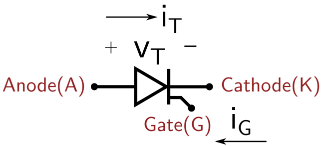
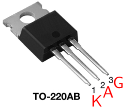
Thyristors: Silicon Controlled Rectifier (SCR)

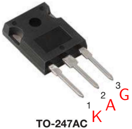
- Switches of "Thyristor" family: p-n-p-n structure
- Silicon controlled rectifier (SCR) is the most popular [Other members of thyristor family are: Asymmetrical SCR, Reverse conducting thyristor, Light-fired thyristor, Gate turn-off thyristor (GTO), Integrated gate commutated thyristor (IGCT), Triode AC switch (TRIAC), Static induction thyristor, MOS controlled thyristor (MCT)]
- SCR:- First solid state power semiconductor device developed to function as a controlled switch (1957), supporting large voltages and currents
- SCR is still 'the' controlled switch with the highest power handling capability - Large voltage and current ratings: 12kV/1.5kA, 8.5kV/4.2kA, 6kV/6kA
- High power (MW) applications: Synchronous motor drives, HVDC transmission, Flexible AC transmission, Locomotives for transportation
- Low and medium power applications: Battery chargers, Uninterruptible power supply (UPS), Welding
- Popular manufactures: Mitsubishi, ABB, Fuji Electric, Toshiba, Vishay

Silicon Controlled Rectifier (SCR)

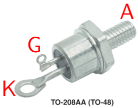




1200V, 25A



1600V, 35A



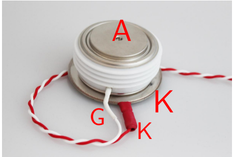
1200V, 25A

1600V, 16A

Long stud

2400V, 350A

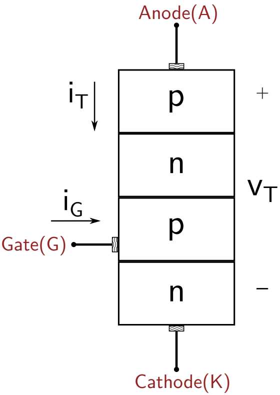
Disc/Hockey puck



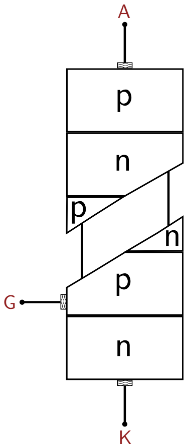
6600V, 4250A

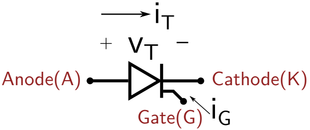
http://www.vishay.com/phase-control-discrete

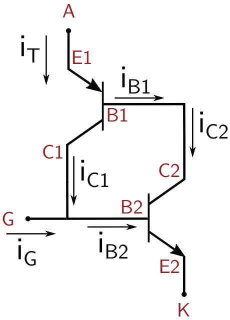
Silicon Controlled Rectifier (SCR)



Basic structure of SCR

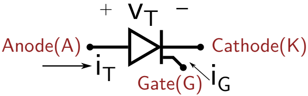


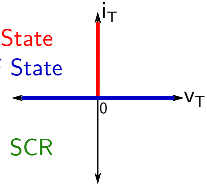




Two transistor model of SCR
to explain the regenerative turn-ON process

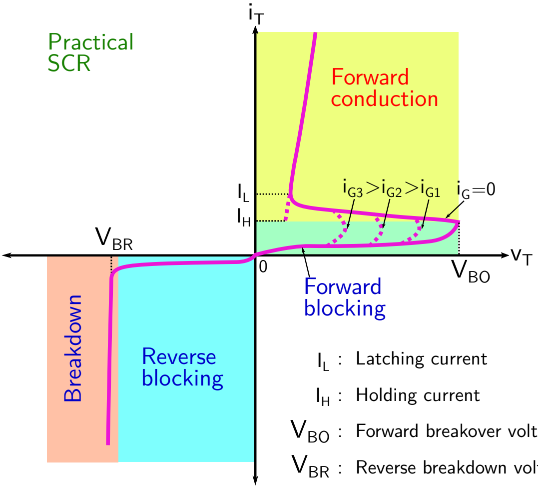
V-I characteristics of an SCR





Ideal SCR

Practical SCR



I_L : Latching current

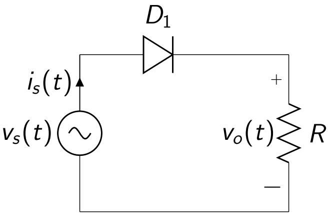
I_H : Holding current

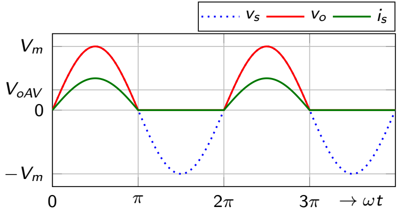
V_{BO} : Forward breakover voltage

V_{BR} : Reverse breakdown voltage

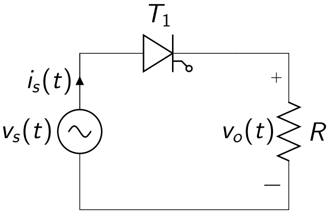
Practical SCR:
Finite ON-state loss (conduction loss)
Negligible OFF-state loss (blocking loss)
OFF to ON: turn-ON loss
ON to OFF: turn-OFF loss
(due to reverse recovery)
Additional time required to regain forward blocking capability after reverse recovery

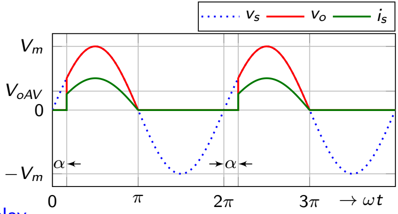
1-phase half-wave rectifiers: Uncontrolled vs controlled





$$V_{oAV} = \frac{V_m}{\pi}$$

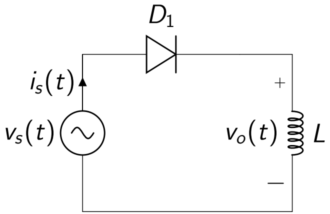


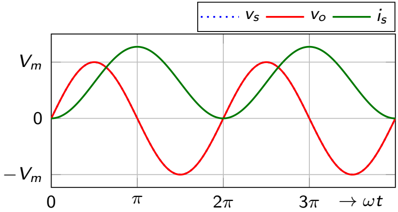


Firing angle α - Represents the switching delay with respect to a "natural" firing instant that would be valid for a circuit consisting of diodes.

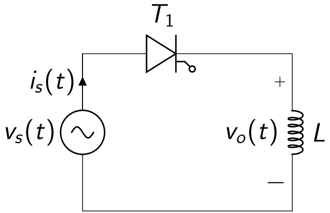
$$V_{oAV} = \frac{V_m}{\pi}\left(\frac{1+\cos\alpha}{2}\right)$$

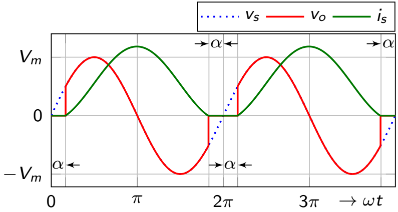
1-phase half-wave rectifiers: Uncontrolled vs controlled





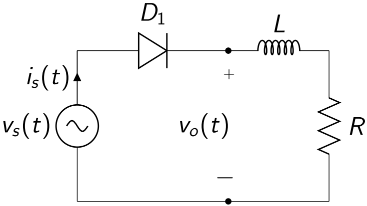
$V_{oAV} = 0$

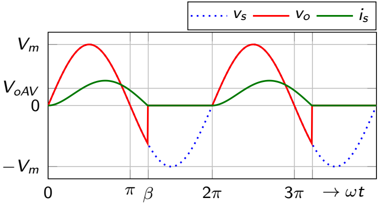




$V_{oAV} = 0$

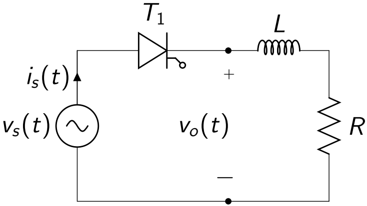
1-phase half-wave rectifiers: Uncontrolled vs controlled

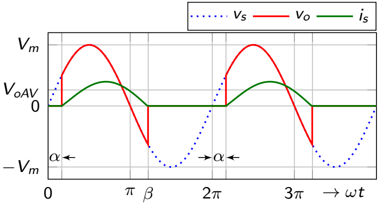




Average of $i_s = \dfrac{V_{oAV}}{R}$

$$V_{oAV} = \frac{V_m}{\pi}\left(\frac{1-\cos\beta}{2}\right)$$

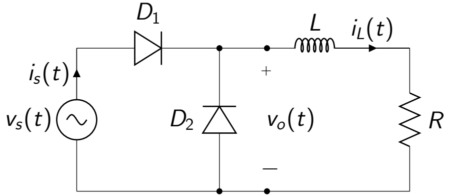


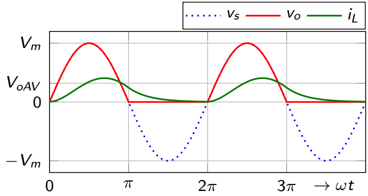


Average of $i_s = \dfrac{V_{oAV}}{R}$

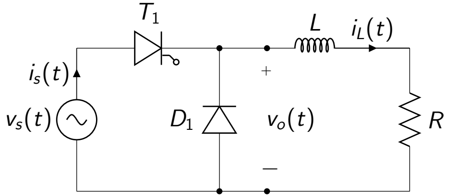
$$V_{oAV} = \frac{V_m}{\pi}\left(\frac{\cos\alpha-\cos\beta}{2}\right)$$

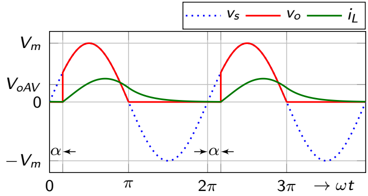
1-phase half-wave rectifiers: Uncontrolled vs controlled





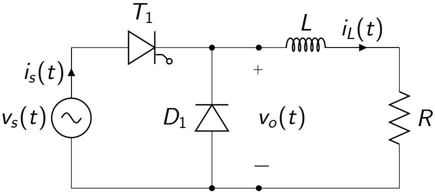
$$\text{Average of } i_L = \frac{V_{oAV}}{R} \qquad V_{oAV} = \frac{V_m}{\pi}$$

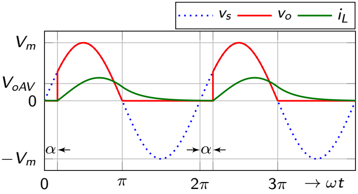




$$\text{Average of } i_L = \frac{V_{oAV}}{R} \qquad V_{oAV} = \frac{V_m}{\pi}\left(\frac{1+\cos\alpha}{2}\right)$$

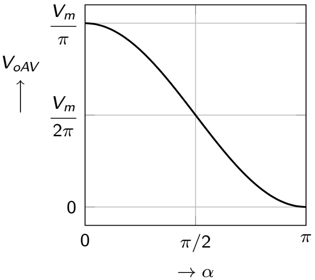
1-phase half-wave controlled rectifier with free-wheeling diode

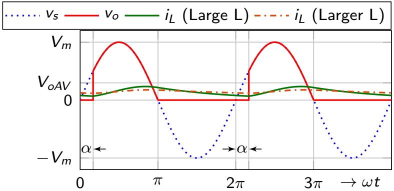




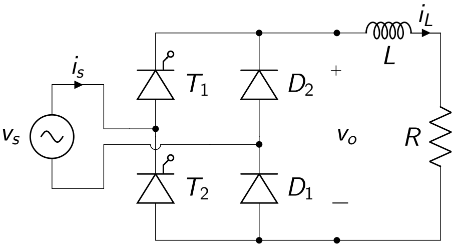
$$V_{oAV} = \frac{V_m}{\pi}\left(\frac{1+\cos\alpha}{2}\right)$$

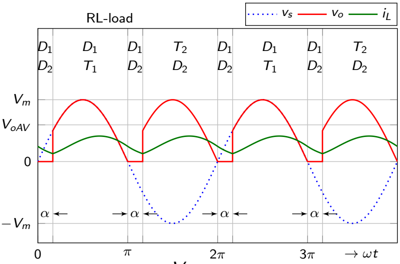
Control characteristic



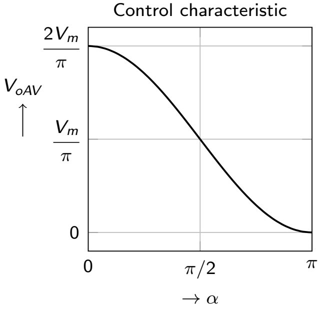


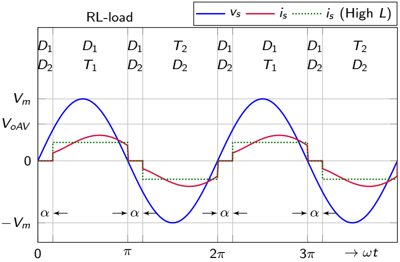
1-phase semi-controlled bridge rectifier: Circuit 1



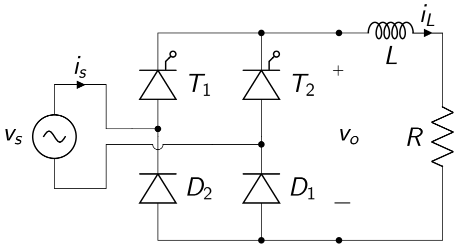


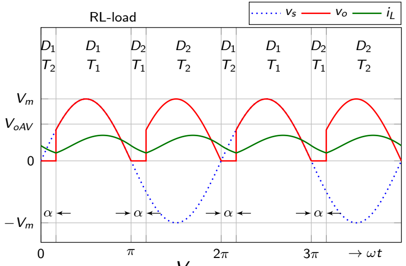
$$V_{oAV} = \frac{V_m}{\pi}(1 + \cos\alpha)$$



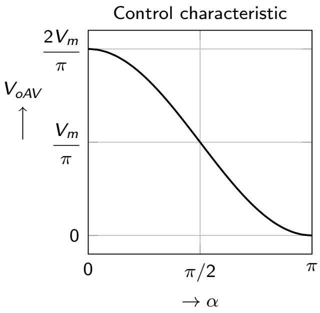


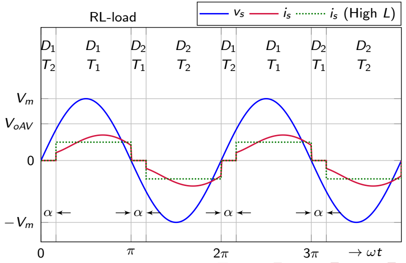
1-phase semi-controlled bridge rectifier: Circuit 2





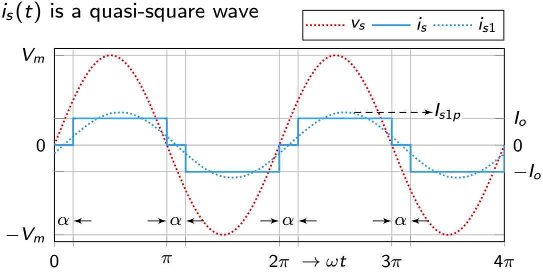
$$V_{oAV} = \frac{V_m}{\pi}(1 + \cos\alpha)$$





1-phase semi-controlled bridge rectifier: Quality of source current i_s

Highly inductive (Constant I_o) load $\Rightarrow$ $i_s(t)$ is a quasi-square wave



- Displacement power factor

  $$DPF = \cos\frac{\alpha}{2}$$

- RMS value of the source current

  $$I_{sRMS} = I_o\sqrt{1-\frac{\alpha}{\pi}}$$

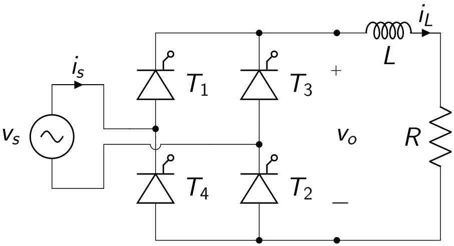
- RMS value of the fundamental component $I_{s1RMS} = \dfrac{2\sqrt{2}\,I_o}{\pi}\cos\dfrac{\alpha}{2}$

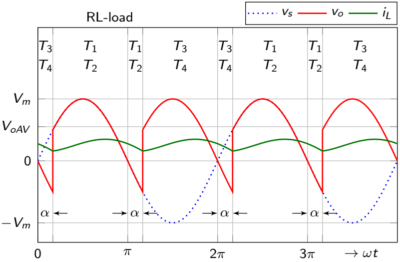
- Distortion factor $DF_1 = 2\cos\dfrac{\alpha}{2}\sqrt{\dfrac{2}{\pi(\pi-\alpha)}}$

- Total power factor $PF = (1+\cos\alpha)\sqrt{\dfrac{2}{\pi(\pi-\alpha)}}$

- $i_s(t)$ doesn't contain even harmonics

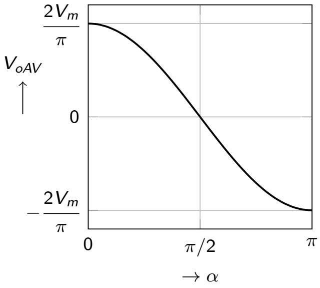
1-phase fully-controlled bridge rectifier: Continuous load current

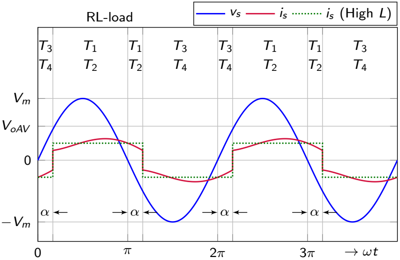




$$V_{oAV} = \frac{2V_m}{\pi} \cos\alpha$$

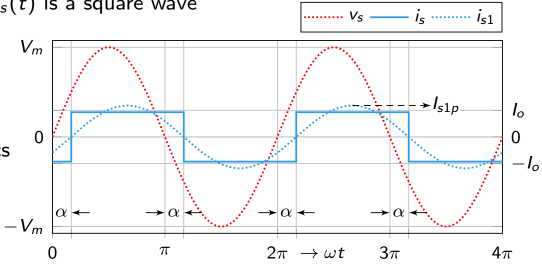
Control characteristic





1-phase fully-controlled bridge rectifier: Quality of source current i_s

Highly inductive (Constant I_o) load $\Rightarrow$ $i_s(t)$ is a square wave



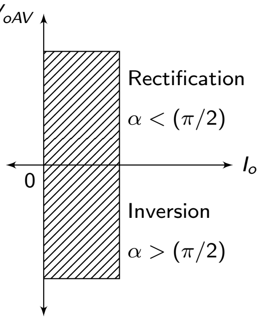
- $i_s(t)$ doesn't contain even harmonics
- Displacement power factor
  $DPF = \cos\alpha$
- RMS value of the source current
  $I_{sRMS} = I_o$
- RMS value of the fundamental component

  $$I_{s1RMS} = \frac{4I_o}{\pi}\frac{1}{\sqrt{2}} = 0.9I_o$$

- RMS value of the nth harmonic component $I_{snRMS} = \dfrac{I_{s1RMS}}{n}$
- $DF_1 = 0.9 \Rightarrow$ power factor $PF = 0.9\cos\alpha$
- Total harmonic distortion $I_{sTHD} = 48.43\%$

1-phase fully-controlled bridge: Output characteristic

A fully-controlled bridge can operate in two quadrants of the ($V_{oAV} - I_o$) plane



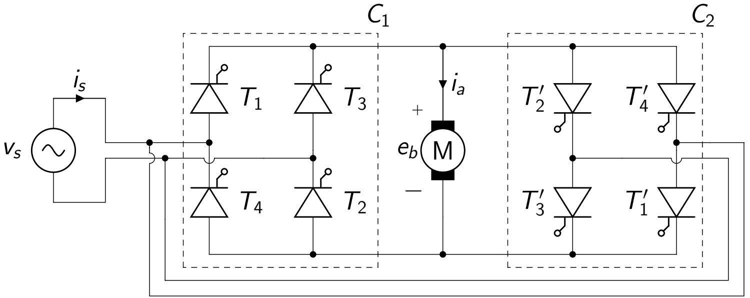
Power is supplied by the AC source

Power is fed back to the AC source

The circuit is commonly referred to as '1-phase fully-controlled converter' since it can be operated either as a rectifier or as an inverter. The term 'inverter' is used in the context of power flow from the DC-side to the AC-side; not referring to DC-AC conversion.

Inversion mode requires a source of energy to be present on the DC side, for example a battery or a DC motor (back e.m.f.).

1-phase dual converter: 4-quadrant DC-motor drive



Speed $\propto e_b$

Forward braking
C_2 is operated as inverter
Gate pulses for C_1 are blocked

Forward motoring
C_1 is operated as rectifier
Gate pulses for C_2 are blocked

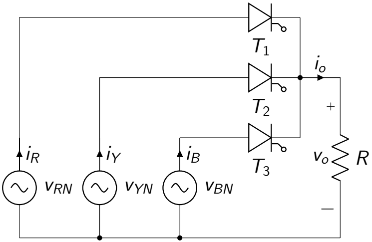
Torque $\propto i_a$

0

Reverse motoring
C_2 is operated as rectifier
Gate pulses for C_1 are blocked

Reverse braking
C_1 is operated as inverter
Gate pulses for C_2 are blocked

3-ph half-wave (3-pulse) controlled rectifier: R-Load

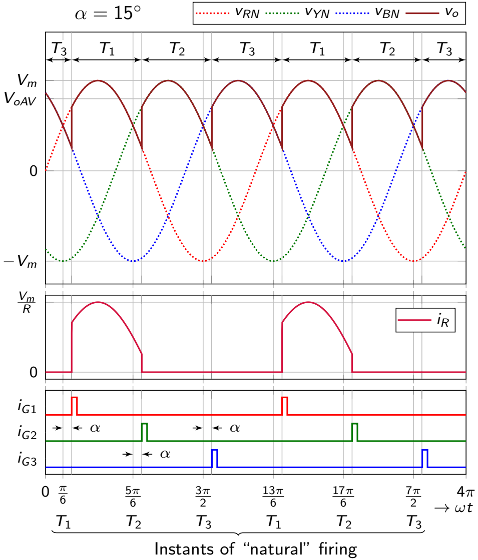


Average output voltage V_{oAV}

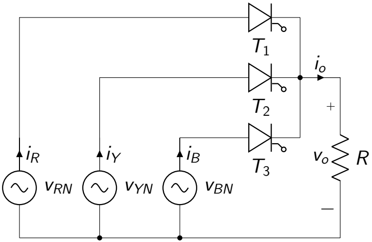
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t)\; d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi} \cos\alpha$$

$$0 \le \alpha \le \frac{\pi}{6}$$



3-ph half-wave (3-pulse) controlled rectifier: R-Load

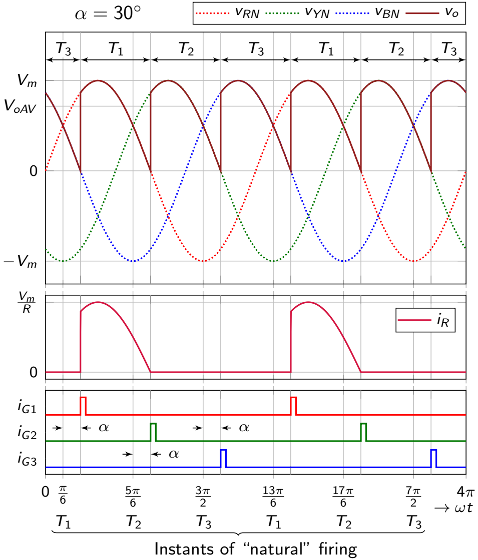


Average output voltage V_{oAV}

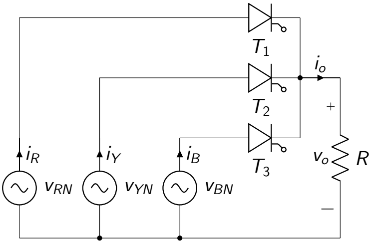
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi} \cos\alpha$$

$$0 \leq \alpha \leq \frac{\pi}{6}$$



3-ph half-wave (3-pulse) controlled rectifier: R-Load

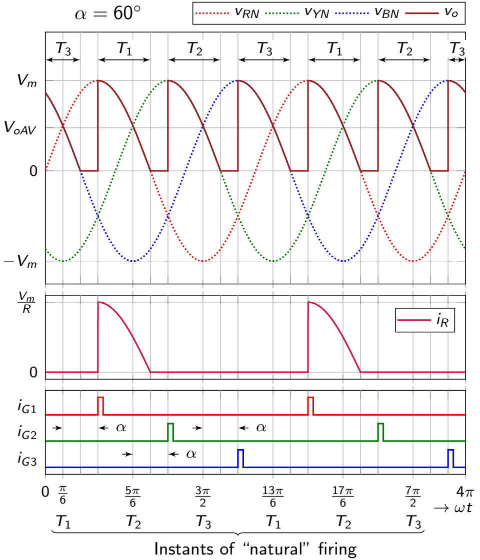


Average output voltage V_{oAV}

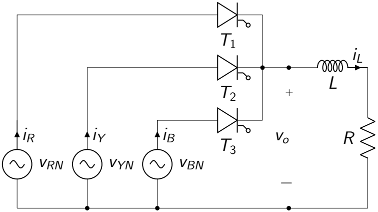
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\pi} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3V_m}{2\pi}\left[1 + \cos\left(\alpha + \frac{\pi}{6}\right)\right]$$

$$\frac{\pi}{6} \leq \alpha \leq \frac{5\pi}{6}$$



3-ph half-wave (3-pulse) controlled rectifier: RL-Load

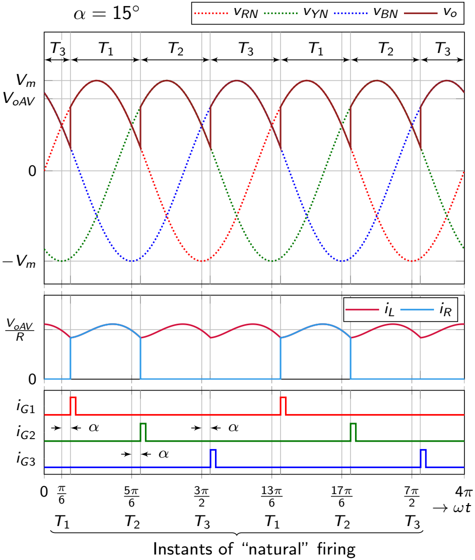


Average output voltage V_{oAV}

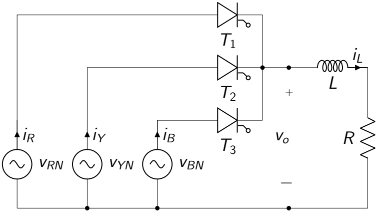
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi} \cos\alpha$$

Valid if i_L is continuous, for any α



3-ph half-wave (3-pulse) controlled rectifier: RL-Load

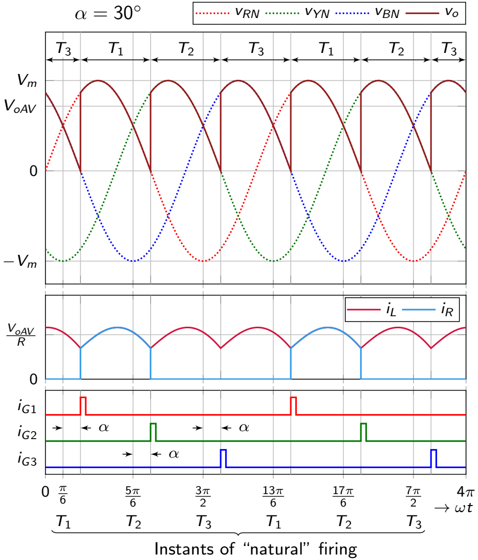


Average output voltage V_{oAV}

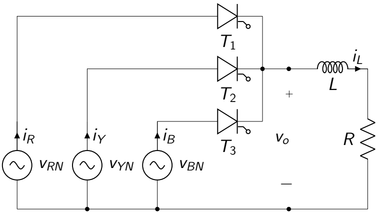
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi} \cos\alpha$$

Valid if i_L is continuous, for any α



3-ph half-wave (3-pulse) controlled rectifier: RL-Load

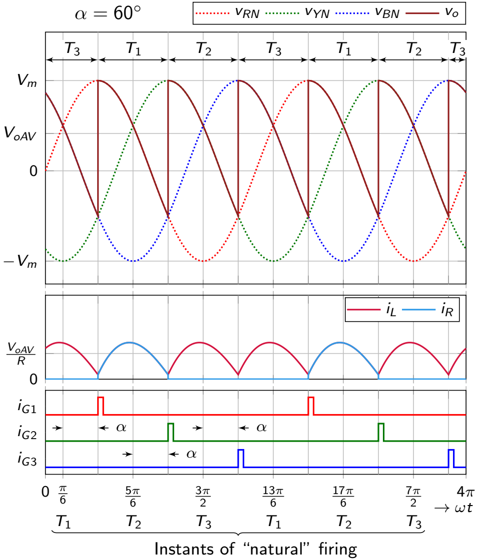


Average output voltage V_{oAV}

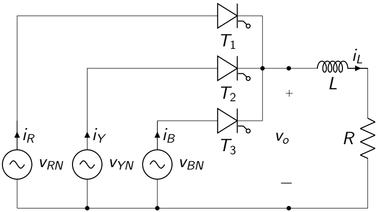
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi} \cos\alpha$$

Valid if i_L is continuous, for any α



3-ph half-wave (3-pulse) controlled rectifier: RL-Load



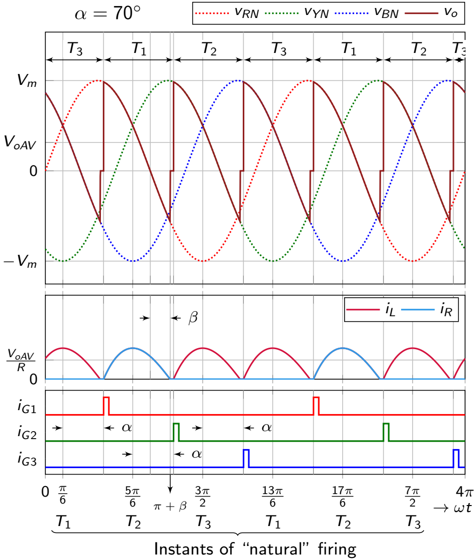
Average output voltage V_{oAV}

$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\pi+\beta} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3V_m}{2\pi} \left[\cos\beta + \cos\left(\frac{\pi}{6}+\alpha\right) \right]$$

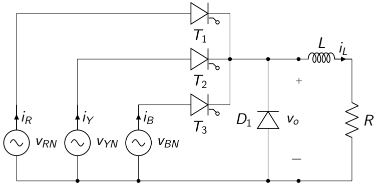
If i_L is discontinuous,

V_{oAV} depends on β



3-ph half-wave (3-pulse) controlled rectifier: RL-Load

Free-wheeling diode avoids negative excursions of v_o

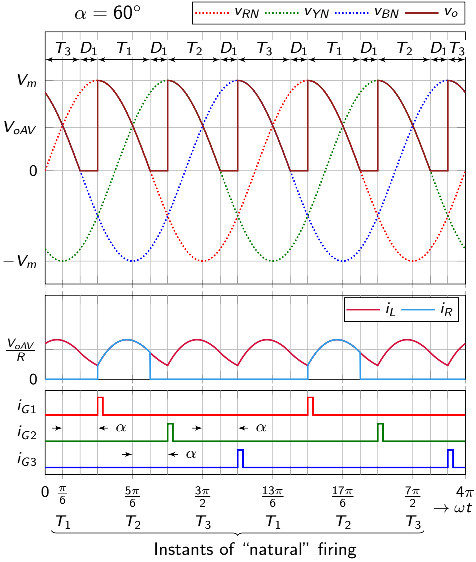


Average output voltage V_{oAV}

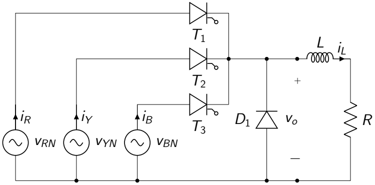
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\pi} V_m \sin(\omega t)\ d(\omega t)$$

$$= \frac{3V_m}{2\pi}\left[1 + \cos\left(\alpha + \frac{\pi}{6}\right)\right]$$

$$\frac{\pi}{6} \leq \alpha \leq \frac{5\pi}{6}$$



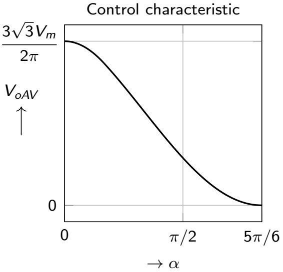
3-ph half-wave (3-pulse) controlled rectifier: Control characteristic



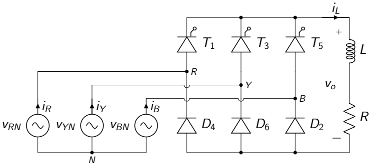
Source current i_R contains DC component (finite average value)

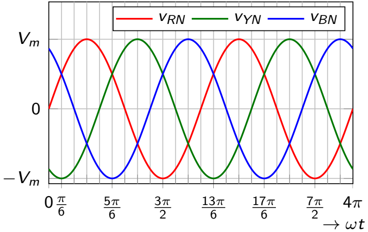
Average output voltage

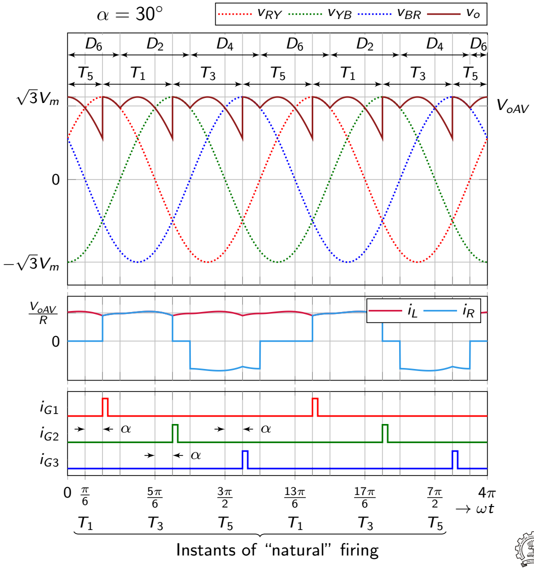
$$V_{oAV} = \begin{cases} \dfrac{3\sqrt{3}V_m}{2\pi}\cos\alpha, 0 \leq \alpha \leq \dfrac{\pi}{6} \\ \dfrac{3V_m}{2\pi}\left[1+\cos\left(\alpha+\frac{\pi}{6}\right)\right], \dfrac{\pi}{6} \leq \alpha \leq \dfrac{5\pi}{6} \end{cases}$$



3-ph semi-controlled bridge rectifier: RL-Load and $0 \leq \alpha \leq \frac{\pi}{3}$





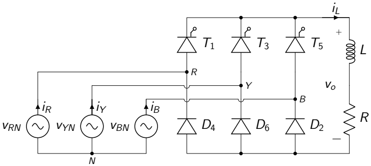


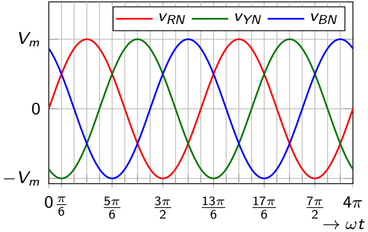
Average output voltage V_{oAV}

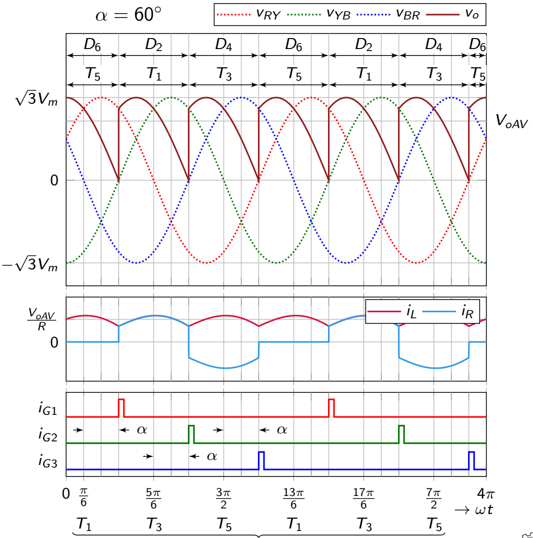
$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} v_o(t)\, d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha)$$

3-ph semi-controlled bridge rectifier: RL-Load and $0 \leq \alpha \leq \frac{\pi}{3}$







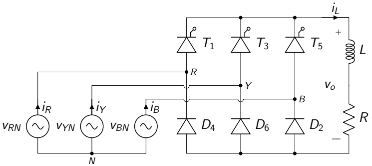
Instants of "natural" firing

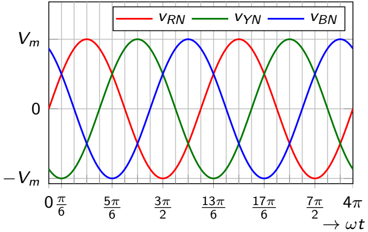
Average output voltage V_{oAV}

$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} v_o(t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha)$$

3-ph semi-controlled bridge rectifier: RL-Load and $\frac{\pi}{3} \leq \alpha \leq \pi$

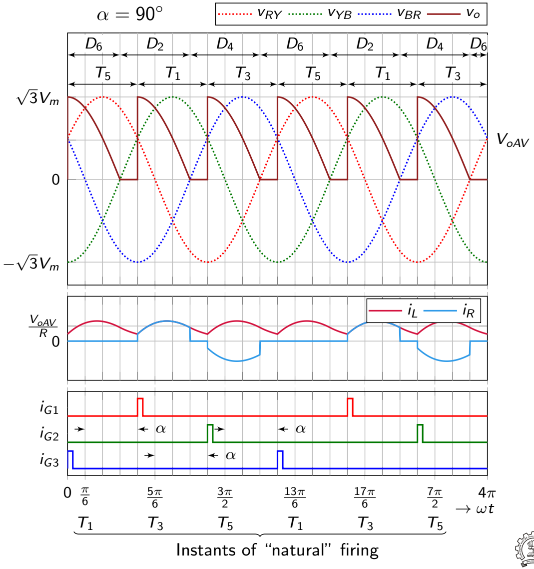




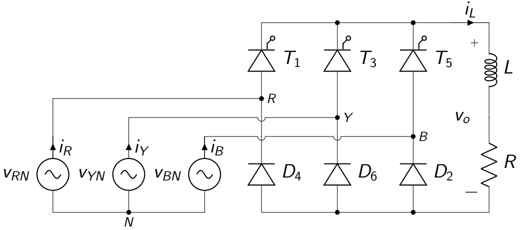
Average output voltage V_{oAV}

$$= \frac{1}{(2\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{7\pi}{6}} v_o(t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha)$$

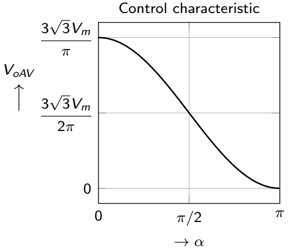


3-ph semi-controlled bridge rectifier: Control characteristic



Average output voltage

$$V_{oAV} = \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha)$$

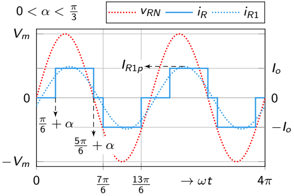


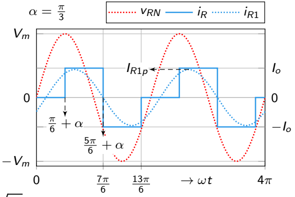
- Each switch (diode/thyristor) conducts for 120°
- Only 2 switches conduct at any given instant
- T_1 and D_2 conduct together for any α
- T_1 and D_6 conduct together only if $\alpha < 60°$
- T_1 and D_4 conduct together only if $\alpha > 60°$
- Similar observations can be made for other thyristors

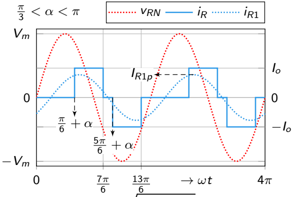
3-ph semi-controlled bridge rectifier: Quality of source current

Highly inductive load (constant I_o)

v_{RN}: R-phase voltage; i_R: R-phase current; i_{R1}: Fundamental component of i_R







$$I_{RRMS} = I_o\sqrt{\frac{2}{3}} \quad \alpha \leq \frac{\pi}{3}$$

$$a_1 = \frac{2}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} I_o \cos(\omega t)d(\omega t) + \int_{\frac{7\pi}{6}}^{\frac{13\pi}{6}} (-I_o)\cos(\omega t)d(\omega t)\right]$$

$$I_{RRMS} = I_o\sqrt{1-\frac{\alpha}{\pi}} \quad \alpha > \frac{\pi}{3}$$

$$a_1 = \frac{2}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{7\pi}{6}} I_o \cos(\omega t)d(\omega t) + \int_{\frac{5\pi}{6}+\alpha}^{\frac{13\pi}{6}} (-I_o)\cos(\omega t)d(\omega t)\right]$$

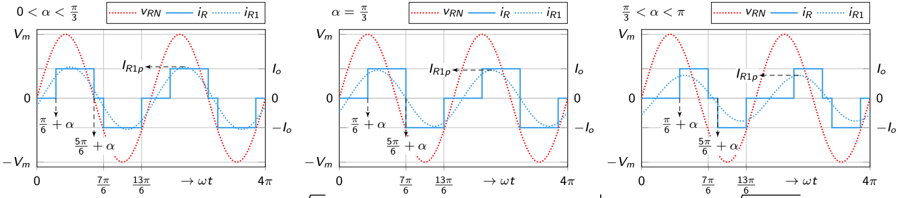
a_1 has the same value in both the cases

Similar is the case with b_1

3-ph semi-controlled bridge rectifier: Quality of source current

Highly inductive load (constant I_o)

v_{RN}: R-phase voltage; i_R: R-phase current; i_{R1}: Fundamental component of i_R



$$I_{RRMS} = I_o\sqrt{\frac{2}{3}} \quad \alpha \le \frac{\pi}{3}$$

$$I_{RRMS} = I_o\sqrt{1 - \frac{\alpha}{\pi}} \quad \alpha > \frac{\pi}{3}$$

$$a_1 = -\frac{I_o\sqrt{3}}{\pi}\sin\alpha \quad \text{and} \quad b_1 = \frac{I_o\sqrt{3}}{\pi}(1+\cos\alpha) \quad \Rightarrow \tan^{-1}\left(\frac{a_1}{b_1}\right) = -\frac{\alpha}{2}$$

i_{R1} lags v_{RN} by $\frac{\alpha}{2}$ $\Rightarrow$ Displacement power factor $DPF = \cos\frac{\alpha}{2}$

$$I_{R1p} = \frac{2\sqrt{3}I_o}{\pi}\cos\frac{\alpha}{2} \quad \textit{and} \quad I_{R1RMS} = \frac{I_o\sqrt{6}}{\pi}\cos\frac{\alpha}{2}$$

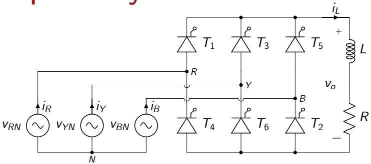
Distortion factor $DF_1 = \frac{3}{\pi}\cos\frac{\alpha}{2} \quad \alpha \le \frac{\pi}{3}$

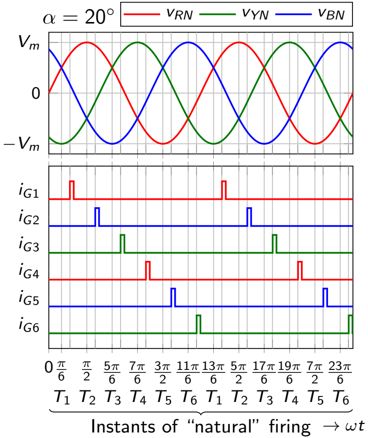
Power factor $PF = \frac{3}{\pi}\cos^2\frac{\alpha}{2} \quad \alpha \le \frac{\pi}{3}$

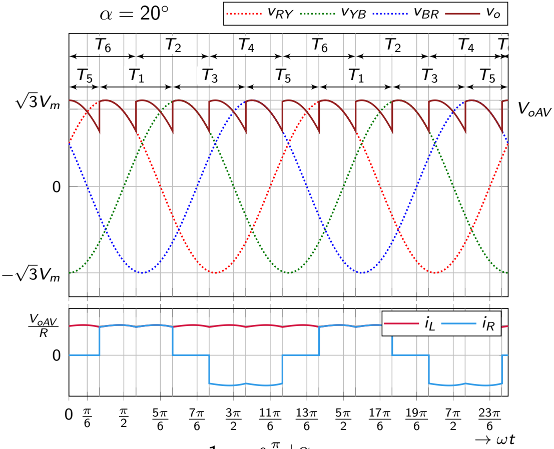
$$DF_1 = \sqrt{\frac{6}{\pi(\pi-\alpha)}}\cos\frac{\alpha}{2} \quad \alpha > \frac{\pi}{3}$$

$$PF = \sqrt{\frac{6}{\pi(\pi-\alpha)}}\cos^2\frac{\alpha}{2} \quad \alpha > \frac{\pi}{3}$$

3-ph fully-controlled bridge rectifier: RL-Load



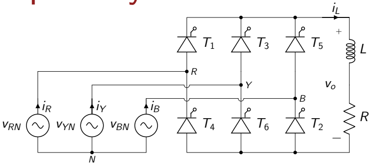


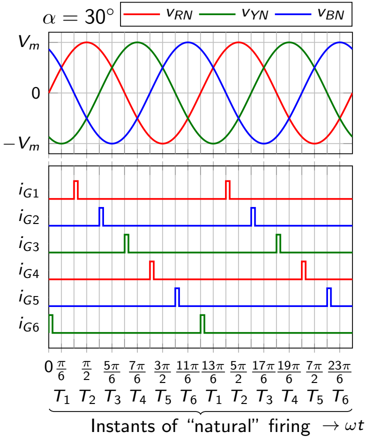


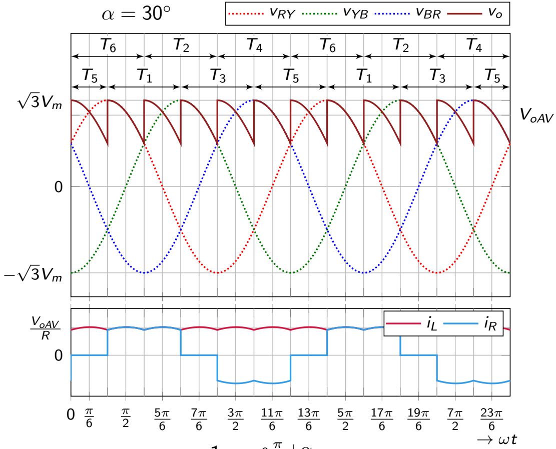
$$V_{oAV} = \frac{1}{(\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o(t)\; d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{\pi} \cos\alpha$$

3-ph fully-controlled bridge rectifier: RL-Load



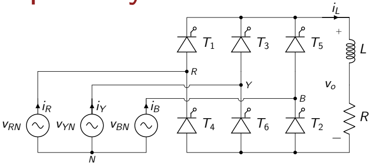


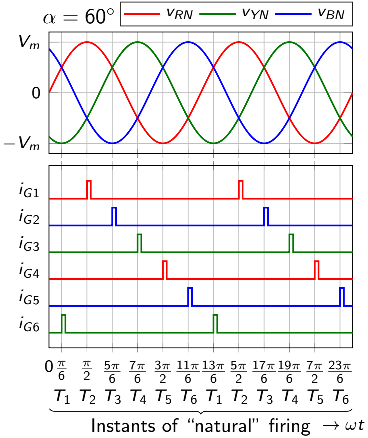


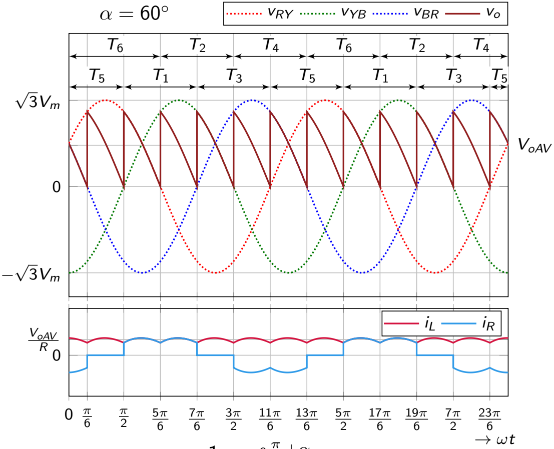
$$V_{oAV} = \frac{1}{(\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o(t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{\pi} \cos\alpha$$

3-ph fully-controlled bridge rectifier: RL-Load



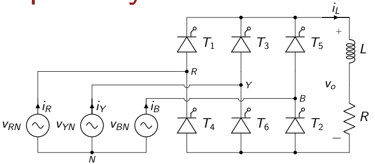


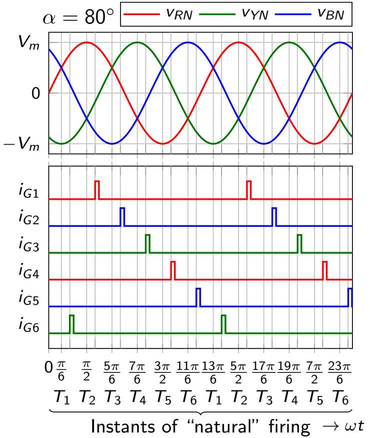


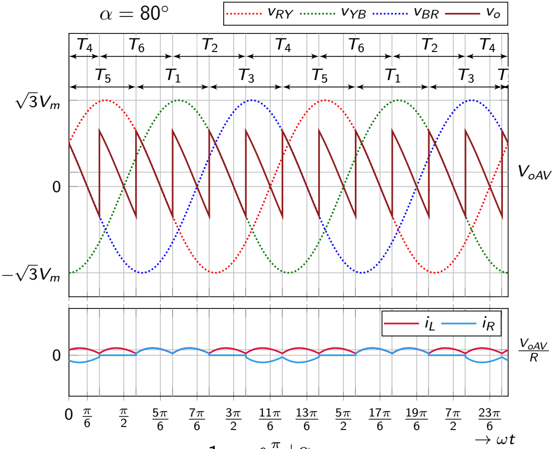
$$V_{oAV} = \frac{1}{(\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o(t)\ d(\omega t)$$

$$= \frac{3\sqrt{3}V_m}{\pi} \cos\alpha$$

3-ph fully-controlled bridge rectifier: RL-Load



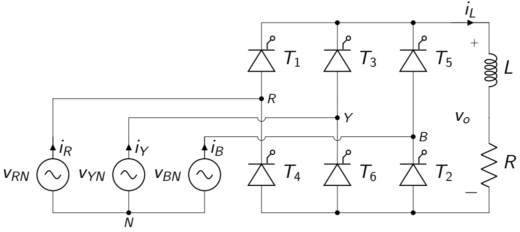




$$V_{oAV} = \frac{1}{(\pi/3)} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o(t)\ d(\omega t)$$

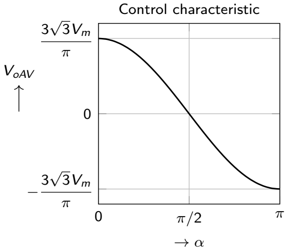
$$= \frac{3\sqrt{3}V_m}{\pi} \cos\alpha$$

3-ph fully-controlled bridge rectifier: Continuous load current



Average output voltage

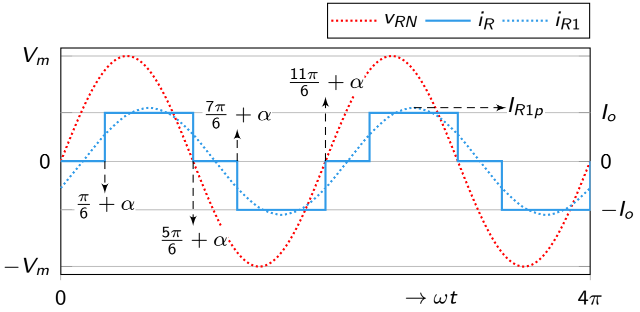
$$V_{oAV} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$



- Each thyristor conducts for 120°
- Only 2 thyristors conduct at any given instant
- Operates as rectifier ($\alpha < 90^\circ$) and inverter ($\alpha > 90^\circ$)
- Average output voltage is negative when $\alpha > 90^\circ$
- Power transfer is from DC-side to AC-side when $\alpha > 90^\circ \rightarrow$ Inversion
- Energy source should be present on the DC-side to operate in inversion mode
- 3-ph dual converter can be used for 4-quadrant motor-drive applications (similar to 1-phase)

3-ph fully-controlled bridge rectifier: Quality of source current

Highly inductive (constant I_o) load



- i_{R1} lags v_{RN} by α $\Rightarrow$Displacement power factor $DPF = \cos\alpha$
- $I_{RRMS} = I_o\sqrt{\dfrac{2}{3}}$ and $I_{R1RMS} = I_o\dfrac{\sqrt{6}}{\pi}$ $\Rightarrow DF_1 = \dfrac{3}{\pi}$ and $I_{RTHD} = 31.08\%$
- Total power factor $PF = \dfrac{3}{\pi}\cos\alpha$
- Order of harmonics in i_R is 5,7,11,13,17,19,... or $6m \pm 1$, $m = 1, 2, 3, \ldots$

Module 2: Summary

- Silicon Controlled Rectifier (SCR): operation and characteristics
- Half-wave and full-wave controlled rectifiers, 1-phase and 3-phase, semi-controlled and fully-controlled
- Controllable DC output voltage from a fixed AC input voltage
- Fully-controlled converters: operation as inverter (Power flow from DC-side to AC-side)
- Dual-converter: four-quadrant motor drive
- Displacement power factor is not unity; the converters draw reactive power from input
- Output DC voltage waveforms are not smooth; input current contains harmonics - distorts the voltage at point of common coupling