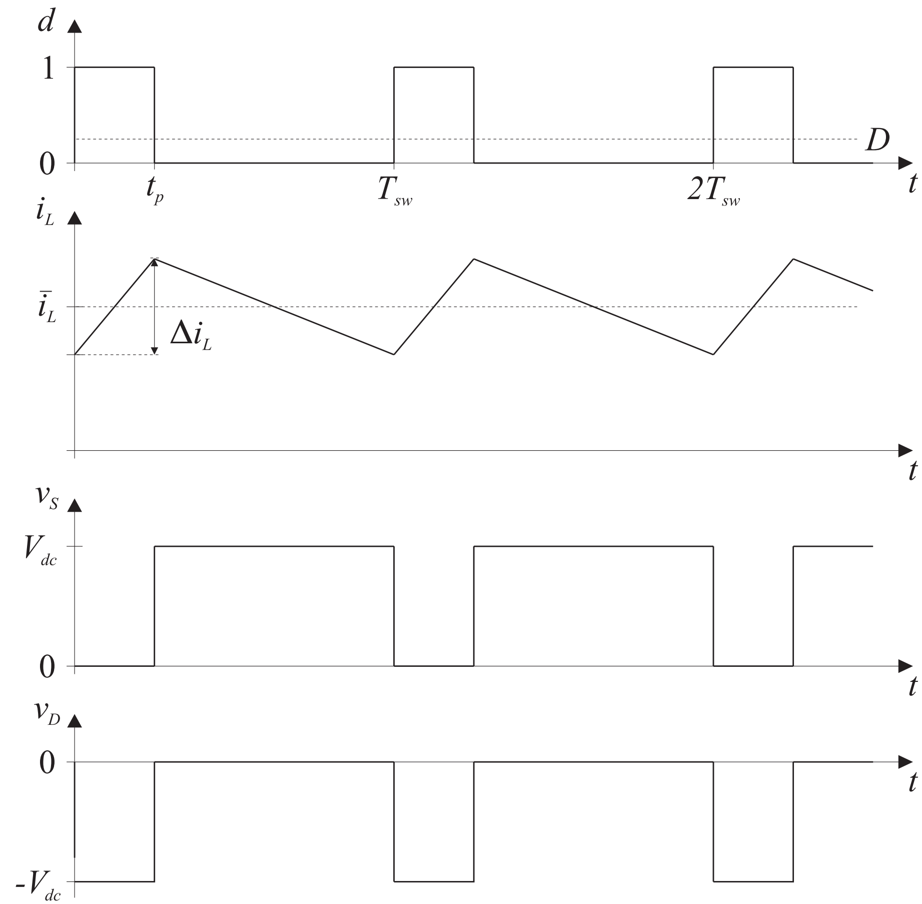
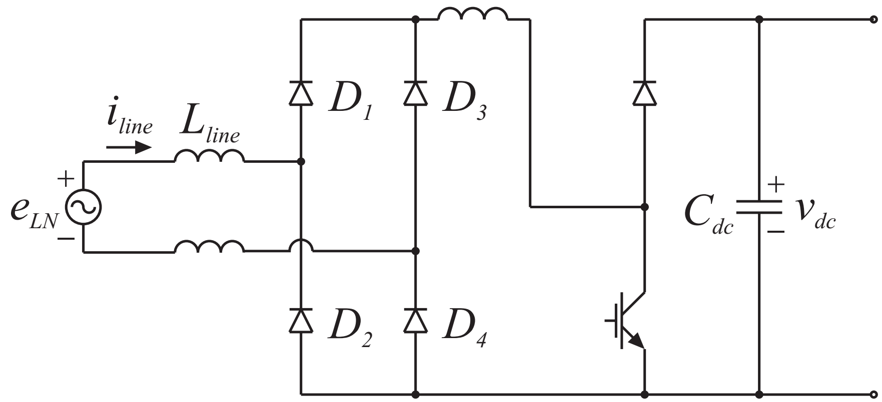
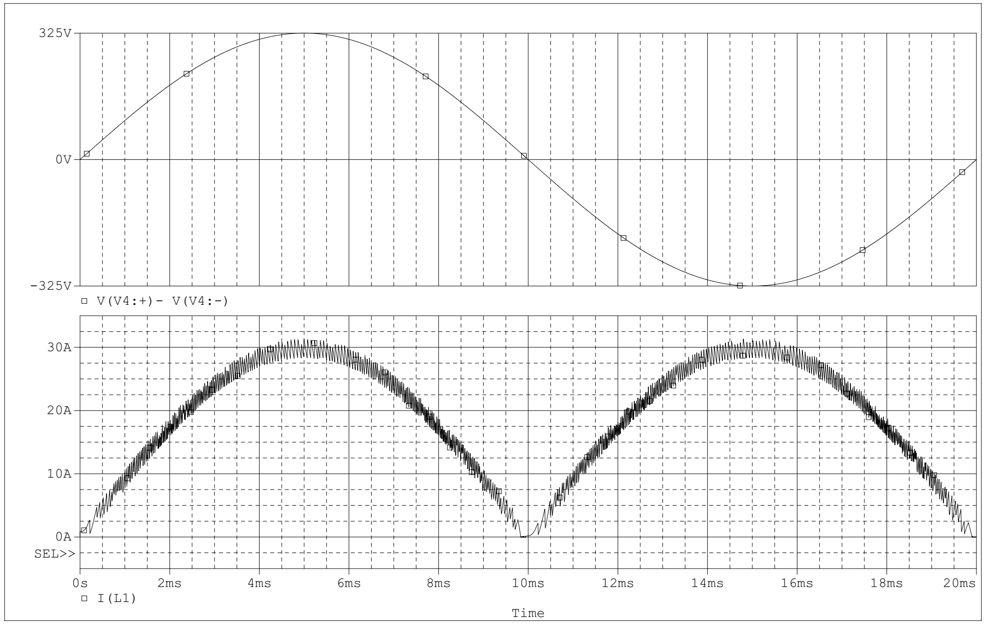


Figure 1.17: Ideal waveforms of the Buck-boost converter.

Diode rectifier with Power Factor Corrector



Single-phase diode rectifier with power factor corrector (PFC).



Line-to-neutral voltage (top) and rectified line current (bottom) for a diode rectifier equipped with PFC.

VSC Based HVDC

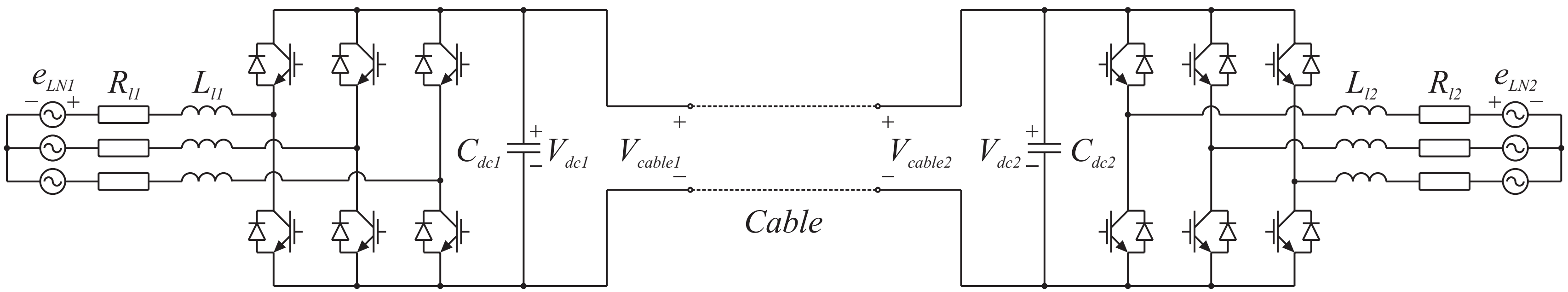


Figure 1.30 Basic VSC based HVDC power transmission interconnection.

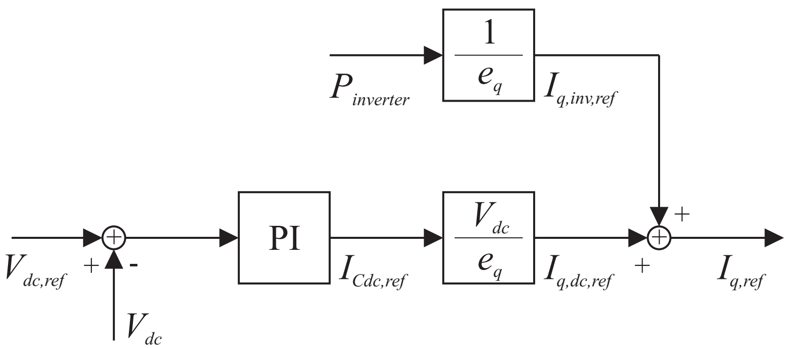


Figure 1.31 DC bus voltage controller for VSC based HVDC.

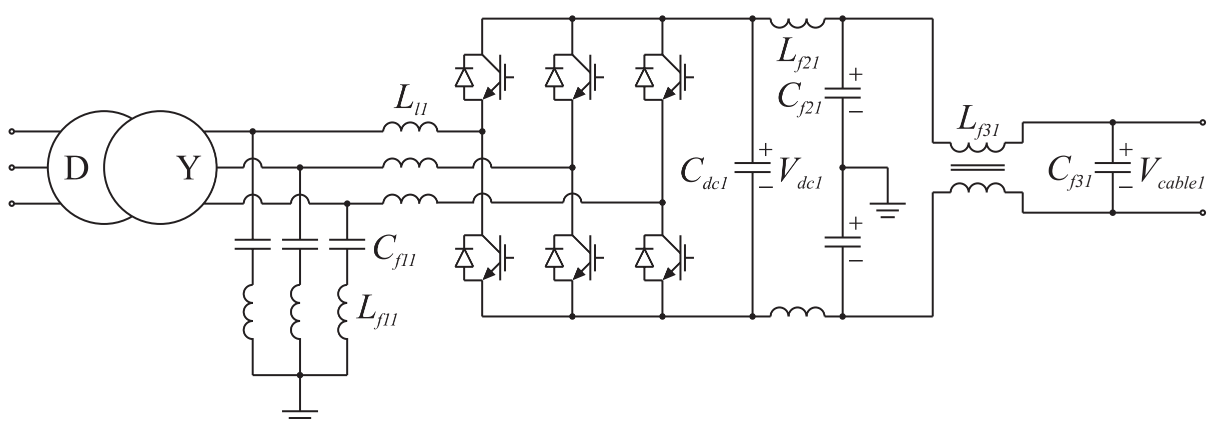


Figure 1.32 Realistic VSC based HVDC light converter station.