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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

Mebtu Beza
mebtu.beza@chalmers.se

Chalmers University of Technology
Department of Electrical Engineering
Division of Electric Power Engineering

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Lecture outline

The three-phase thyristor rectifier

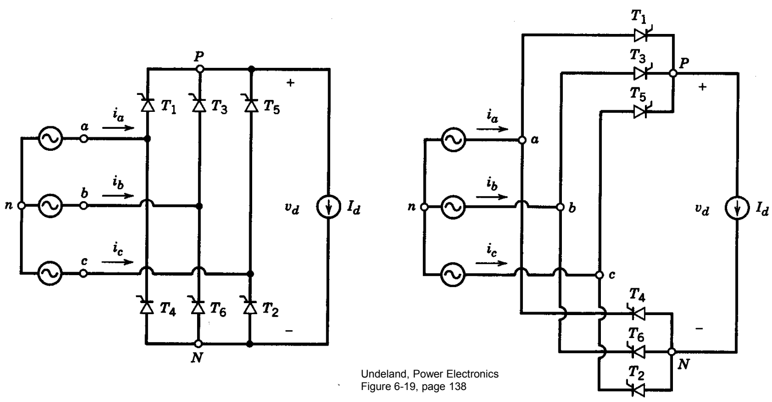
- Three-phase thyristor rectifiers without source inductance
- Source inductance and current commutation
- Three-phase thyristor rectifier as inverter
- Impact of thyristor loads
- Practical applications of three-phase thyristor rectifiers
- Summary

Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase AC/DC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel converters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

Three-Phase Thyristor Rectifier

- For most practical applications where higher powers are handled, a three-phase thyristor rectifier with constant DC-side current is used



Undeland, Power Electronics
Figure 6-19, page 138

Single-Phase Thyristor with Constant DC-Side Current (α=30°)

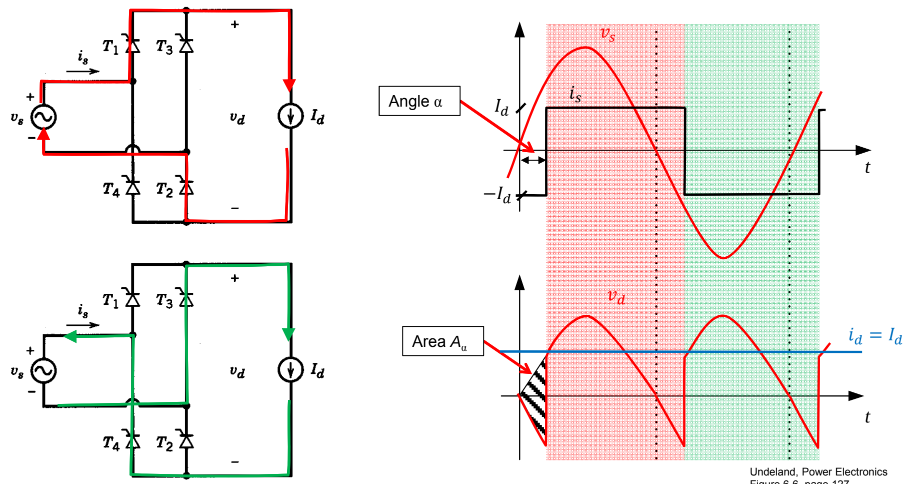


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Figure 6-6, page 127

Three-Phase Thyristor Rectifier Delay α=60°

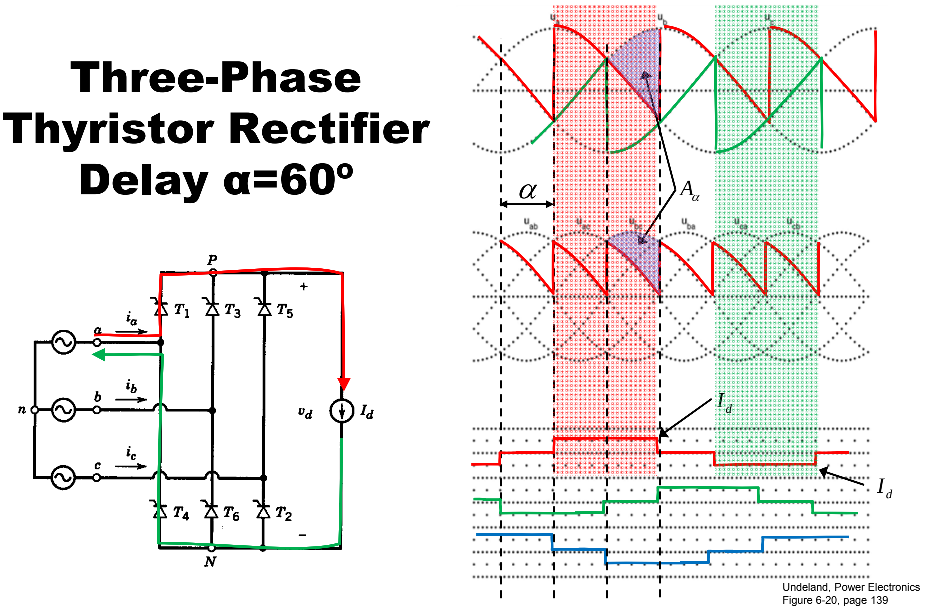

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Figure 6-20, page 139

Three-Phase Thyristor Rectifier Delay α=60º

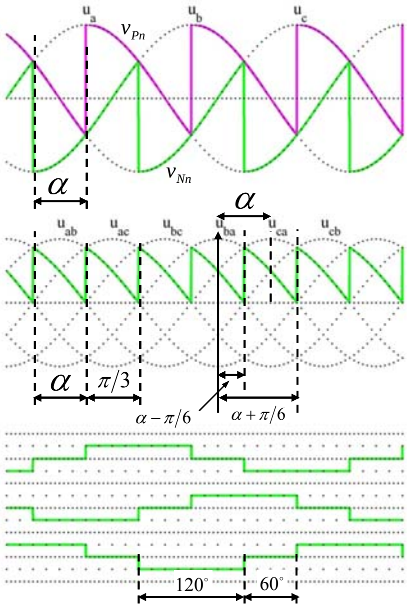
- Average DC-voltage

$$V_d = \frac{1}{\pi/3}\int_{\alpha-\pi/6}^{\alpha+\pi/6}\sqrt{2}V_{LL}\cos(\gamma)\mathrm{d}\gamma =$$

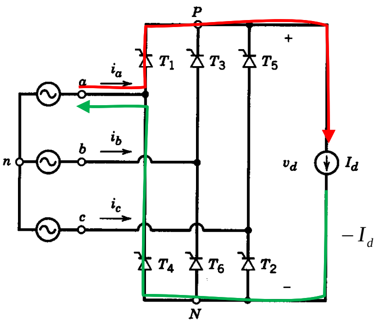
$$= \frac{3\sqrt{2}}{\pi}V_{LL}\left[\sin(\gamma)\right]_{\alpha-\pi/6}^{\alpha+\pi/6} =$$

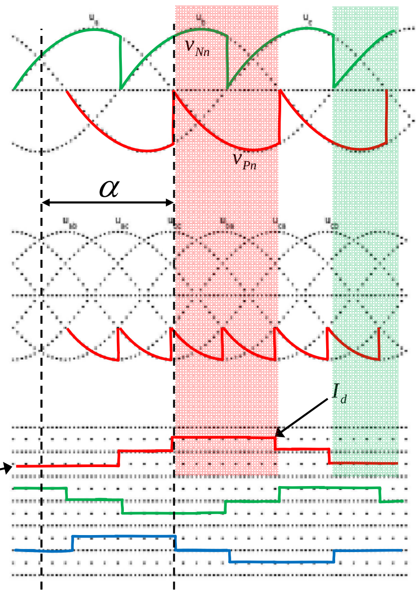
$$= \frac{3\sqrt{2}}{\pi}V_{LL}\left(\sin\left(\alpha+\frac{\pi}{6}\right)-\sin\left(\alpha-\frac{\pi}{6}\right)\right) =$$

$$= \frac{3\sqrt{2}}{\pi}V_{LL}\cos(\alpha)$$



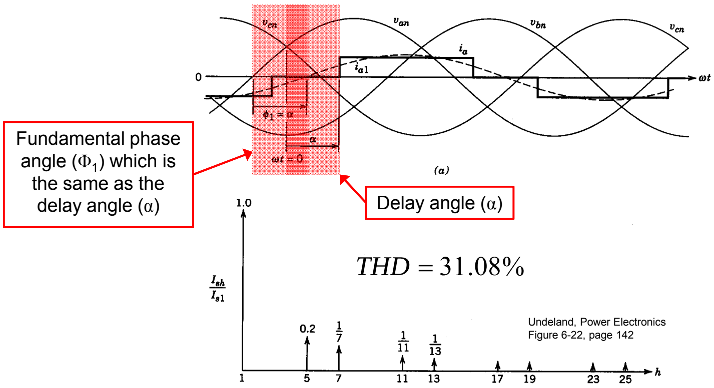
Three-Phase Thyristor Rectifier Delay α=150º





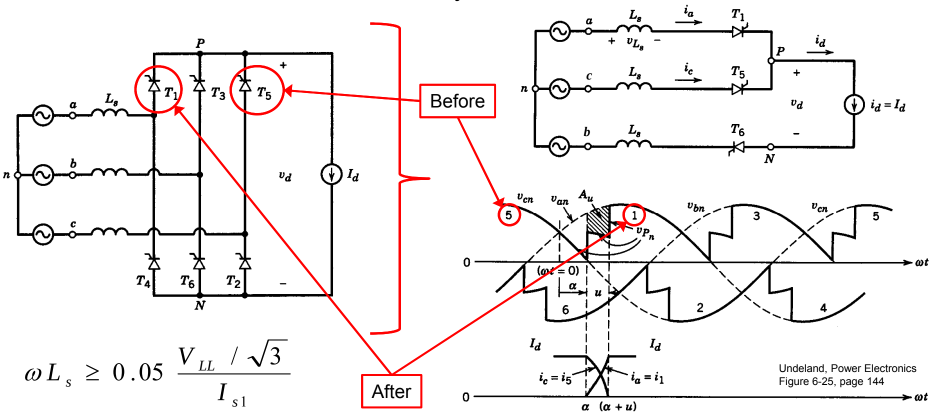
Three-Phase Thyristor Rectifier Input Line Current Waveforms

- The current drawn from the source is quasi square-wave where the fundamental frequency is phase delayed with α



Three-Phase Thyristor Rectifier with AC-side Inductance

- To study the current commutation, the circuit is redrawn so that the only commutation is included



$$\omega L_s \geq 0.05 \frac{V_{LL} / \sqrt{3}}{I_{s1}}$$

Three-Phase Thyristor Rectifier with AC-side Inductance

Before commutation: $(\omega t < \alpha)$

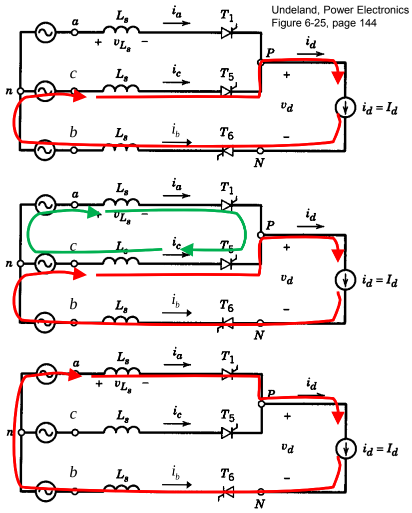
$$i_c = I_d$$
$$i_b = -I_d$$

During commutation: $(\alpha \le \omega t \le \alpha + u)$

$$i_a = i_u$$
$$i_b = -I_d$$
$$i_c = I_d - i_u$$

After commutation: $(\omega t > \alpha + u)$

$$i_a = I_d$$
$$i_b = -I_d$$



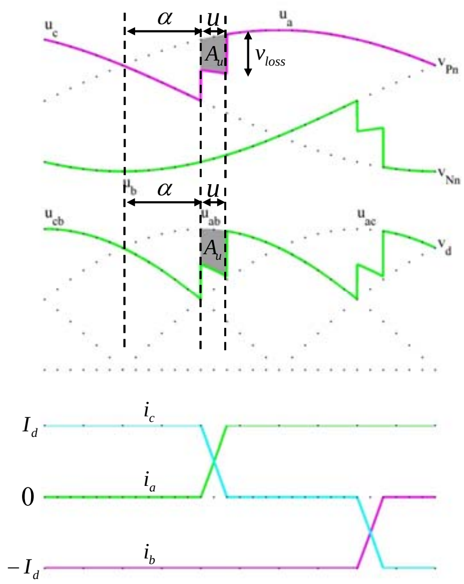
Three-Phase Thyristor Rectifier with AC-side Inductance

During commutation:

$$v_{Pn} = v_c - v_{Lc} = v_c - L_s \frac{\mathrm{d}(I_d - i_u)}{\mathrm{d}t} \Rightarrow$$

$$\left.\begin{aligned} v_{Pn} &= v_c + L_s \frac{\mathrm{d}i_u}{\mathrm{d}t} \\ + \quad v_{Pn} &= v_a - v_{La} = v_a - L_s \frac{\mathrm{d}i_u}{\mathrm{d}t} \end{aligned}\right\}$$

$$v_{Pn} = \frac{v_c + v_a}{2}$$



Three-Phase Thyristor Rectifier with AC-side Inductance

The commutation circuit gives:

$$v_{ac} = \sqrt{2}V_{LL}\sin(\gamma) = v_{La} - v_{Lc} =$$

$$= L_s\frac{di_u}{dt} - L_s\frac{d(I_d - i_u)}{dt} \Rightarrow$$

$$\sqrt{2}V_{LL}\sin(\gamma) = 2\omega L_s\frac{di_u}{d\gamma} \Rightarrow$$

$$\int_0^{I_d} 2\omega L_s di_u = 2\omega L_s I_d = \int_\alpha^{\alpha+u}\sqrt{2}V_{LL}\sin(\gamma)d\gamma =$$

$$= \sqrt{2}V_{LL}(\cos(\alpha) - \cos(\alpha+u)) \Rightarrow$$

$$\cos(\alpha+u) = \cos(\alpha) - \frac{2\omega L_s I_d}{\sqrt{2}V_{LL}}$$

Calculation of the average DC voltage:

$$v_{Pn} = v_a - v_{La} = v_a - v_{loss} \Rightarrow$$

Ideally: $v_{Pn} = v_a$

$$v_{loss} = v_{La} = L_s\frac{di_u}{dt} = \omega L_s\frac{di_u}{d\gamma} \Rightarrow$$

$$A_u = \int_\alpha^{\alpha+u} v_{loss}d\gamma = \int_0^{I_d}\omega L_s di_u = \omega L_s I_d$$

$$V_d = \frac{1}{\pi/3}\int_{\alpha-\pi/6}^{\alpha+\pi/6} v_d d\gamma =$$

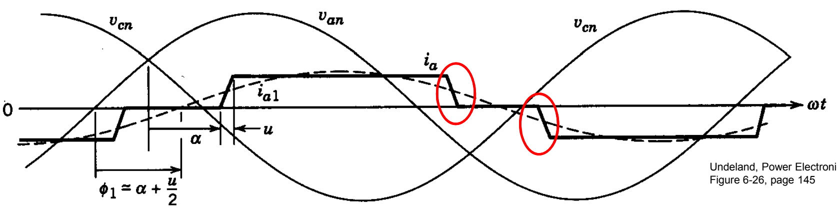
$$= \frac{3}{\pi}\left(\int_{\alpha-\pi/6}^{\alpha+\pi/6}\sqrt{2}V_{LL}\cos(\gamma)d\gamma - A_u\right) =$$

$$= \frac{3\sqrt{2}}{\pi}V_{LL}\cos(\alpha) - \frac{3\omega L_s I_d}{\pi}$$

Ideal voltage-angle area without L_s

Three-Phase Thyristor Rectifier with AC-side Inductance – Input Current

- The current during the commutation has in the previous slides been idealized.



Undeland, Power Electronics Figure 6-26, page 145

- The real current can be expressed as:

$$i_u(\theta) = \frac{1}{2\omega L_s}\int_\alpha^{\alpha+\theta} v_u d\theta$$

$$= \frac{1}{2\omega L_s}\int_\alpha^{\alpha+\theta} 2\sqrt{2}V_s\sin(\theta)\,d\theta = \frac{\sqrt{2}V_s}{\omega L_s}[-\cos(\theta)]_\alpha^\theta = \frac{\sqrt{2}V_s}{\omega L_s}(\cos(\alpha) - \cos(\alpha+\theta))$$

$$DPF = \cos(\alpha + u/2)$$

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Finite AC-side Inductance Input Current Harmonics

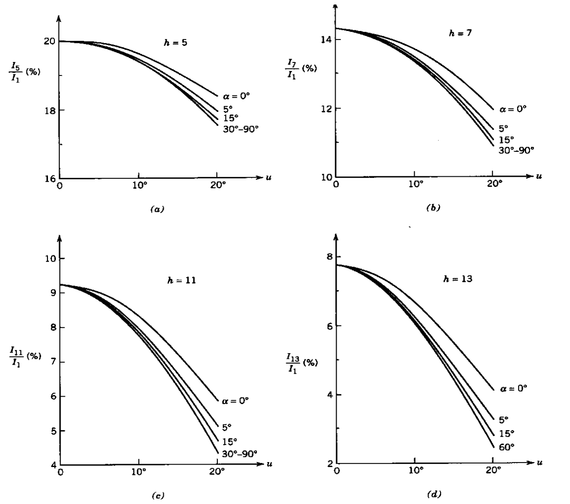

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Figure 6-27, page 147

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Three-Phase Thyristor Rectifier Continuous DC-side Current

- Practical application of a thyristor rectifier

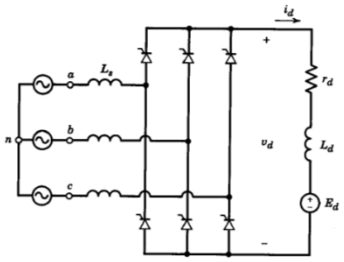

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Figure 6-28, page 148

- The current flowing on the DC-side can be continuous but not constant

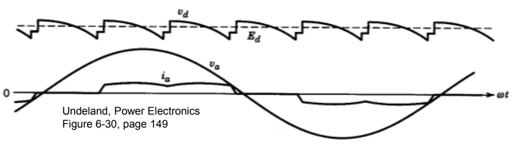

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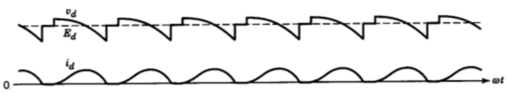
Figure 6-30, page 149

- The DC-side current becomes discontinuous below a certain average value for a given delay angle.



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Three-Phase Thyristor Rectifier Inverter Mode

- For delay angles greater than 90^o, the resulting output voltage (V_d) will become negative.

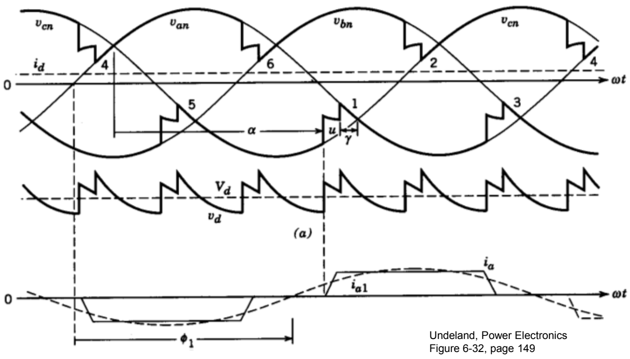

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Figure 6-32, page 149

Thyristor inverter mode Importance of extinction angle γ

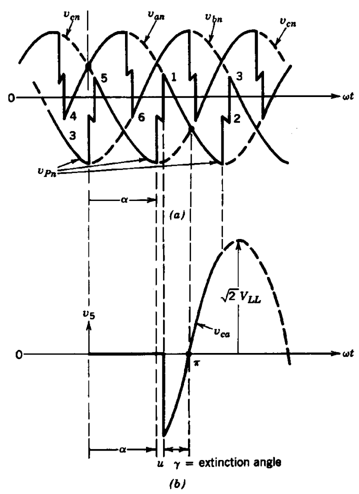

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Figure 6-34, page 151

Impact of thyristor loads PCC voltage Notching and harmonics

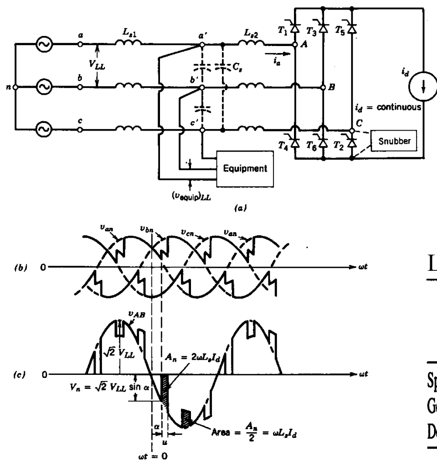

Figure 6-35 Line notching in other equipment voltage: (*a*) circuit, (*b*) phase voltages, (*c*) line-to-line voltage v_{AB}.

$$\text{Notch width } u = \frac{\text{Notch area } A_n}{\text{Notch depth } V_n}$$

$$\text{Notch area and depth at PCC} = \rho A_n, \rho V_n$$

$$\rho = \frac{L_{s1}}{L_{s1} + L_{s2}} \Rightarrow \omega L_s I_{s2} \geq 0.05 V_{LL} / \sqrt{3}$$

importance of the external inductace L_{S2}

Limits for 460 - V systems

Class	Line Notch Depth ρ(%)	Line Notch Area (V·μs)	Voltage Total Harmonic Distortion (%)
Special applications	10	16,400	3
General system	20	22,800	5
Dedicated system	50	36,500	10

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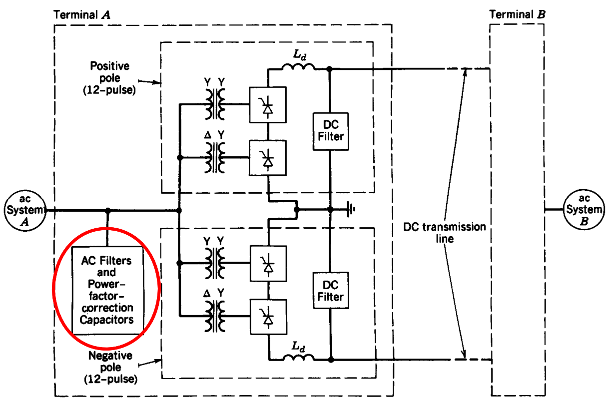
Figure 6-34/35/Table 6-2, page 151/152/153

Thyristor Applications – HVDC Converters and 12-Pulse Rectification

- Typical application of a thyristor rectifier is a HVDC Transmission
- Uses 12-pulse rectification and power factor correction capacitors



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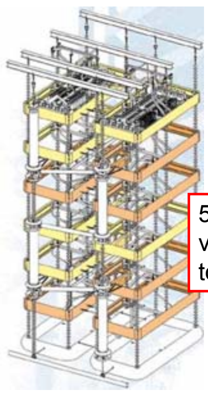

500kV valve tower

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Thyristor Applications – HVDC Converters and 12-Pulse Rectification

- A HVDC transmission is typically designed in a 12-pulse configuration

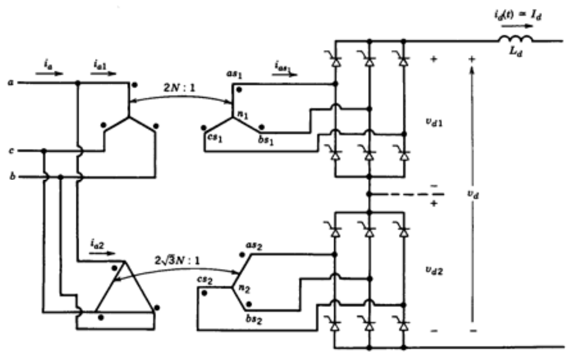

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Figure 17-2, page 462

- To reduce line current THD
- To improve input power factor
- To avoid semi-conductor devices in series.

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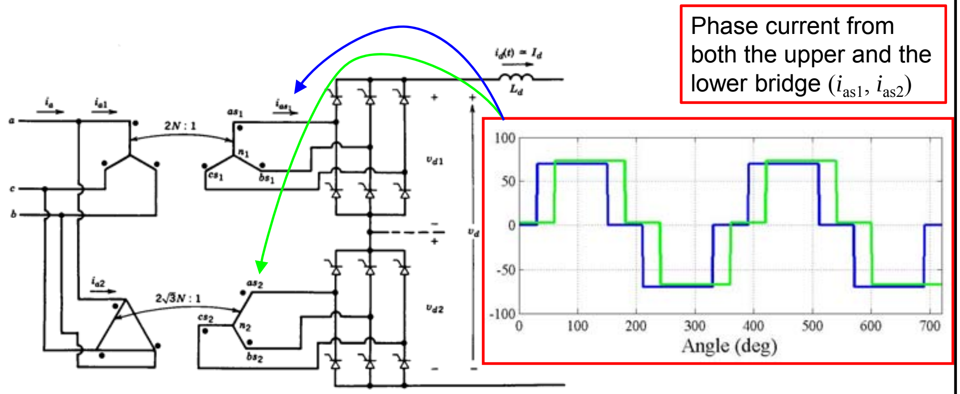
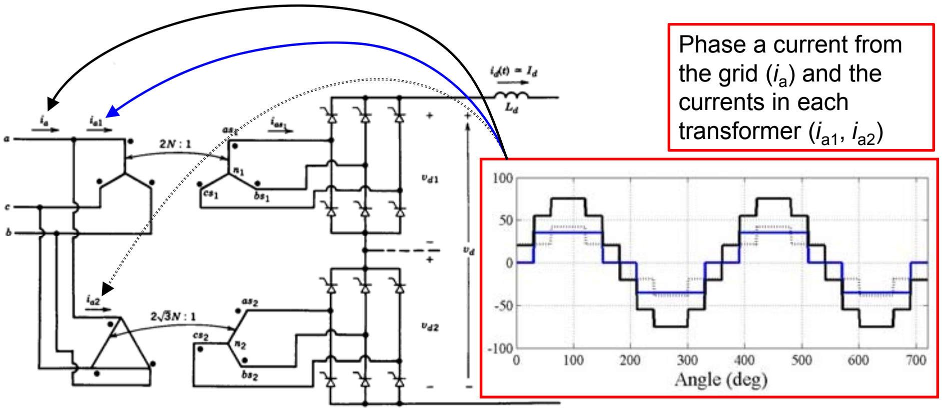
Thyristor Applications – HVDC Converters and 12-Pulse Rectification

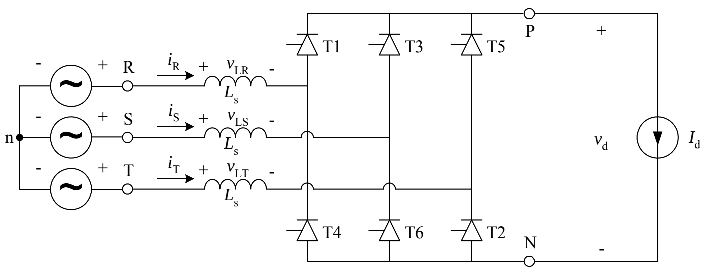
Phase current from both the upper and the lower bridge (i_{as1}, i_{as2})



Thyristor Applications – HVDC Converters and 12-Pulse Rectification



Tutorial 11



For L_s = 25 uH and V_{LL} = 460 V RMS at 60 Hz

- Calculate the commutation angle u for V_d = 525 V and P_d = 500 kW

Summary

- Three-phase thyristor rectifiers without source inductance
- Impact of source inductance on current commutation
- Thyristor converters in inverter mode of operation
- Impact of thyristor loads
- Applications of Thyristors
- Benefits of 12-pulse operation
- Learning outcome:
  - Operation of a three-phase thyristor rectifier operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.