TSTE19 Power Electronics

Lecture 4

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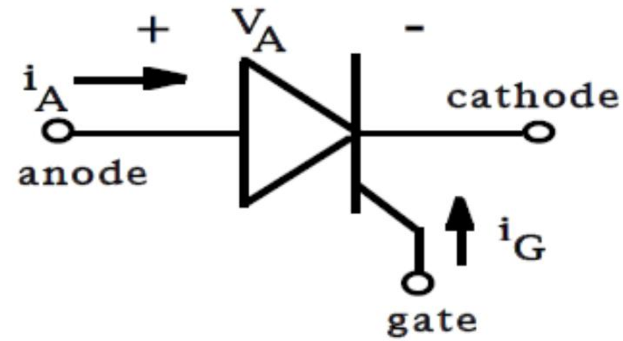
ISY/EKS

Outline

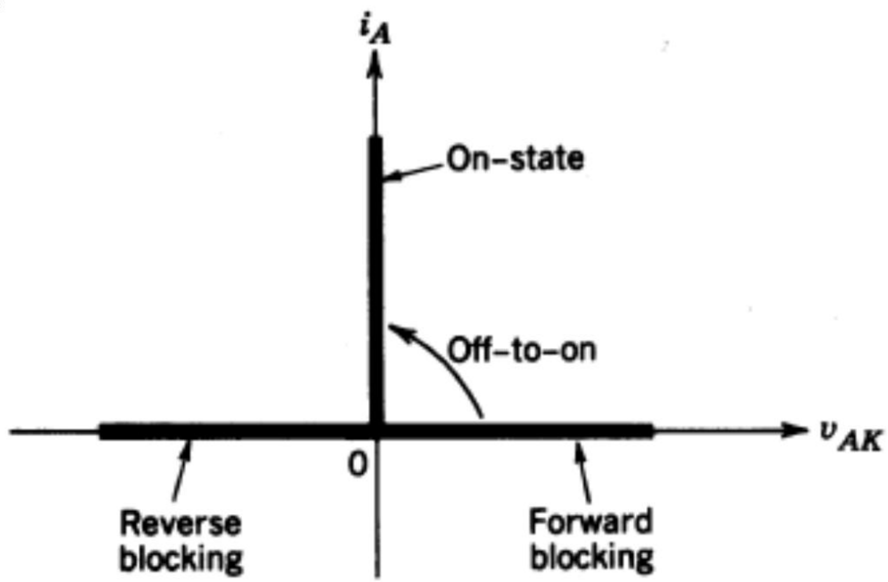
- The thyristor
- Controlled rectifier and inverters
  - Single phase
  - Three phase

Thyristors

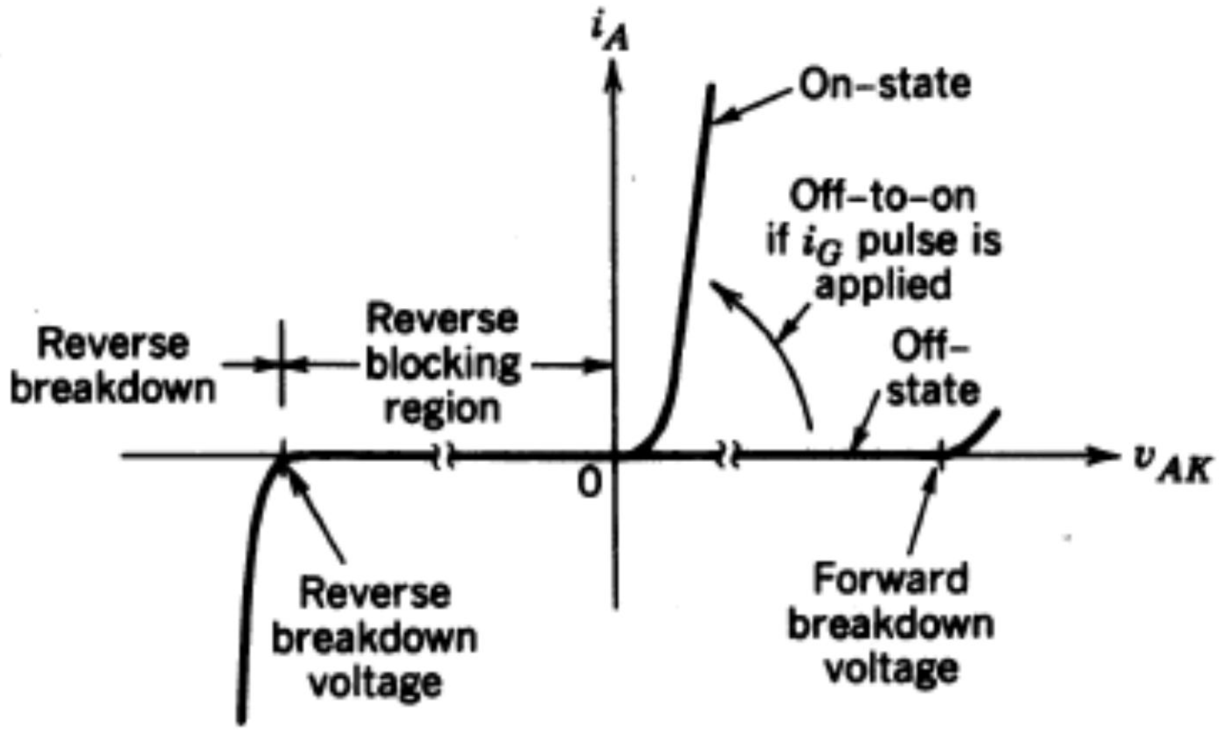
Thyristor circuit symbol.



- Only possible to turn on
- Pulse on gate when forward blocking turns on thyristor
- Current reversal followed by reverse blocking turns off thyris
- 3 modes:
  - Forward blocking
  - On-state
  - Reverse blocking

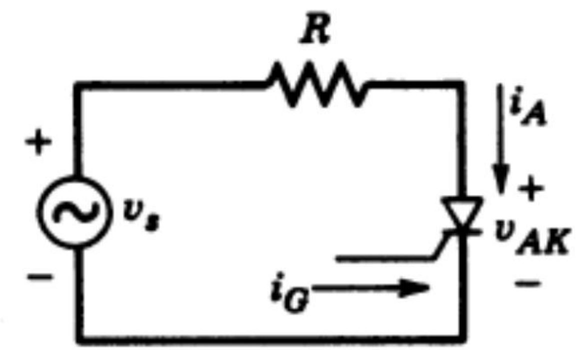


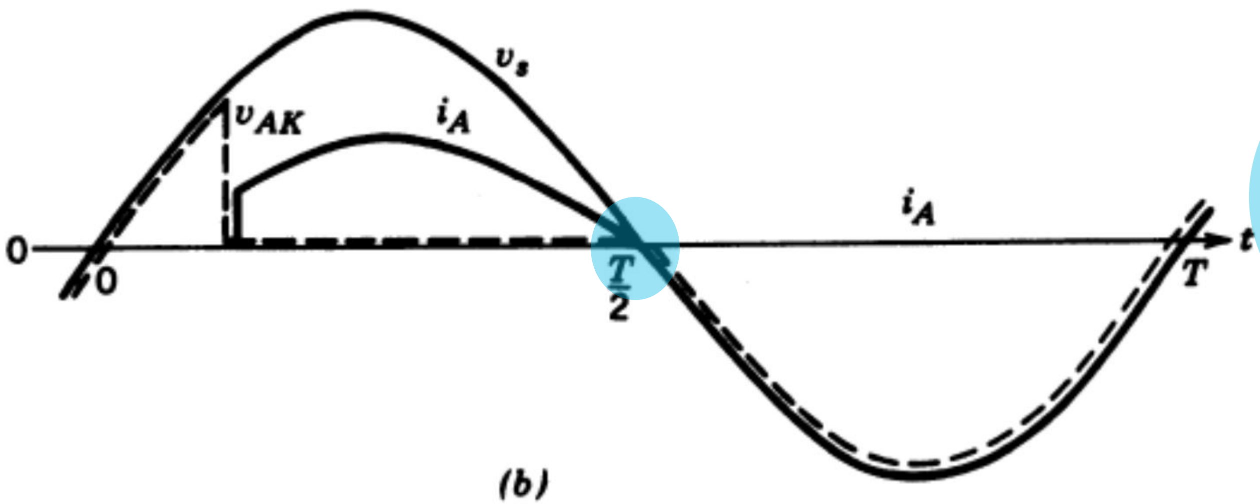
Actual thyristor characteristics

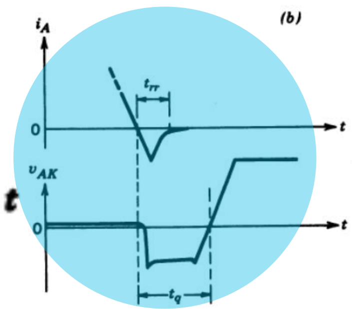


Thyristor, example circuit

- Thyristor can be triggered in interval
  $0 < t < T/2$



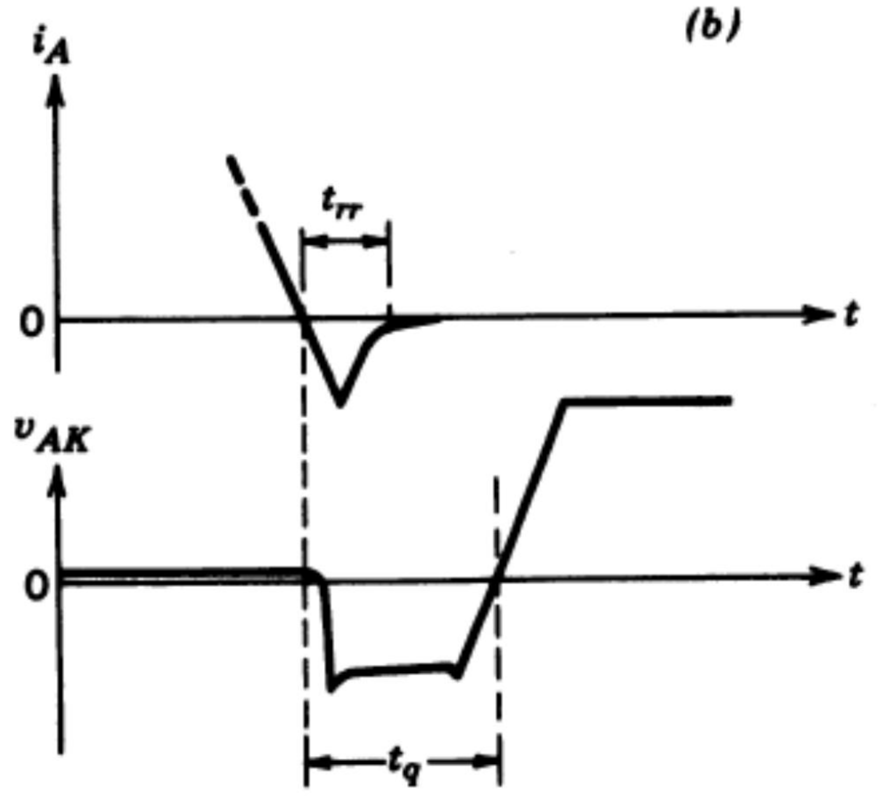




Thyristor turn-off process

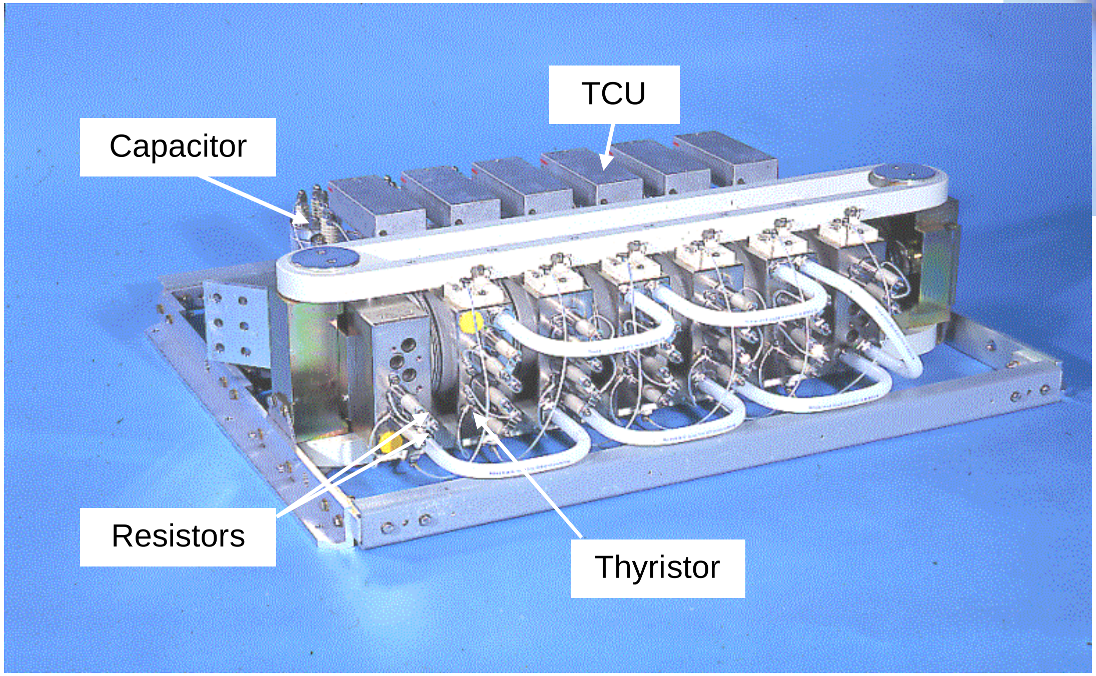
Succesful turn-off:

- Current reversal
  - reverse recovery as a diode
- Reverse blocking for $t \geq t_q$



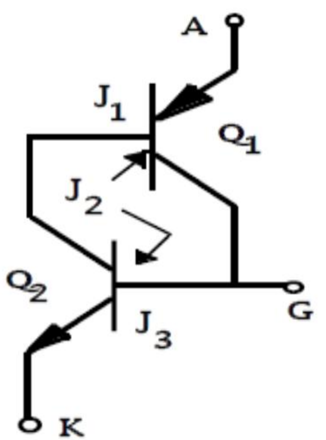
Thyristor presspack

- Active part on a single silicon wafer.



Thyristor, junction structure

Two transistor equivalent circuit



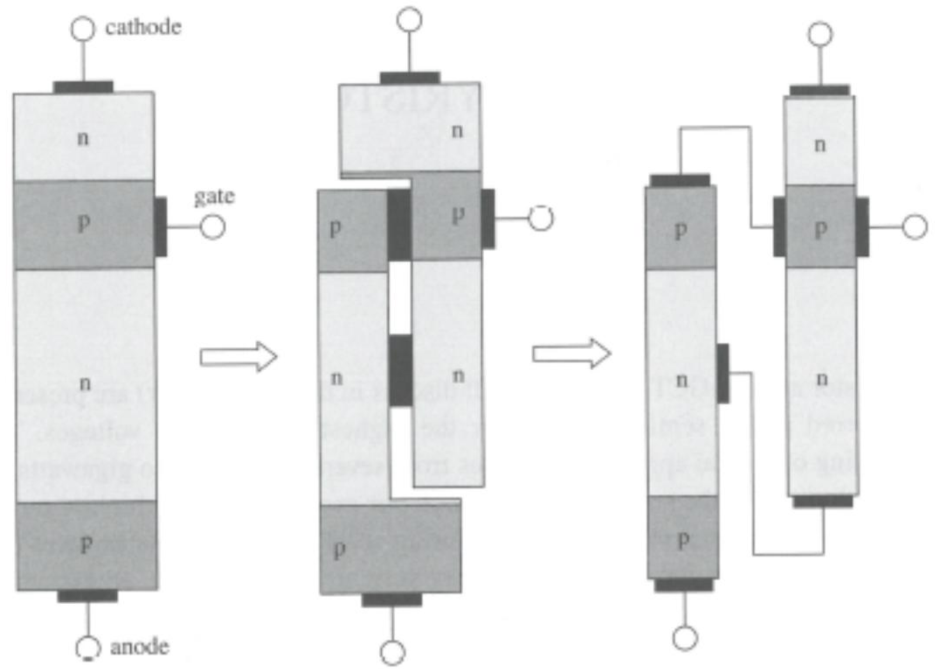


Fig. 5.1 Left: basic structure of the thyristor. Right: an equivalent model consisting of two bipolar transistors.

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Thyristor triggering to latched on-state

- $I_{C2} = \beta_2 I_G$
  - β: common emitter current gain
- $I_{B1} = I_{C2}$
- $I_{C1} = \beta_1 I_{B1}$
- $I_{B2} = I_{C1}$
- $I_{C1} = \beta_1 \beta_2 (I_G + I_{C1})$
- *Thyristor trigger at* $\beta_1 \beta_2 \geq 1$
- $\beta = \frac{\alpha}{1-\alpha}$ where α: common base current gain
- $\Rightarrow \alpha_1 + \alpha_2 \geq 1$

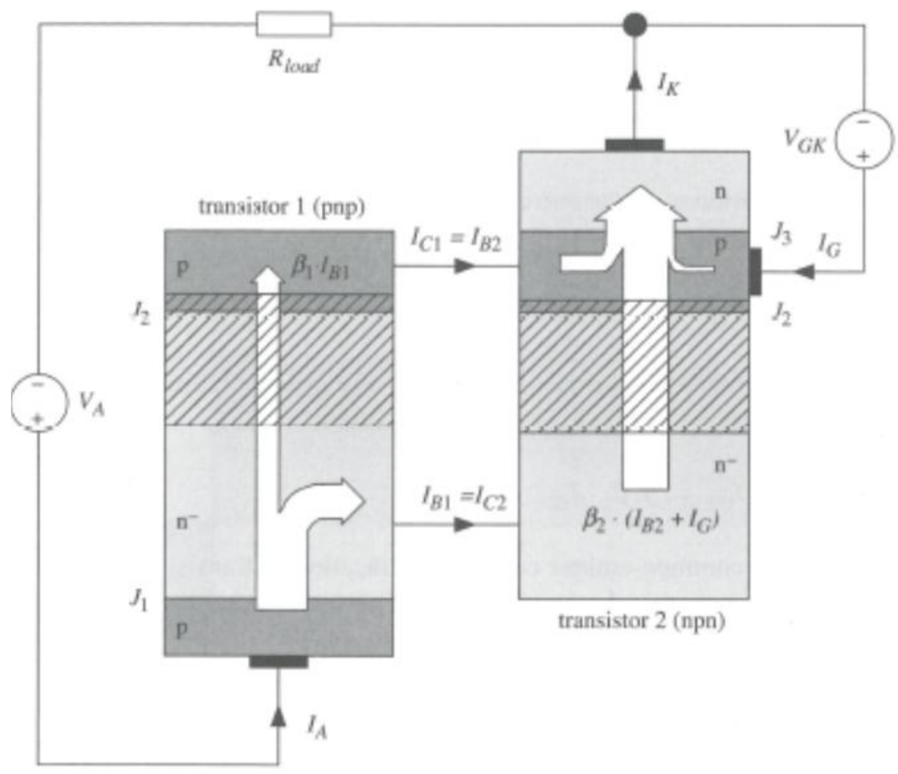

Fig. 5.2 Operation of the thyristor.

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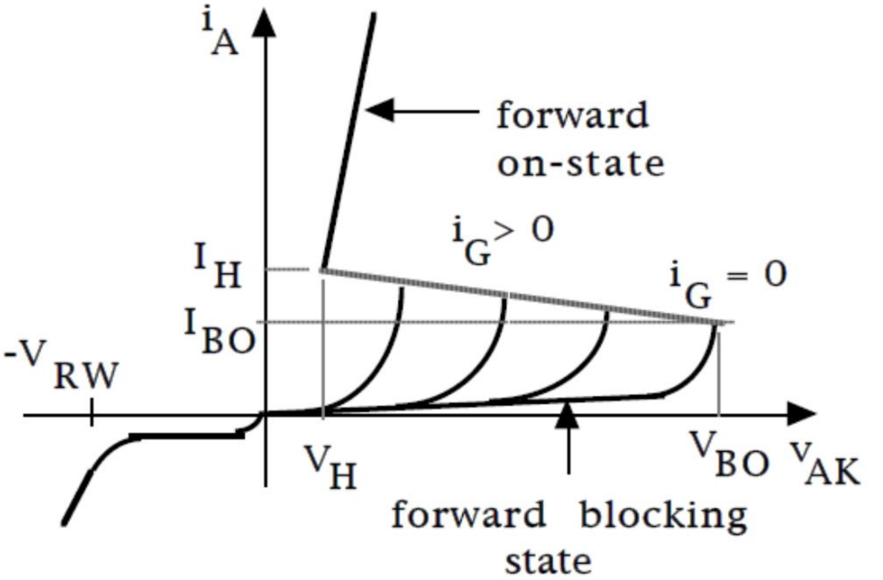
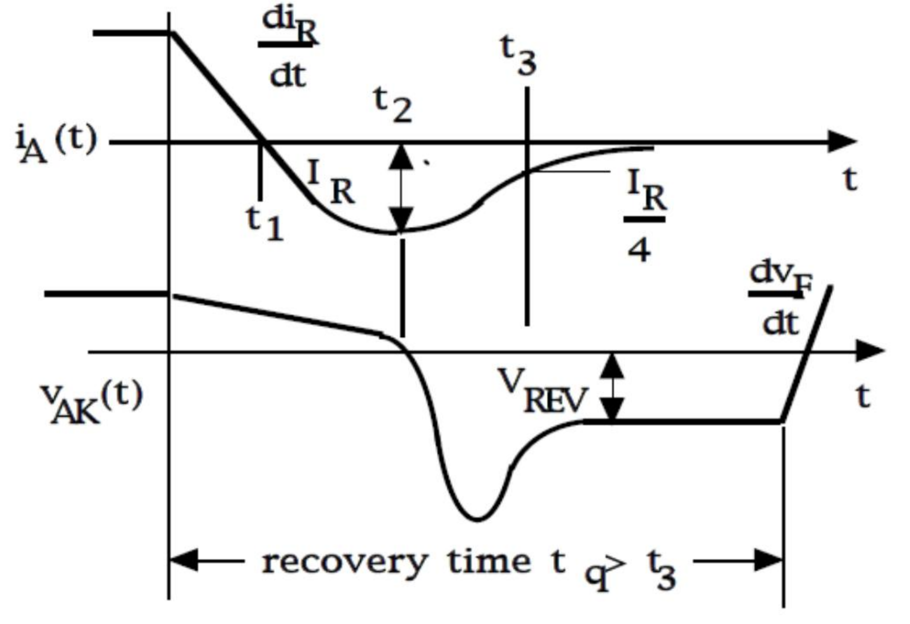
Thyristor, non-ideal characteristics

- I_H = Holding current
  V_H = holding voltage
- I_{BO} = Breakover current
  V_{BO} = Breakover voltage
- i_G can be a current pulse
- V_{RW} = Reverse working voltage
  – Thyristors found with V_{RW} > 7kV
- Forward voltage drop only a few volts even at I_A > 2kA



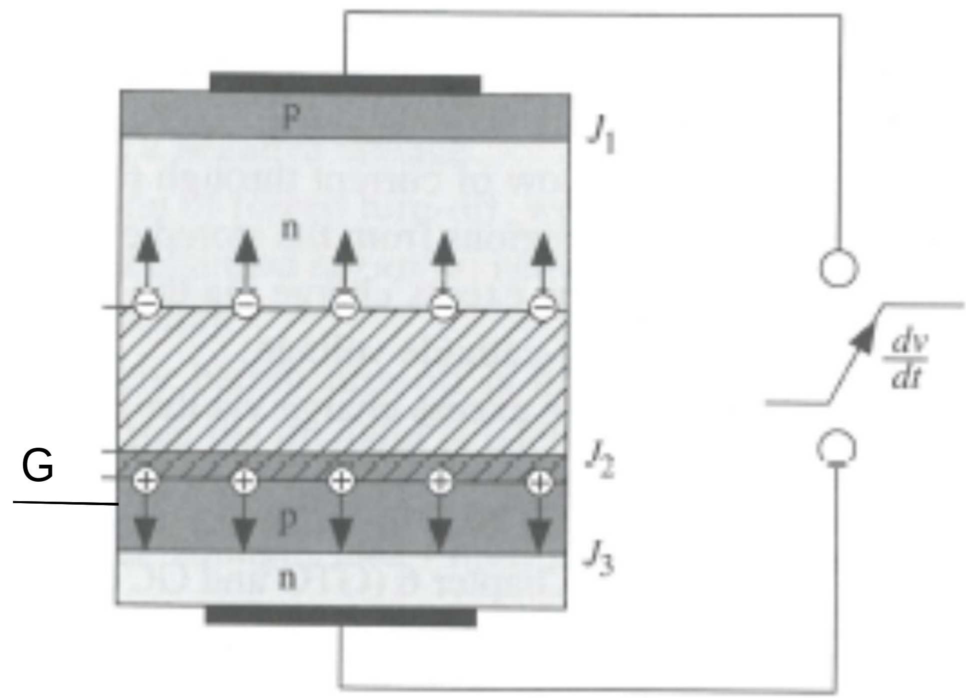
Thyristor turn-off timing

- Turn-off similar to diode
- Thyristor turn-off require negative V_{AK} longer than t_q (otherwise still on)
- dV_F/dt limit to keep thyristor off (fast forward voltage increase may turn on thyristor!)



dV_A/dt triggering

- Forward blocking
- Junction J2 is depleted and has a capacitance
- High dV_A/dt will charge C_{J2}.
- Charging current through pn-junction J3 may trigger the thyristor



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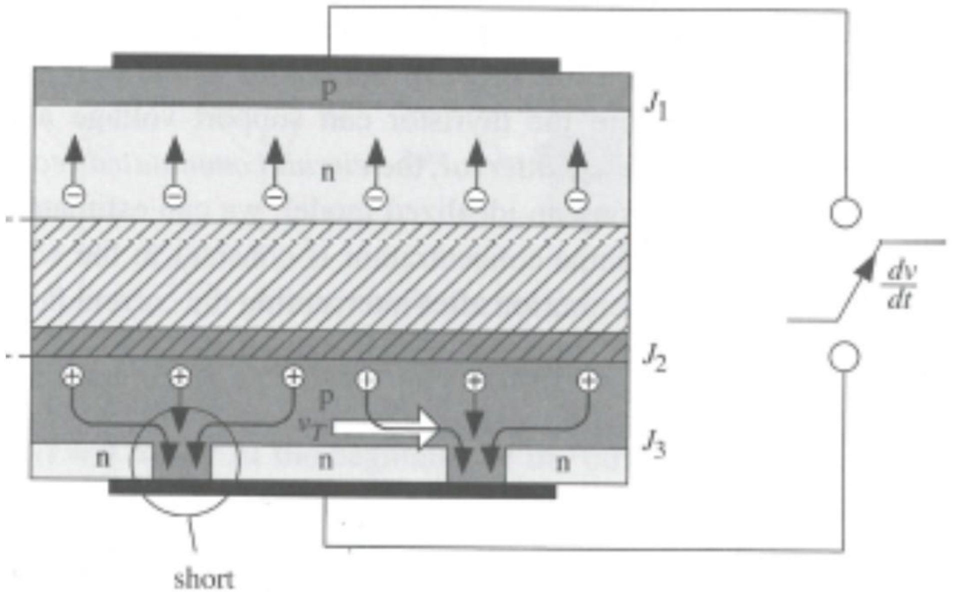
Improved dV_A/dt capability

- Emitter shorts
- Provide a current path bypassing the pn-junction J3
- On-state voltage drop increased related to



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Thyristor types

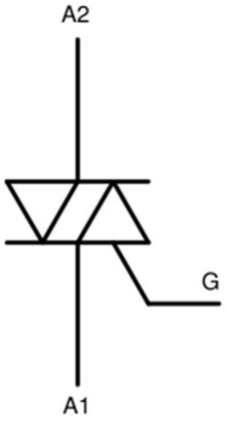
- Phase-control
  - Used for rectifying line-frequency voltages and currents, low on-state voltage and large voltage and current range
  - > 4 kA, > 7 kV, 1.5 - 3 V on-state voltage

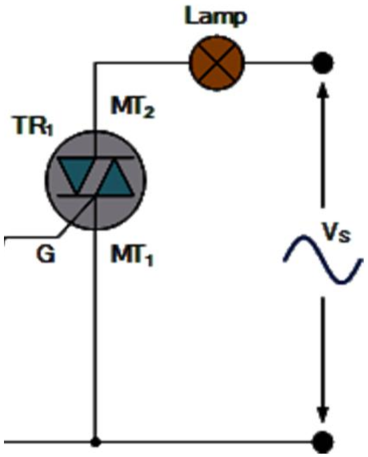
Datasheet

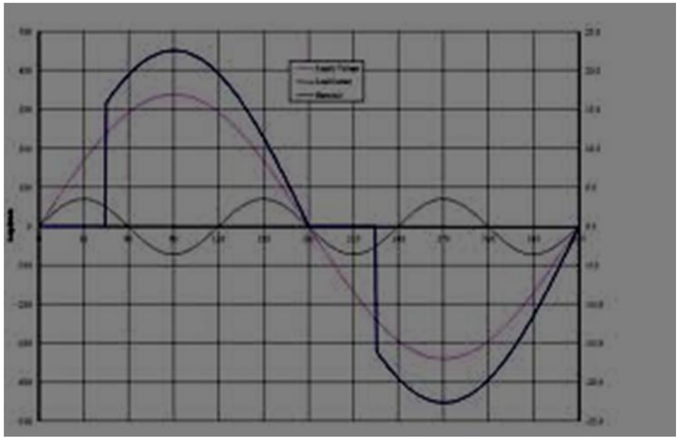
- Inverter-grade
  - Small turn-off time (1 us < tq < 100 us) and low on-state voltages
- Light-triggered
  - Trigger by light pulse instead of current
  - Used in high-voltage applications, where series connected thyristors used to support high voltages
  - ~ 5 mW light pulse to trigger

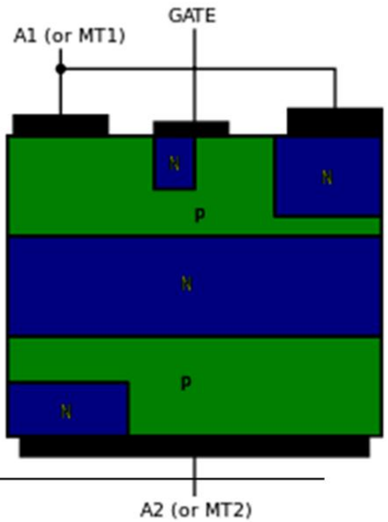
Support current in both directions: Triac

- Function as antiparallell thyristor
- Enable triggering on both positive and negative part of the cycle









Lecture 4

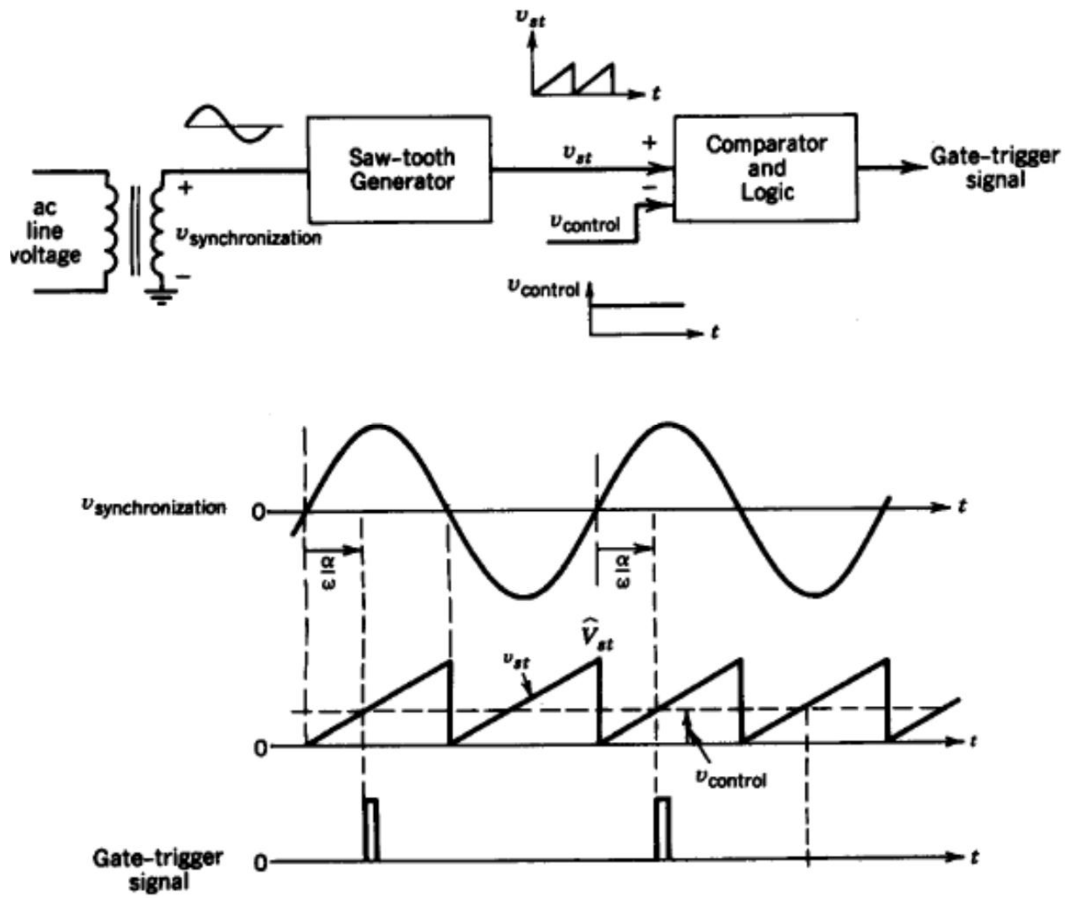
Thyristor operation

- Gate control
- Single phase
- Three phase
- Rectifier vs inverter mode

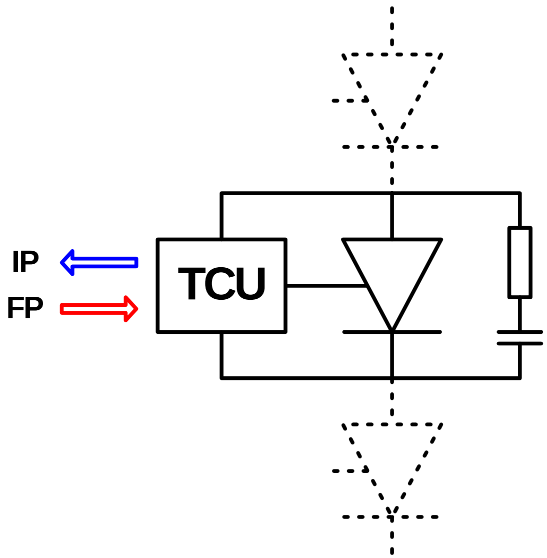
How to control gate

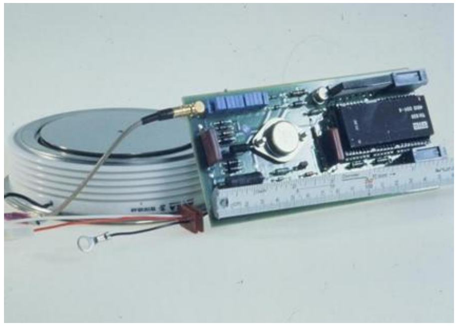
- IC circuits available

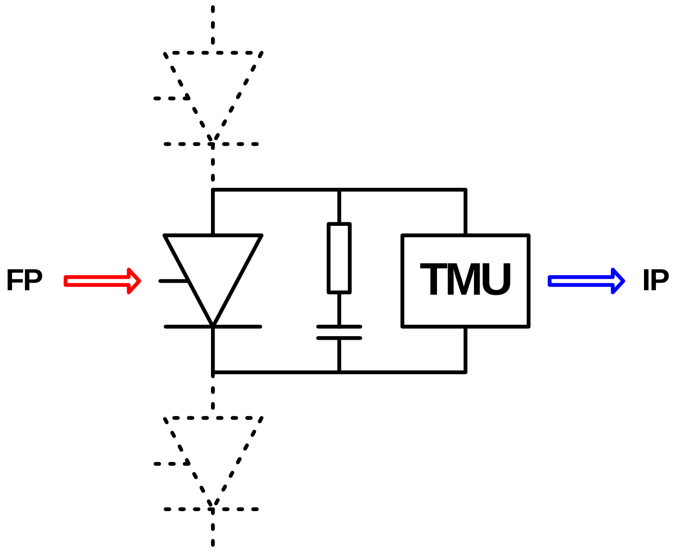
$$\alpha = 180 \frac{v_{control}}{\hat{V}_{st}}$$



Thyristor triggering in HVDC applications







FP = Firing pulse

IP = Indicating pulse

Electrically triggered thyristor (ETT)

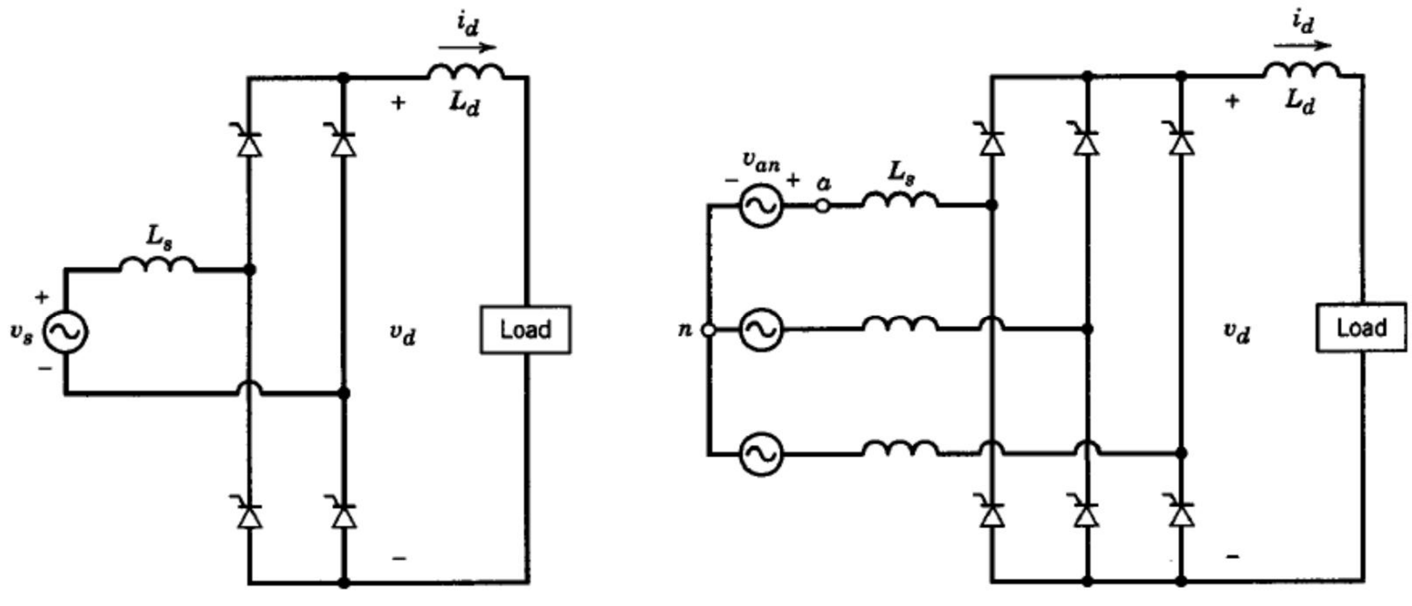
- The ETT is triggered by the thyristor control unit (TCU).
- The TCU is energized by the main circuit, and triggering is initiated by an optical pulse
- The TCU protects and monitors the ETT

Light-triggered thyristor (LTT)

- The LTT is triggered directly by an optical pulse
- The LTT is self-protected against overvoltage
- Separate recovery protection is provided
- The TMU monitors the LTT

Full bridge thyristor converters

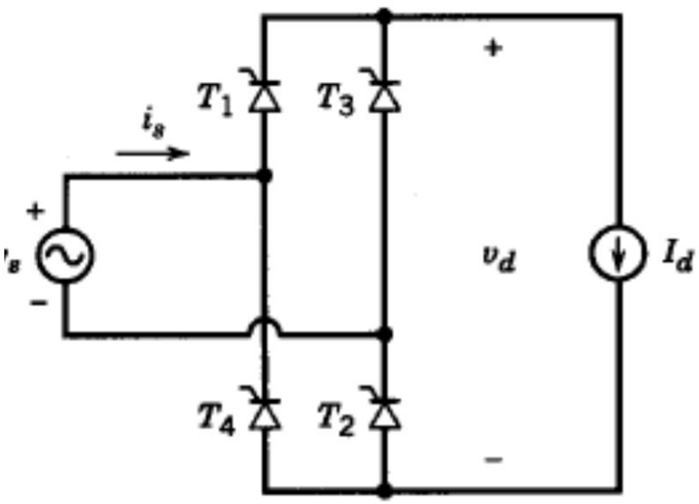
- Includes source inductance L_s and load inductance L_d
- Source inductance

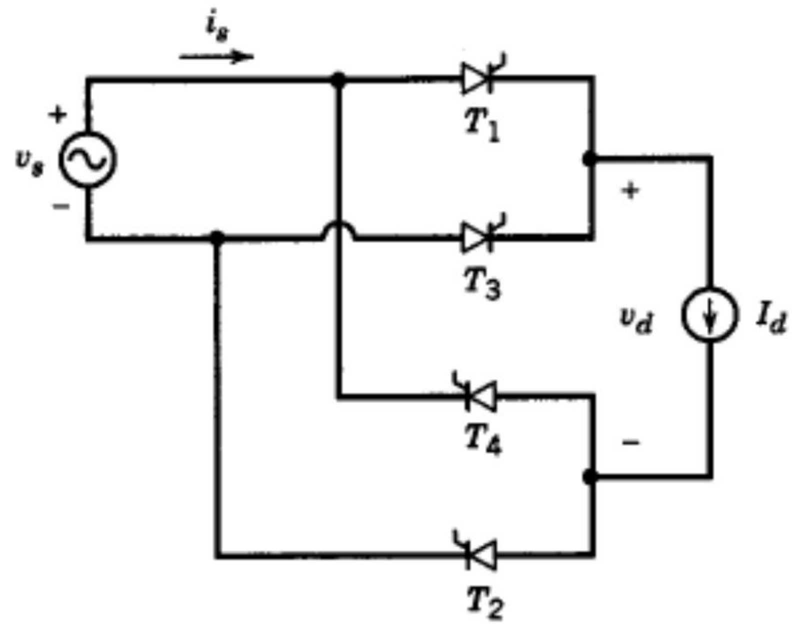


(a) (b)

Single-phase thyristor converter

- Either thyristor T1 and T2, or T3 and T4 conducting





Single-phase thyristor converter waveforms

- I_d constant => thyristor does not turn off unless other thyristor turns on (current commutation)
- V_d and P controlled by α

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

$$P = I_d\left(\frac{1}{T}\int_0^T v_d dt\right) = I_d V_d = 0.9V_s I_d\cos\alpha$$

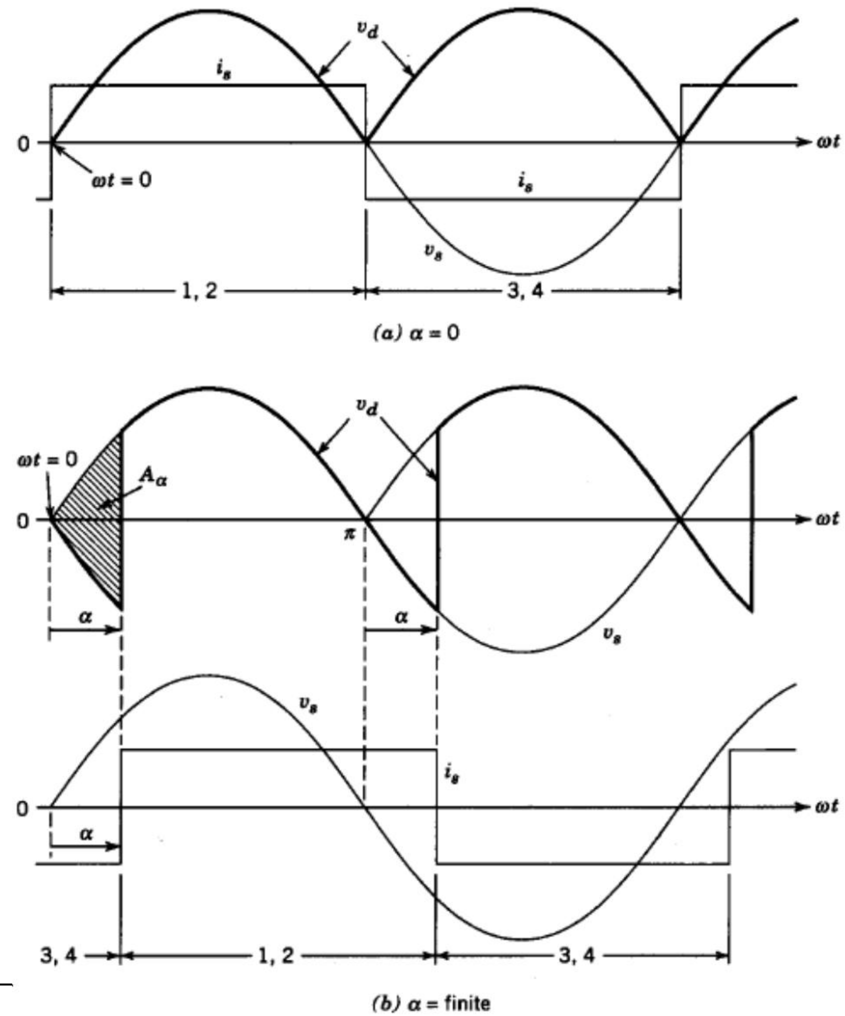
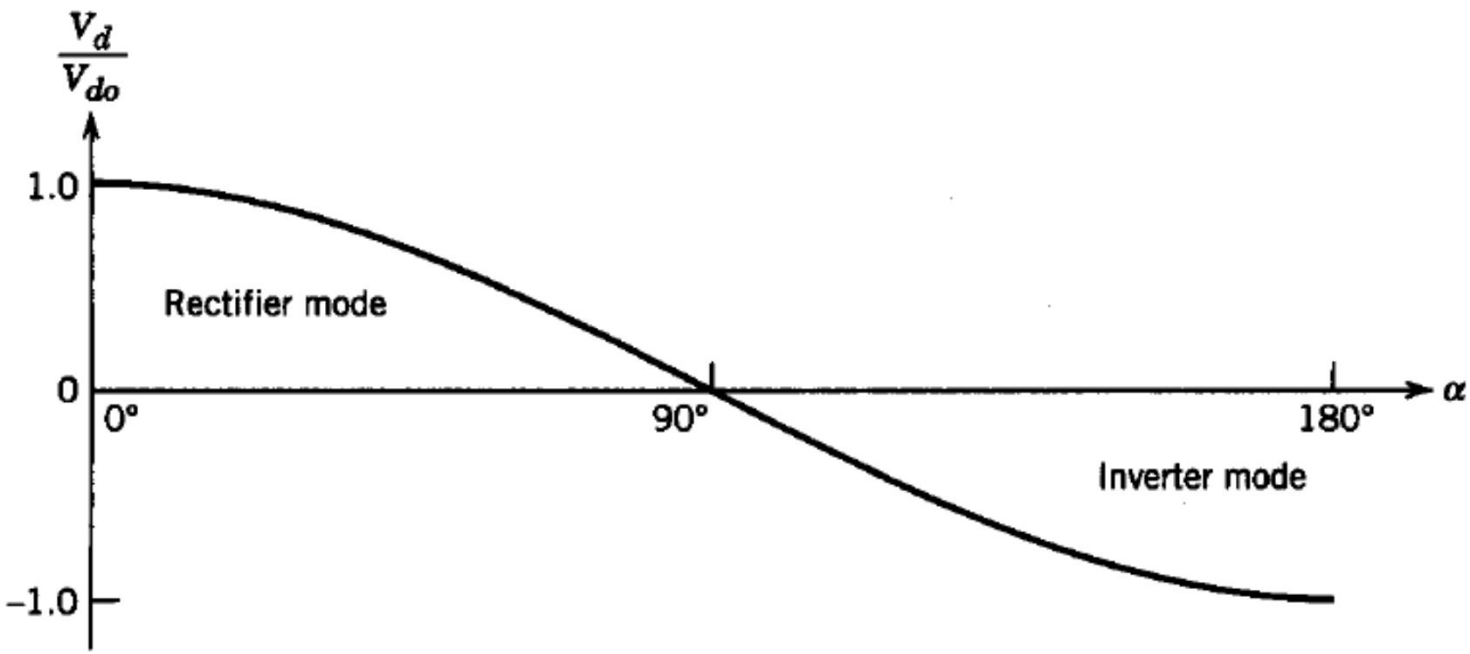


Figure 6-6 Waveforms in the converter of Fig. 6-5.

DC voltage level

- Power from DC to AC side when $\alpha > 90$ degrees

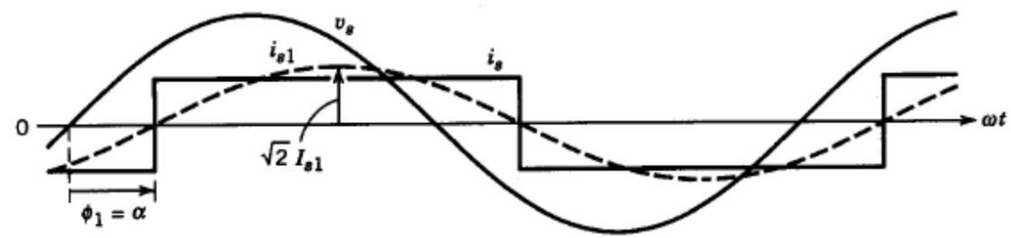


Line current properties

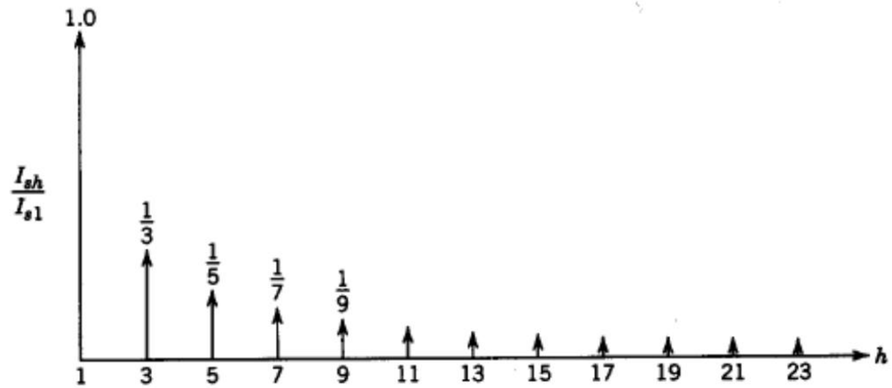
$I_{s1} = 0.9 I_d$

$I_s = I_d (rms)$

$THD = 48.3\%$



(a)



(b)

Power, power factor, reactive power

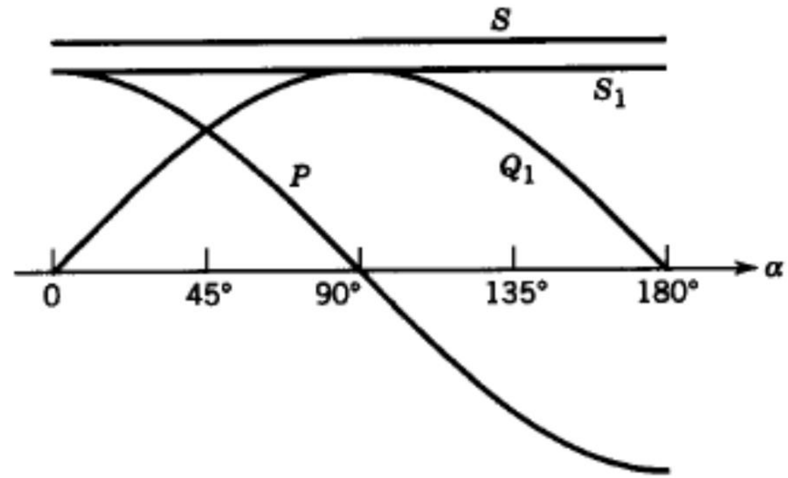
$$DPF = \cos\Phi_1 = \cos\alpha$$

$$PF = \frac{I_{s1}}{I_s} DPF = 0.9\cos\alpha$$

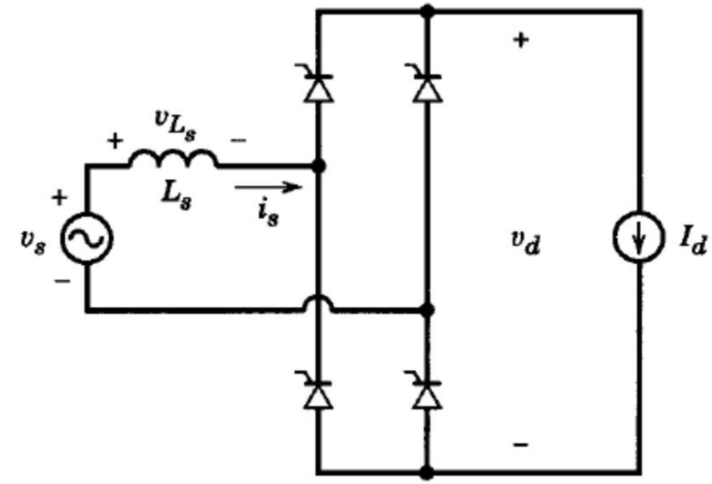
$$P = V_s I_{s1} \cos\Phi_1 = 0.9 V_s I_d \cos\alpha$$

$$Q_1 = V_s I_s \sin\Phi_1 = 0.9 V_s I_d \sin\alpha$$

$$S_1 = V_s I_{s1}$$

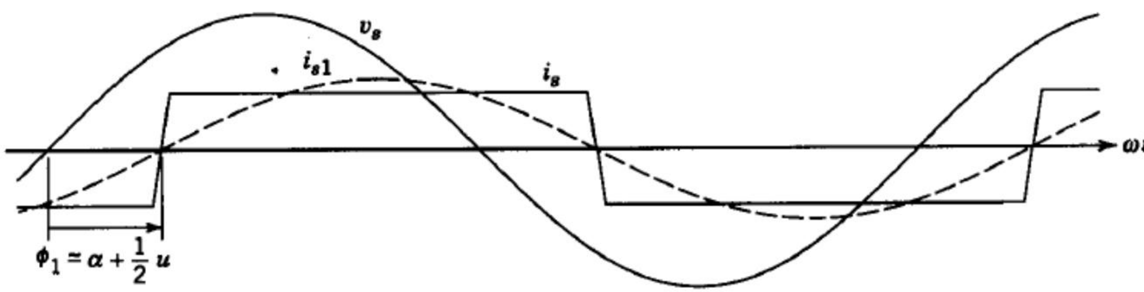


L_s effect

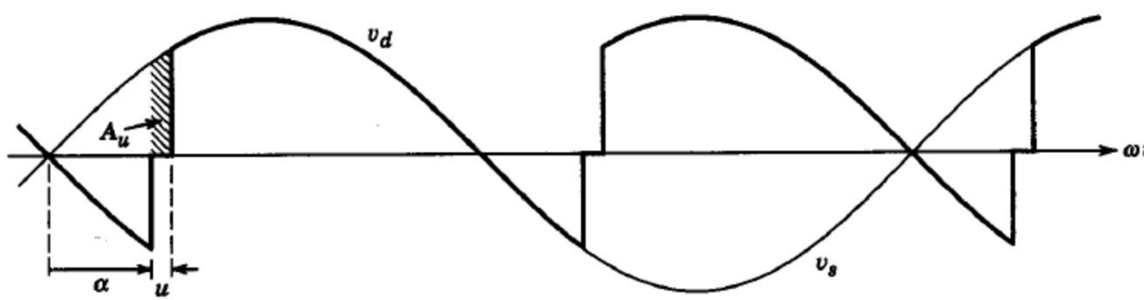


$$A_u = 2\omega L_s I_d \cos(\alpha + u) = \cos\alpha - \frac{2\omega L_s I_d}{\sqrt{2}V_s}$$

$$V_d = 0.9V_s\cos\alpha - \frac{2}{\pi}\omega L_s I_d$$

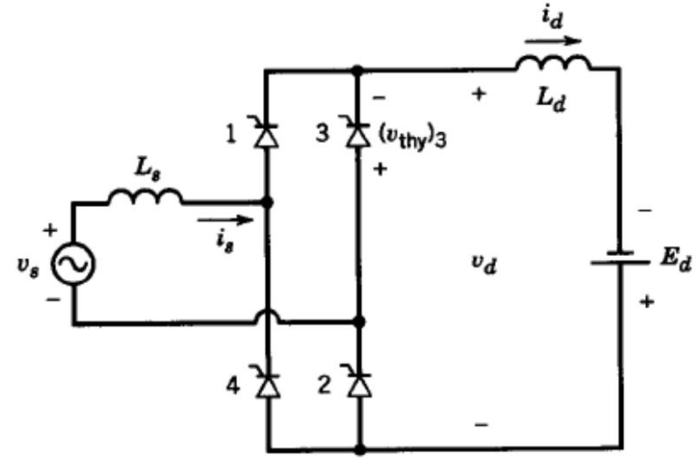


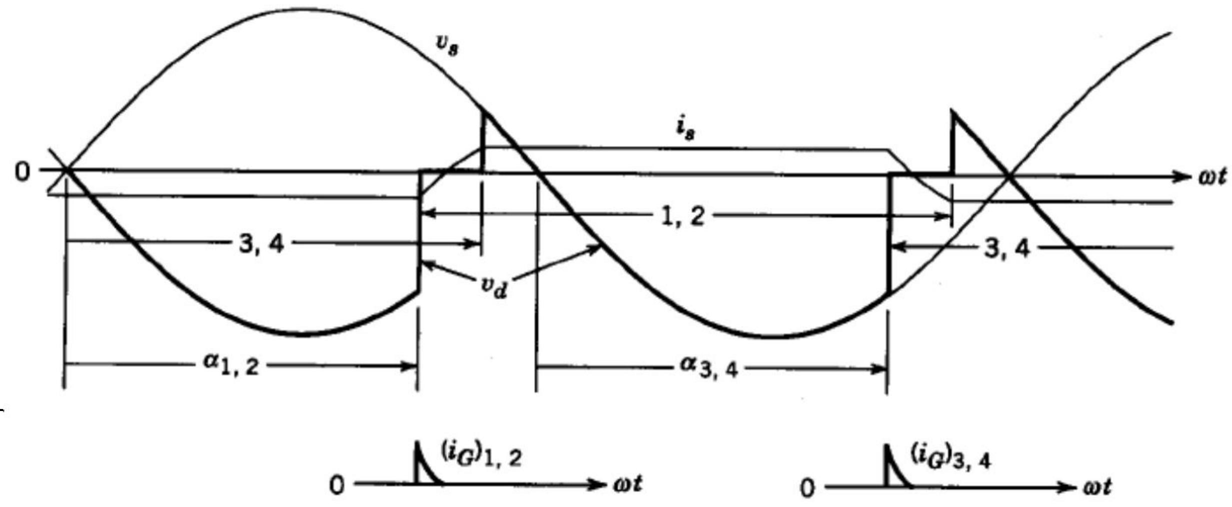
(a)



Inverter mode

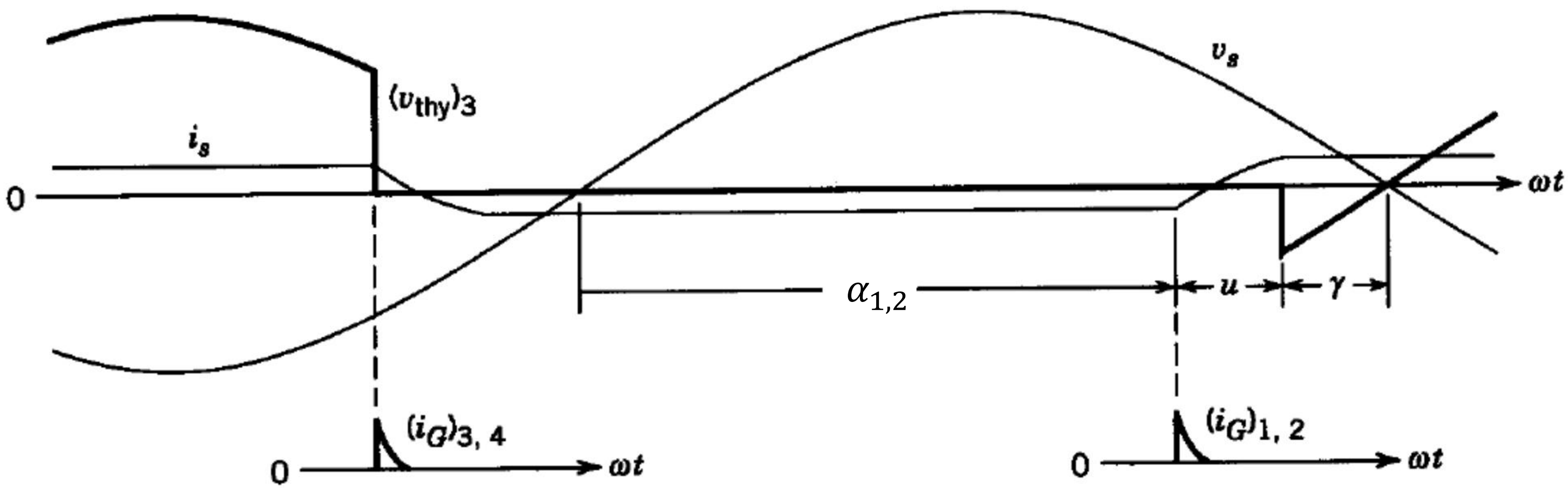
- Negative dc-side voltage, v_d, E_d
- Always positive current. Thyristor conducts in one direction only
- P<0: $(v_d<0)(i_d>0)$
- Power flows from DC to AC side
- V_s controls switching of current between thyristors





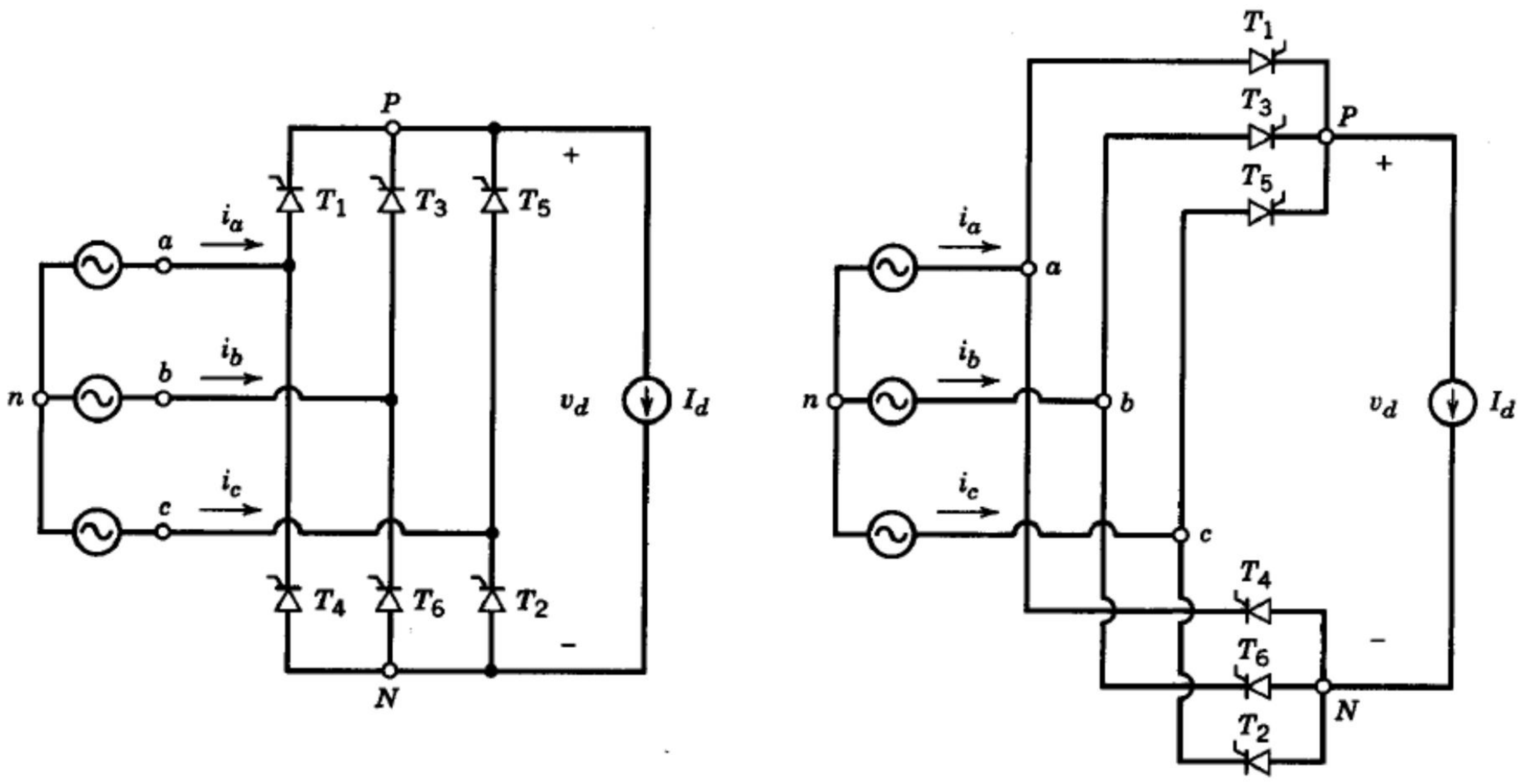
Inverter thyristor voltage

- Extinction angle $\gamma = 180 - (\alpha + u)$
- Thyristor require $t_\gamma = \gamma/\omega > t_q$ (turn off time)
- Failing requirement leads to retriggering of the thyristor too early (commutation failure)
  => large currents (all thyristors conduct for long time)!

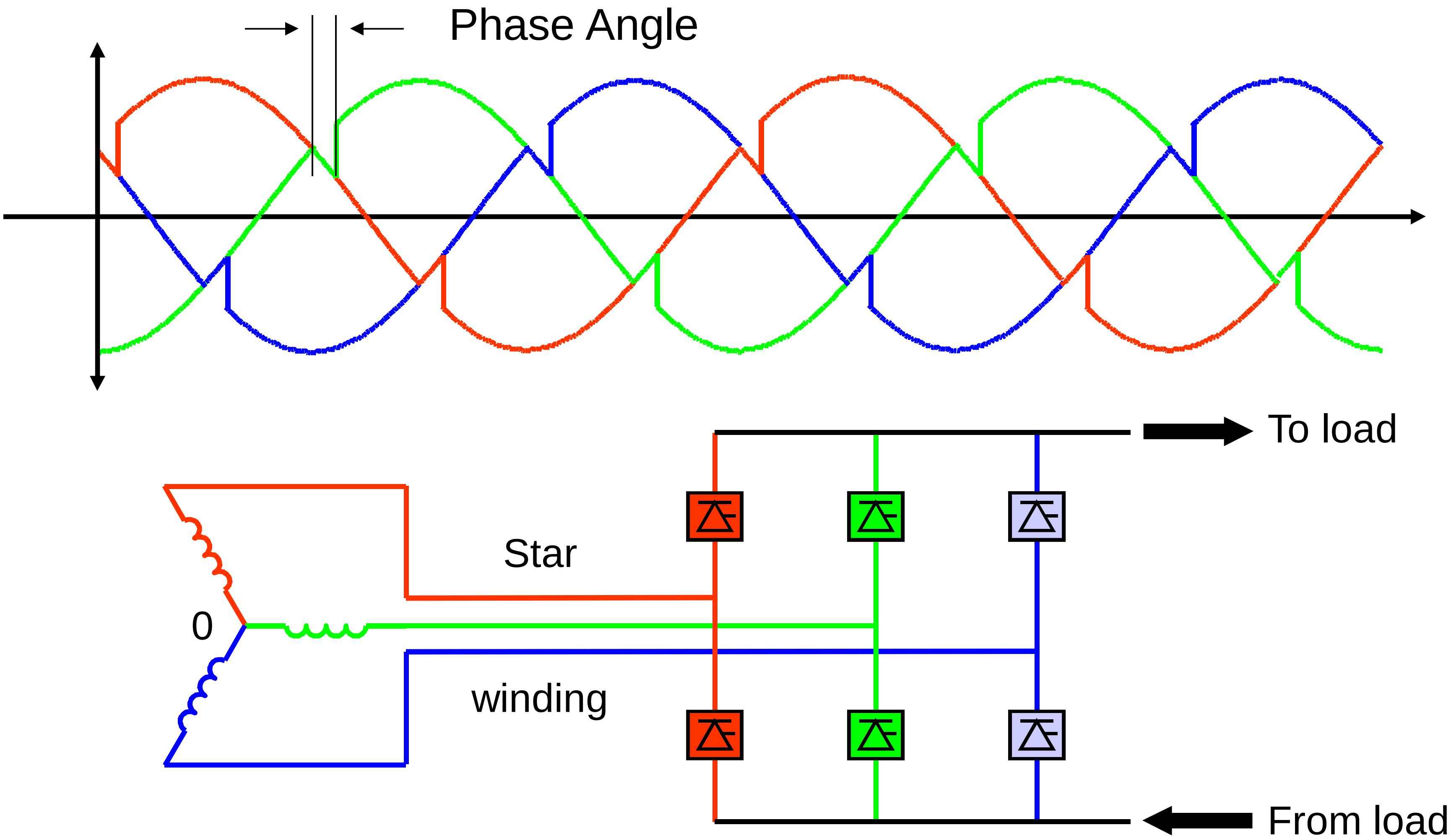


Three-phase thyristor converter

- One thyristor active in top group and one in bottom group

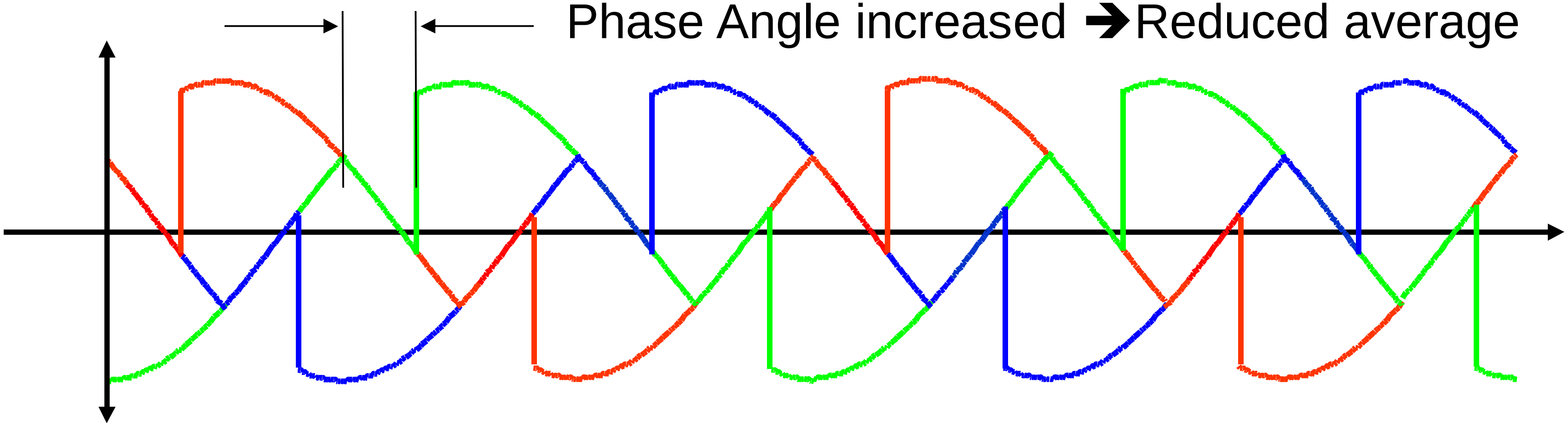


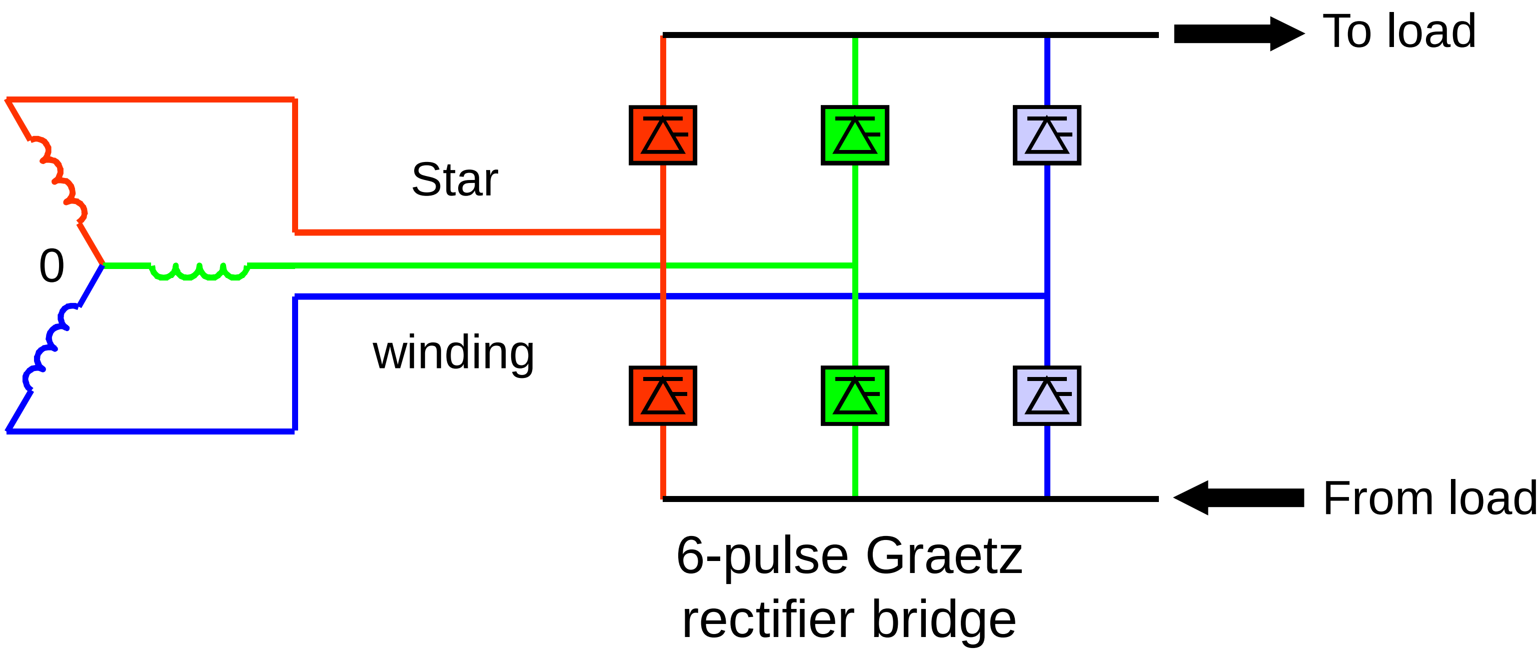
Thyristor rectifier operation



6-pulse Graetz rectifier bridge

Thyristor rectifier operation

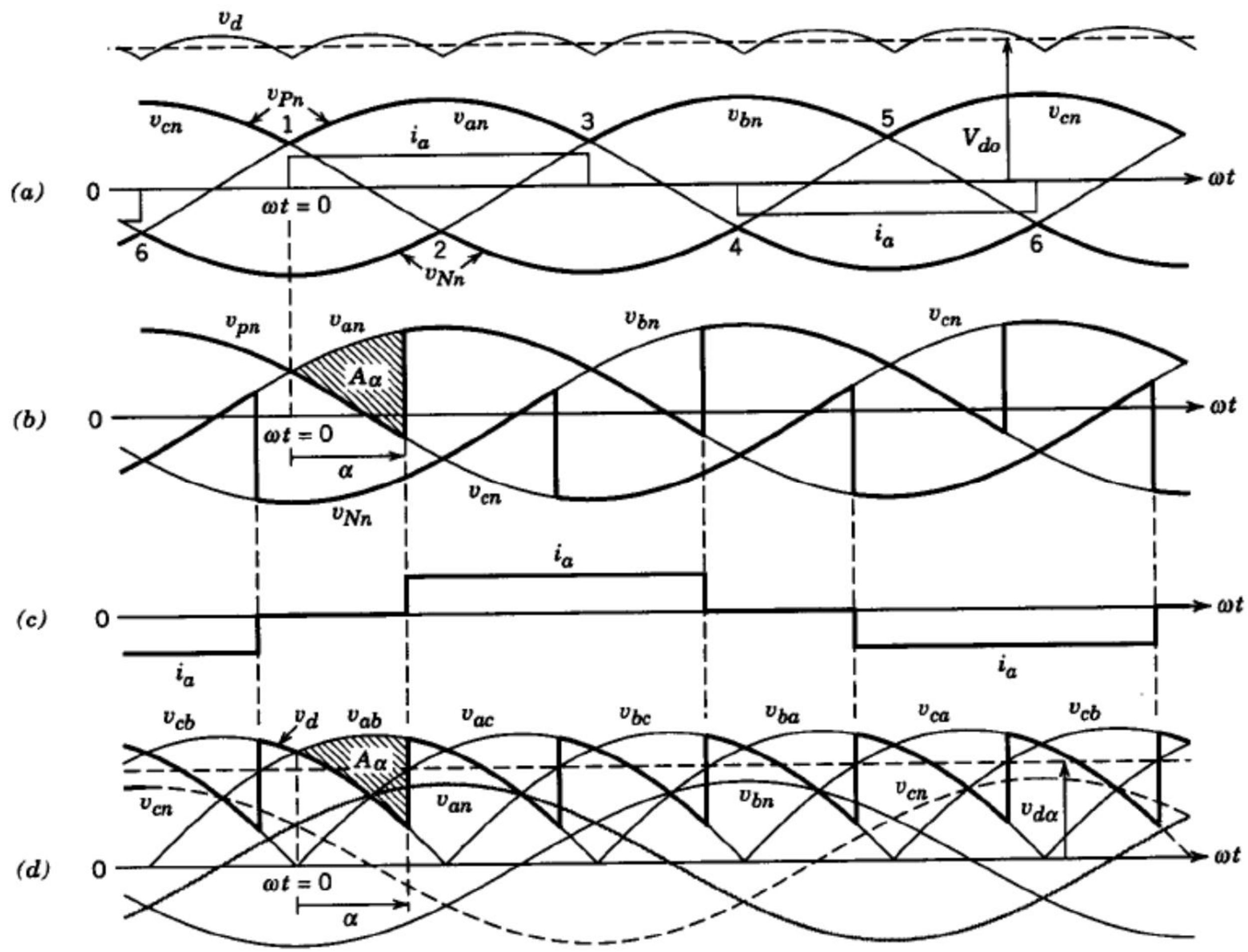




Converter waveforms

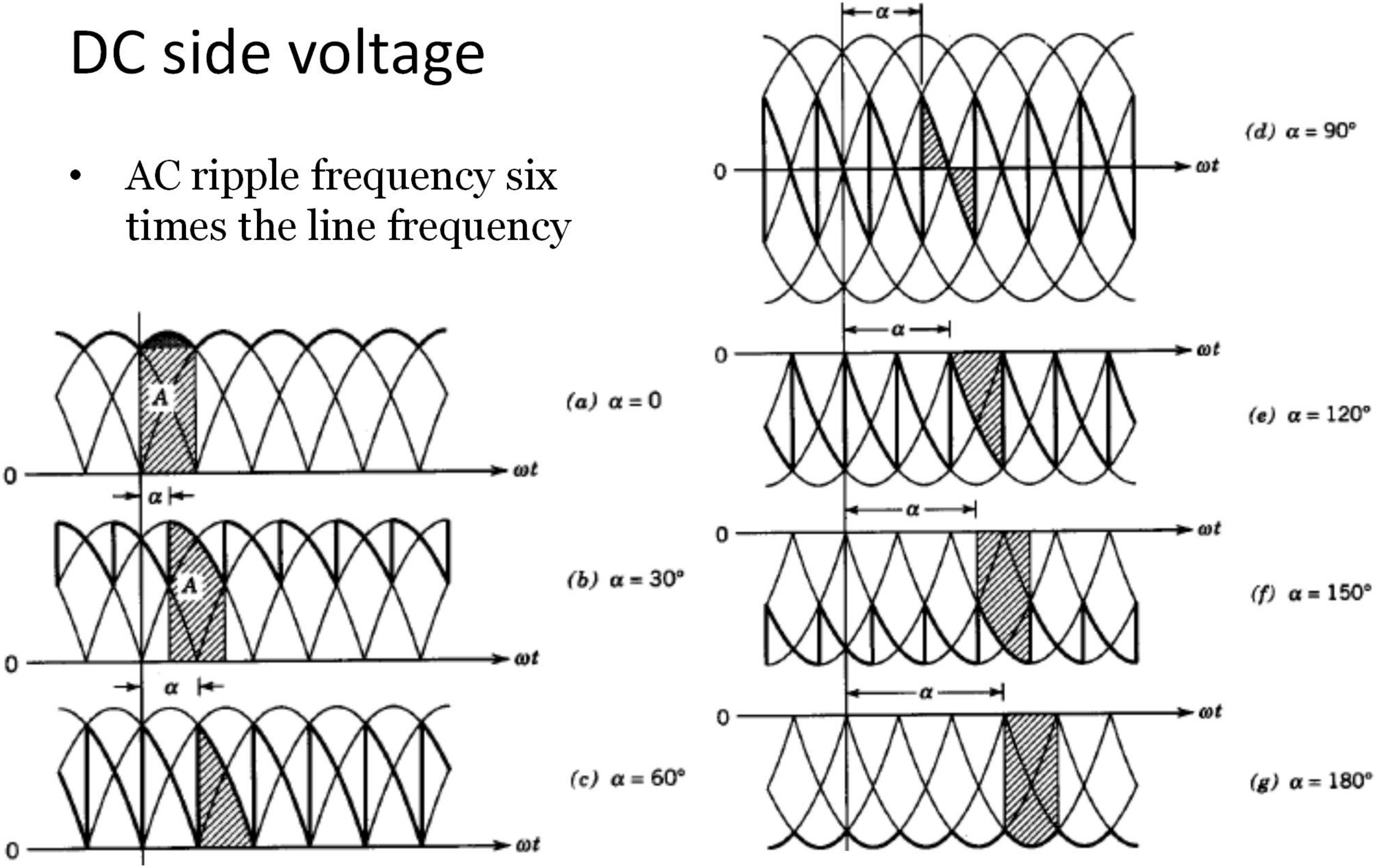
$$V_{d\alpha} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

$$V_{d\alpha} = 1.35 V_{LL} \cos\alpha$$

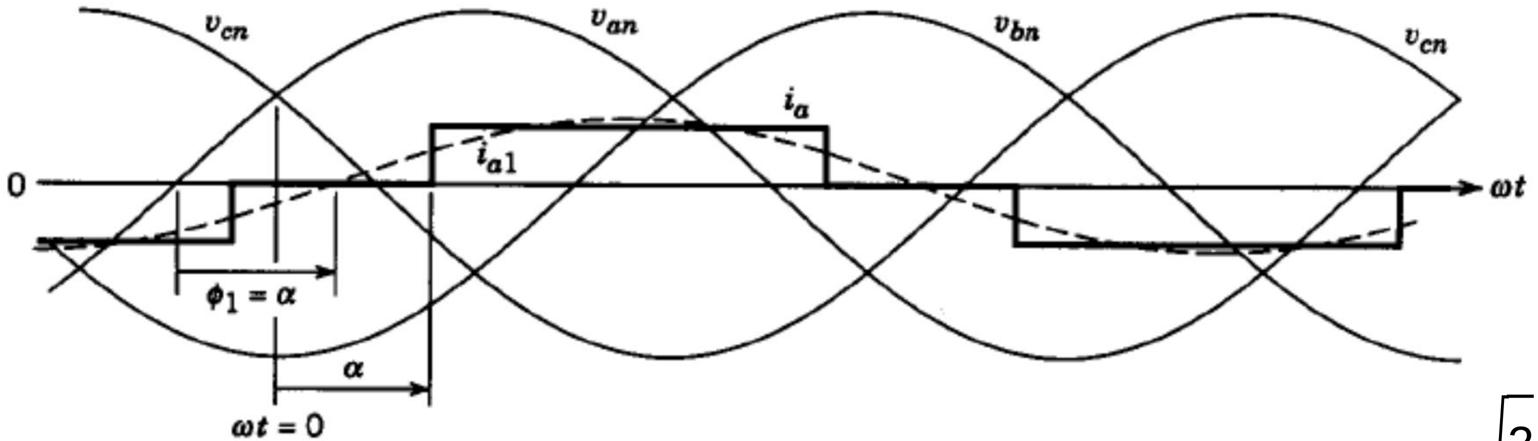


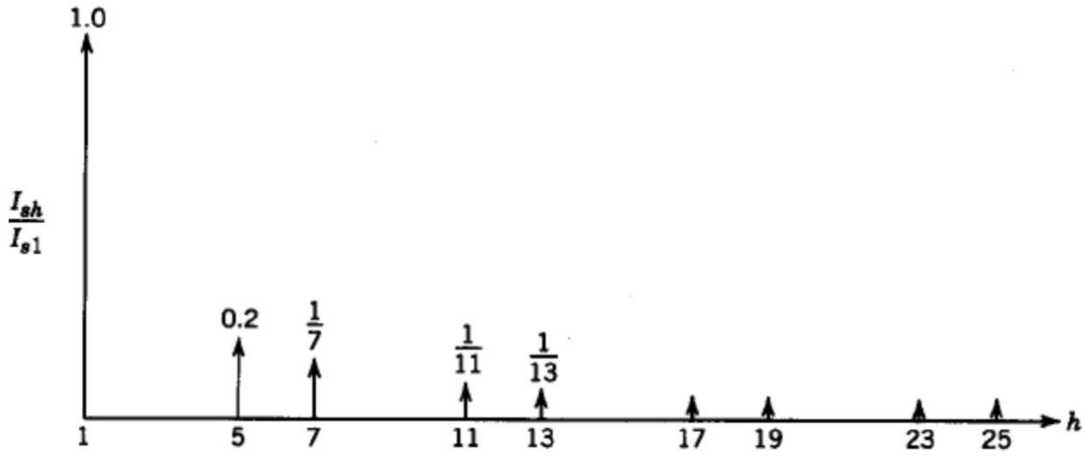
DC side voltage

- AC ripple frequency six times the line frequency



Input line current





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

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

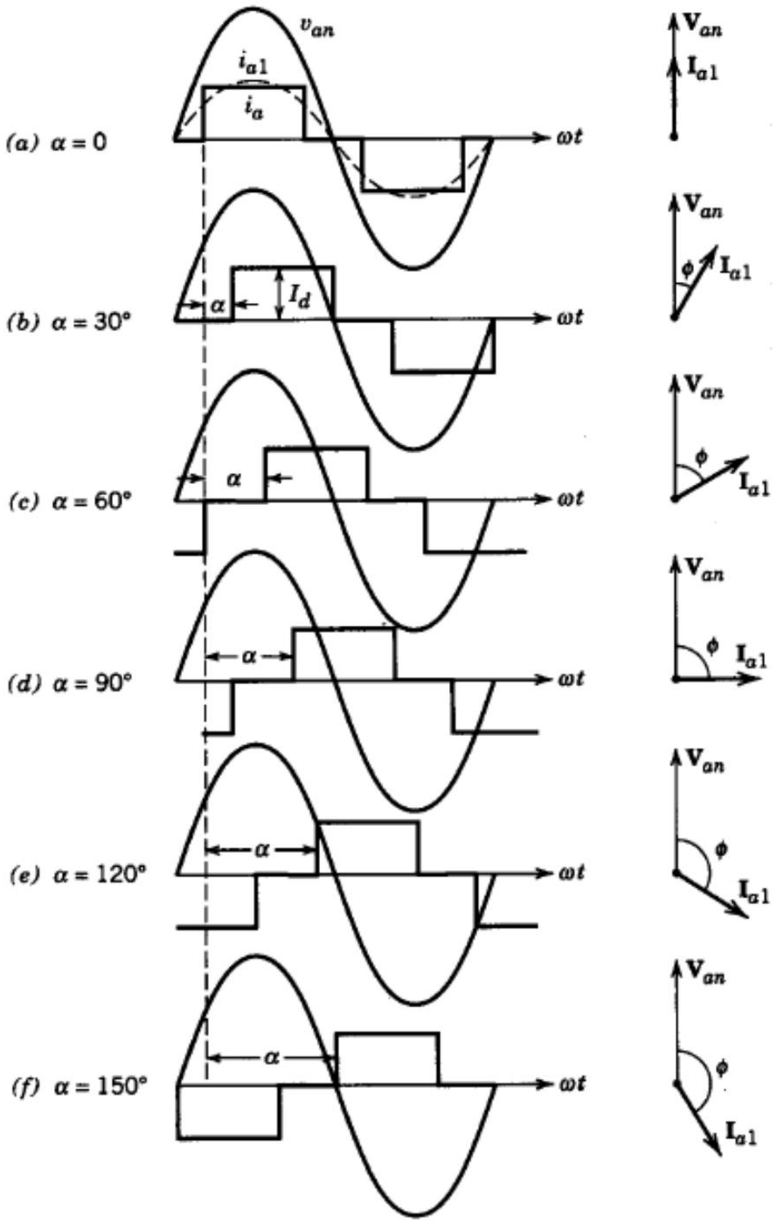
$$\text{THD} = \frac{\sqrt{\sum_{h=5,7,11,13.....}(I_{sh}^2)}}{I_{s1}} = 31\%$$

Line current vs alpha

- *Current phase shift equal to* α

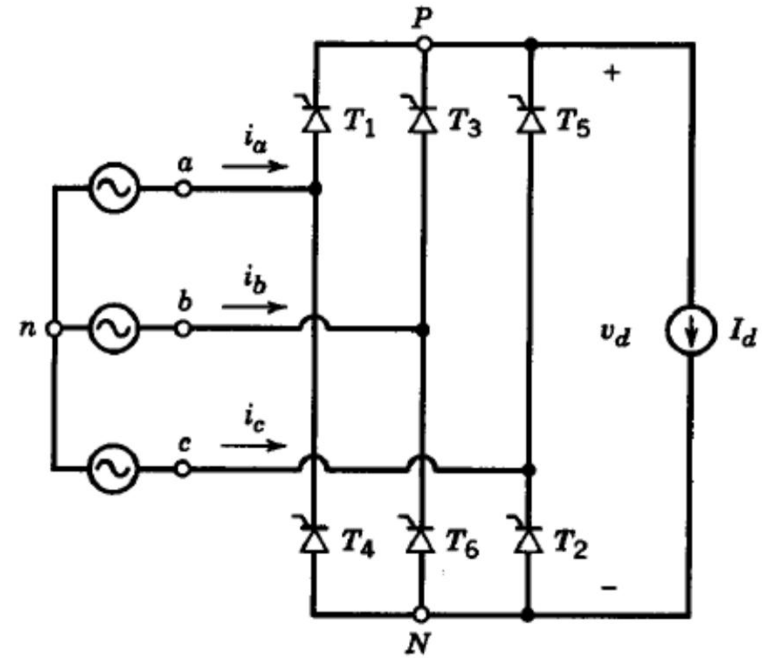
$$DPF = \cos\Phi_1 = \cos\alpha$$

$$PF = \frac{I_{s1}}{I_s} DPF = \frac{3}{\pi}\cos\alpha$$

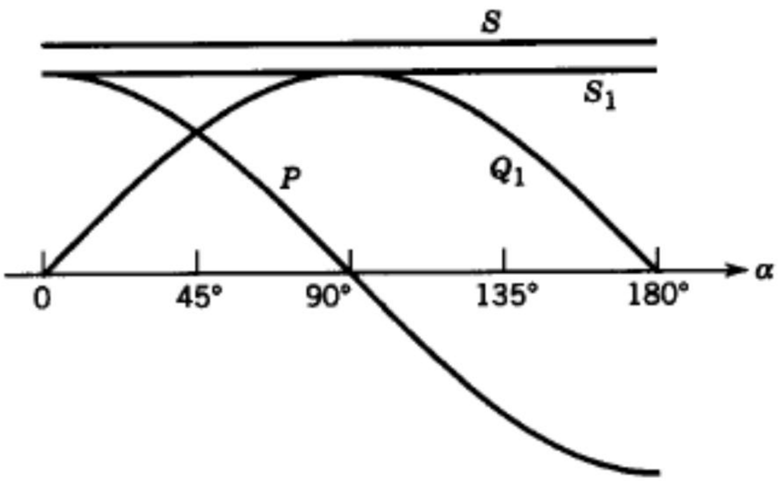


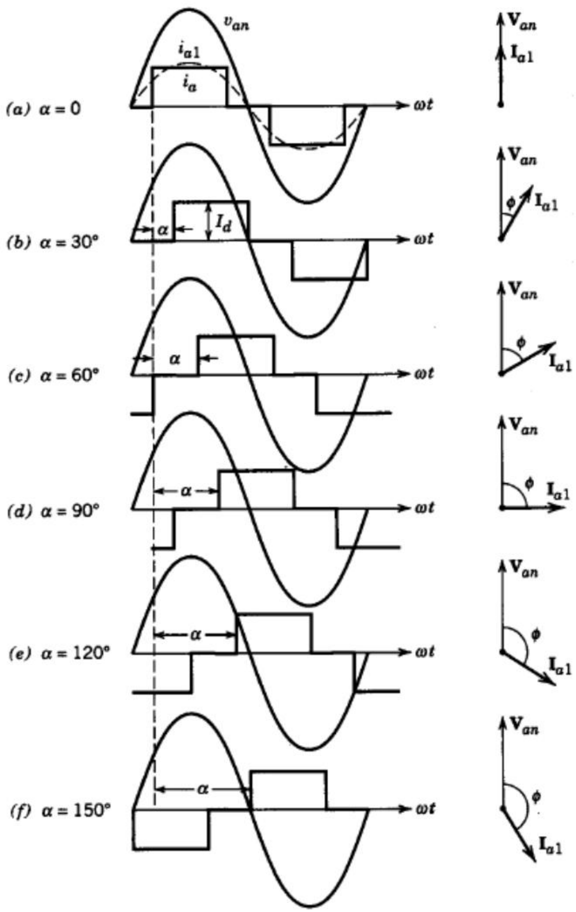
Exercise 4-100

- In the ideal three-phase thyristor rectifier circuit, *the firing angle* α*=30 deg*
  - *a) Construct the thyristor* T_1 *voltage and current*
  - *b) Construct the wave form of the dc-output voltage*
  - *c) Calculate the average dc-output voltage for* V_{LL}*=400V*



Active and reactive power vs alpha





$$DPF = \cos\Phi_1 = \cos\alpha$$

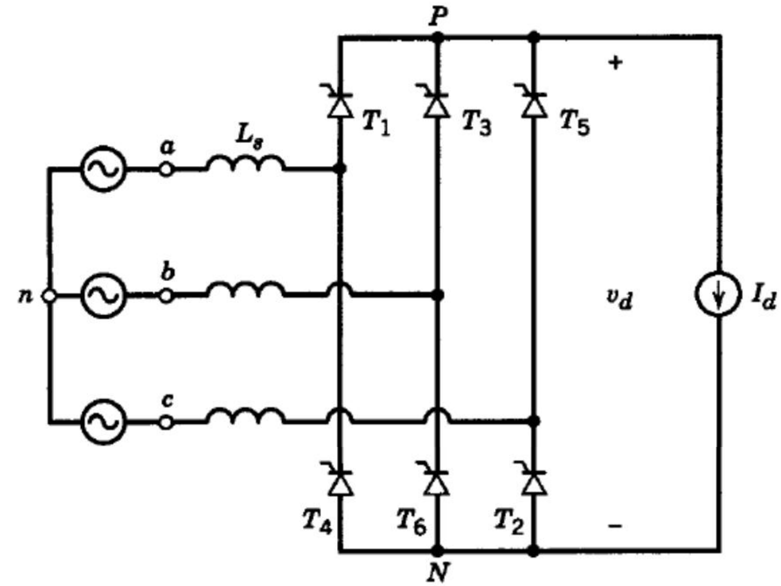
$$PF = \frac{I_{s1}}{I_s} DPF = \frac{3}{\pi}\cos\alpha$$

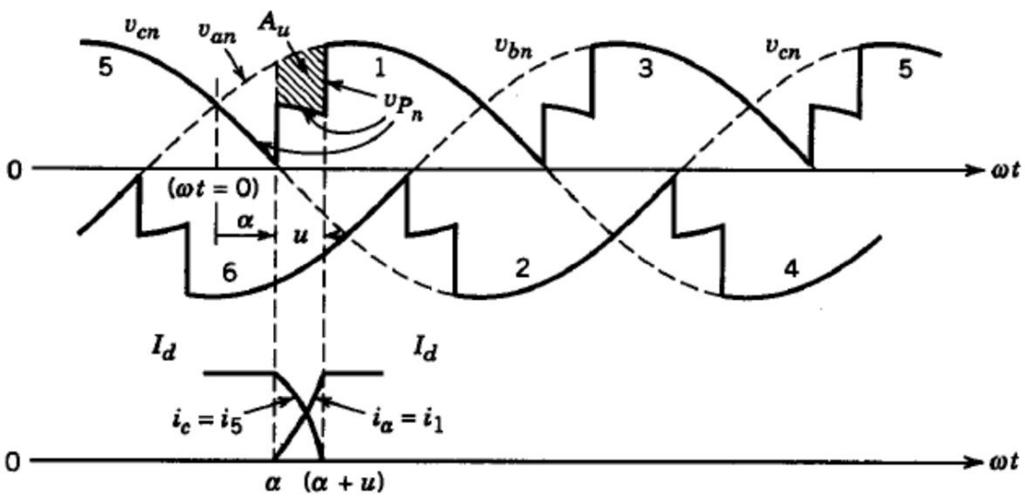
$$P = \sqrt{3}V_{LL}I_{s1}\cos\Phi_1 = \sqrt{3}V_{LL}0.78I_d\cos\alpha = 1.35V_{LL}I_d\cos\alpha$$

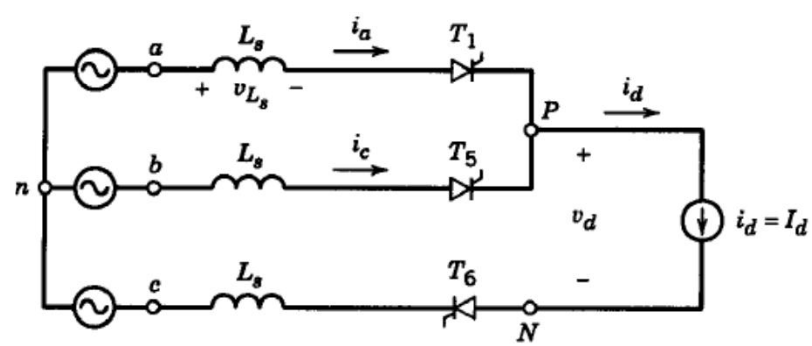
$$Q_1 = \sqrt{3}V_{LL}I_{s1}\sin\Phi_1 = \sqrt{3}V_{LL}0.78I_d\sin\alpha = 1.35V_{LL}I_d\sin\alpha$$

Converter with source inductance

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

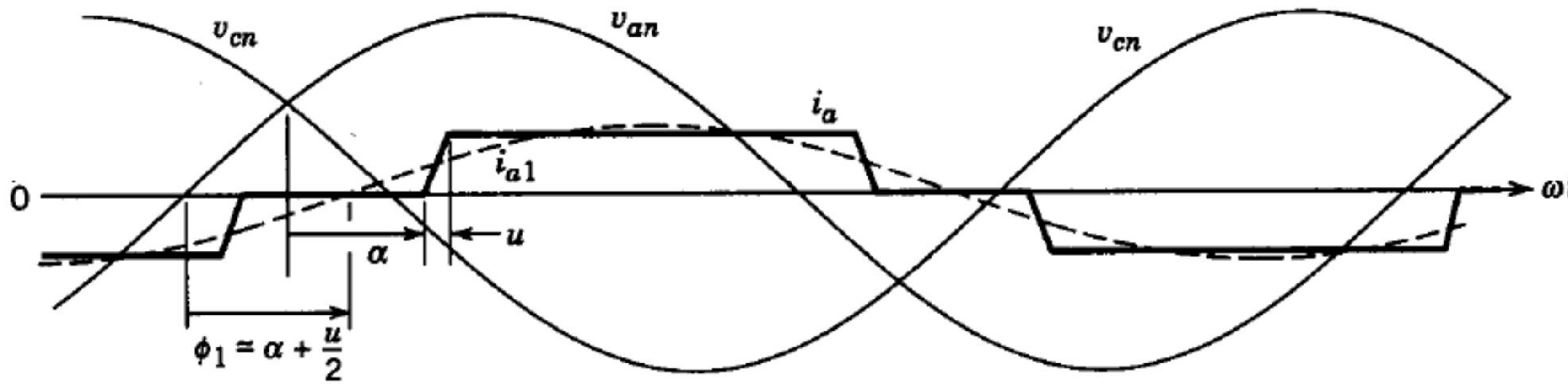






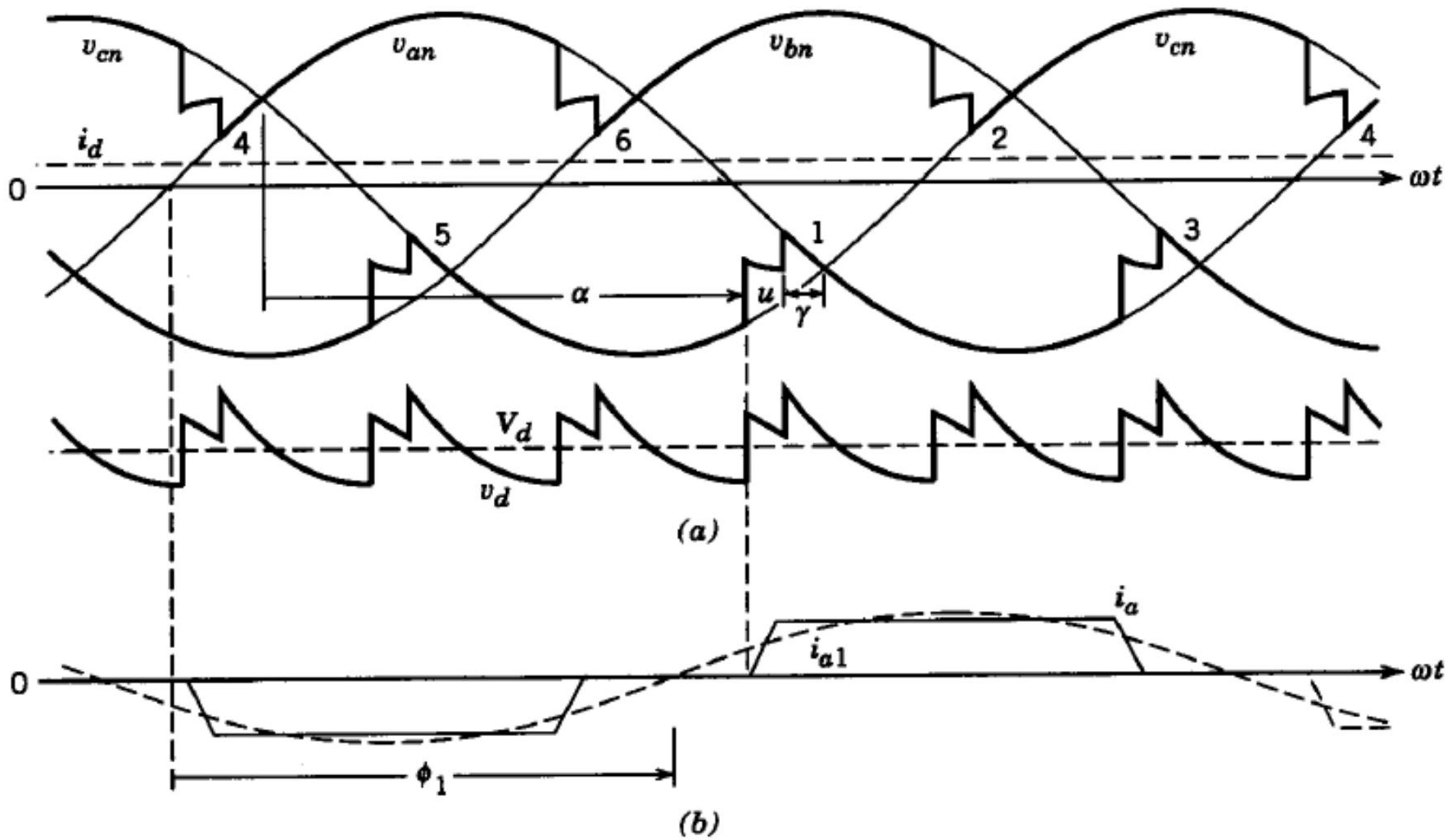
Input line current waveform

- DPF ≈ cos (α + ½ u)



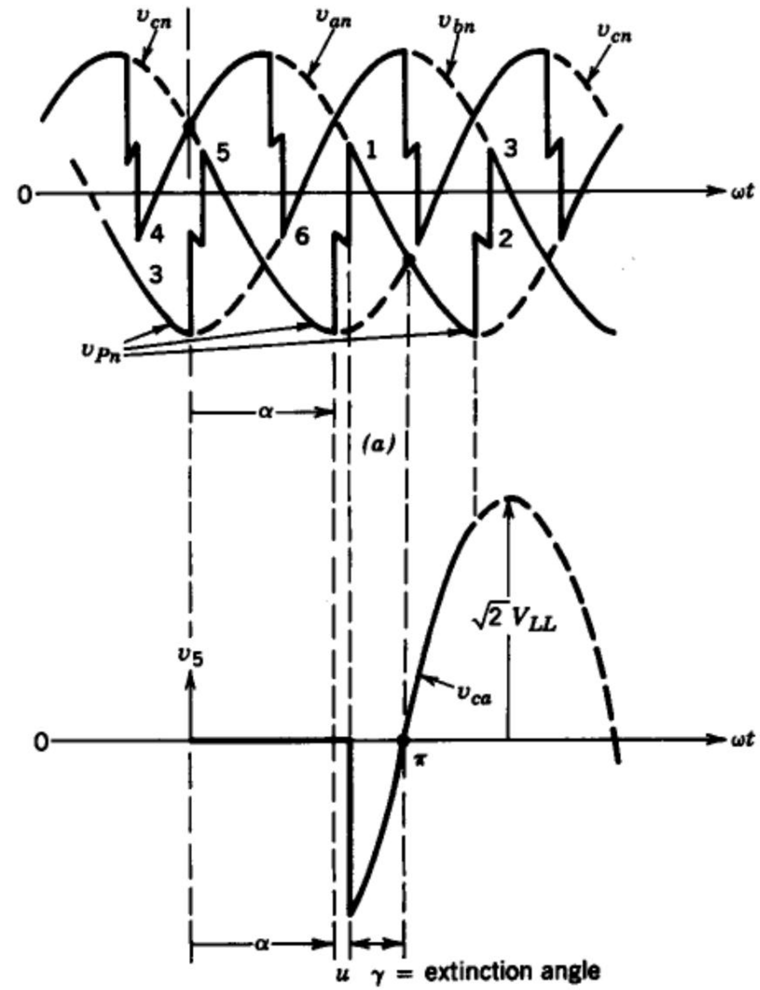
$$\cos(\alpha) - \cos(\alpha + u) = \frac{2\omega L_s}{\sqrt{2}V_{LL}} I_d$$

Inverter waveform



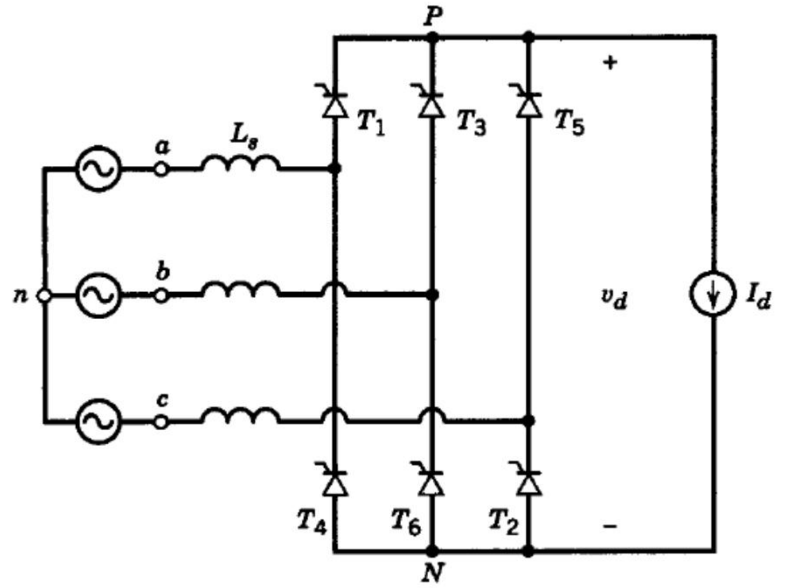
Inverter voltage over thyristor

- Extinction angle
  $\gamma = 180 - (\alpha + u)$
- Thyristor require
  $t_\gamma = \gamma/\omega > t_q$
  (turn off time)
- Failing requirement leads to retriggering of the thyristor too early (commutation failure) => large currents (both thyristors in the same phase conducts)!

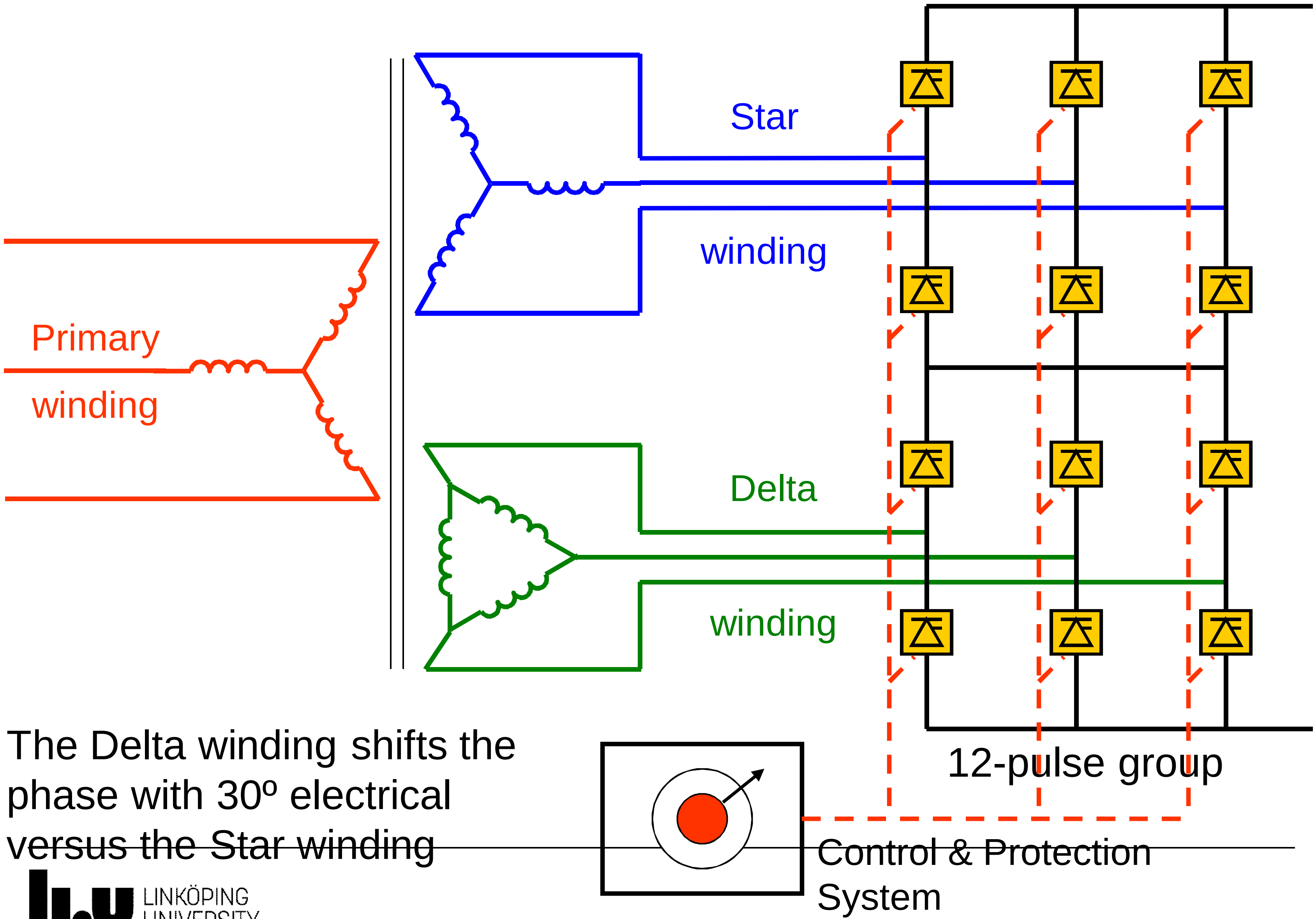


Exercise 4-101

- In the three-phase thyristor rectifier circuit with the following data:
  V_{LL} = 400 V at 50 Hz, L_s = 7 mH,
  I_d = 10A
  a) *What firing angle α shall be used to get an average dc-voltage of 500V (rectifier mode)*
  b) *What firing angle α shall be used to get an average dc-voltage of -500V (inverter mode)*
  c) *Calculate γ. What minimum t_q is required?*

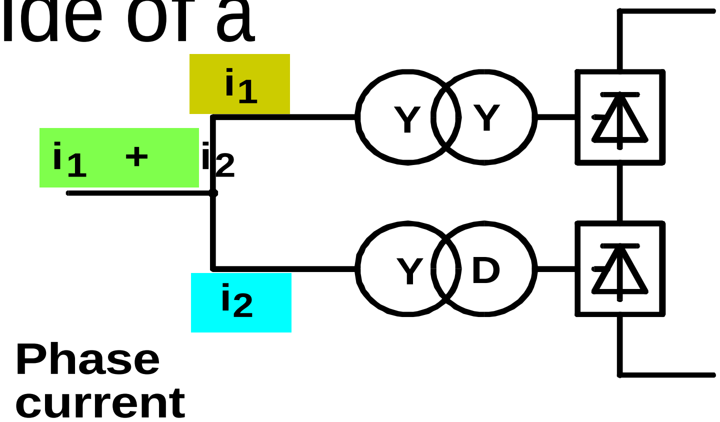


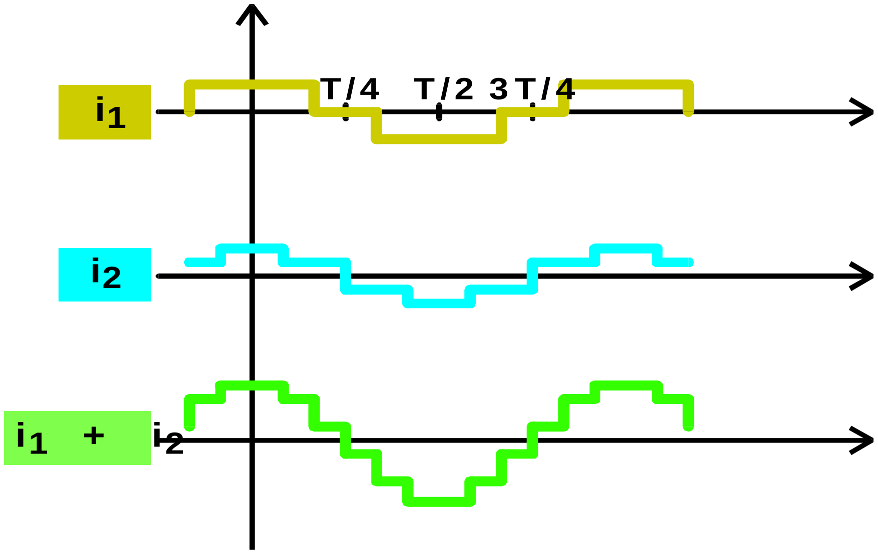
12-pulse converter

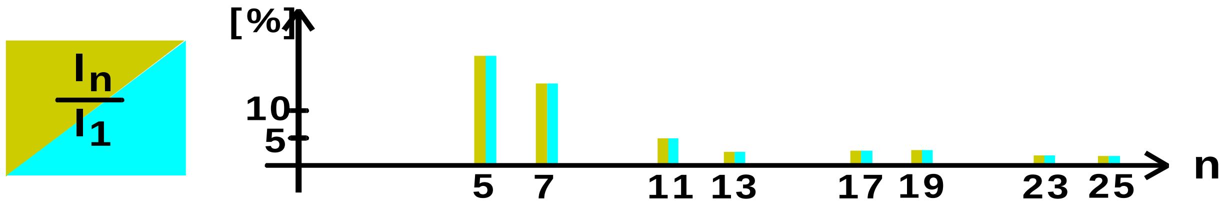


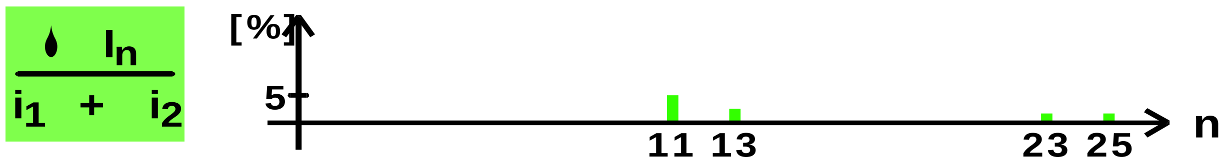
The Delta winding shifts the phase with 30º electrical versus the Star winding

Harmonic currents on the AC side of a converter









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