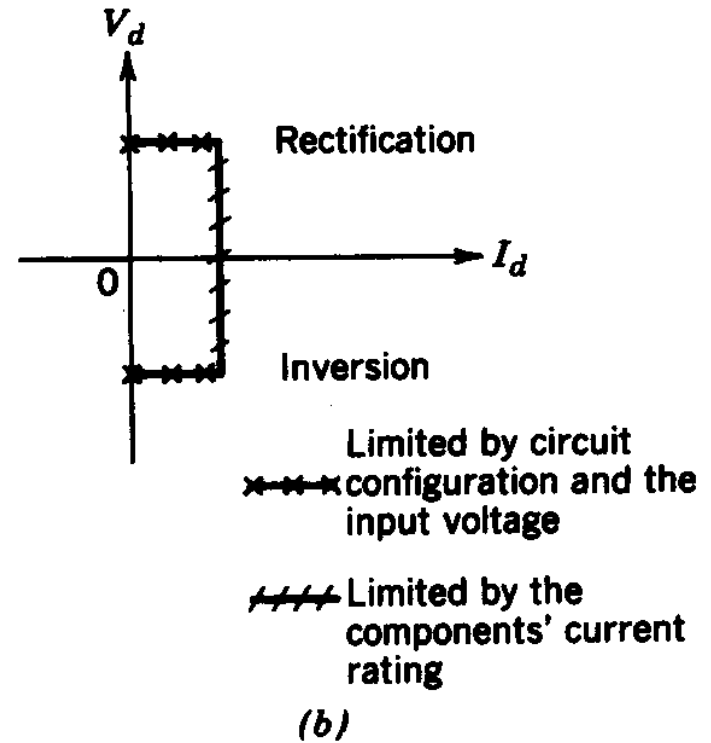
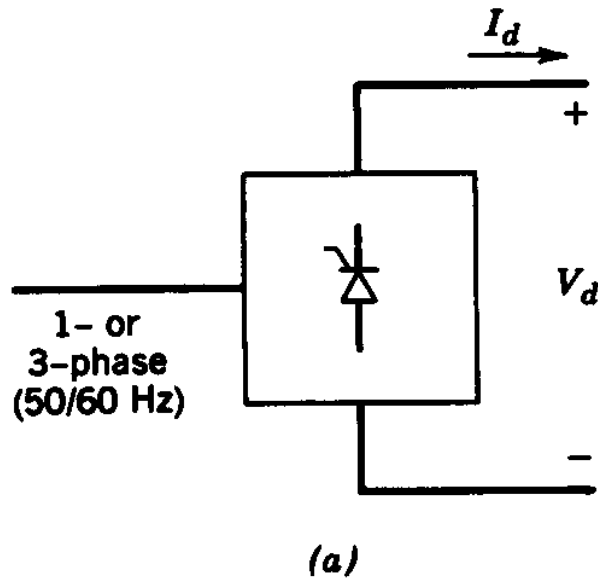


Thyristor Converters

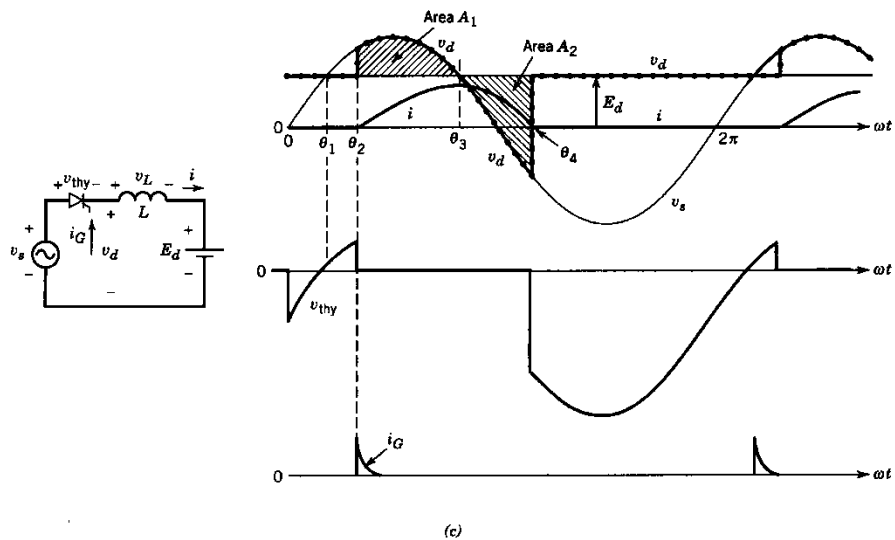
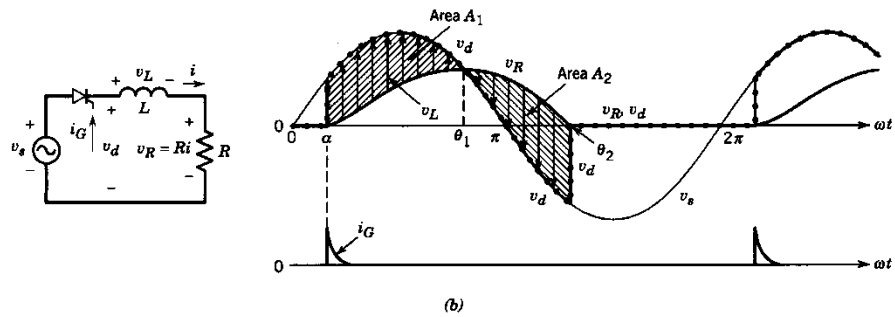
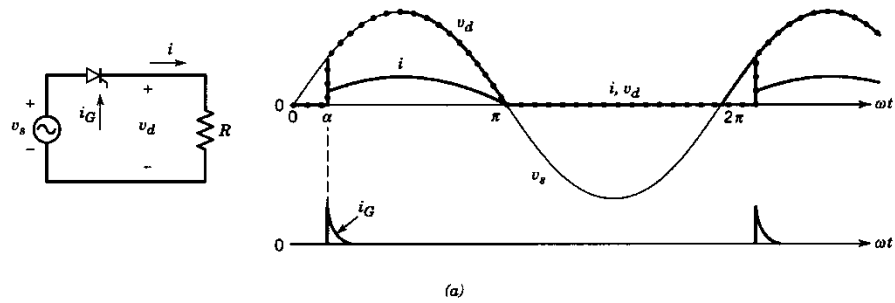
EE 442-642

Thyristor Converters

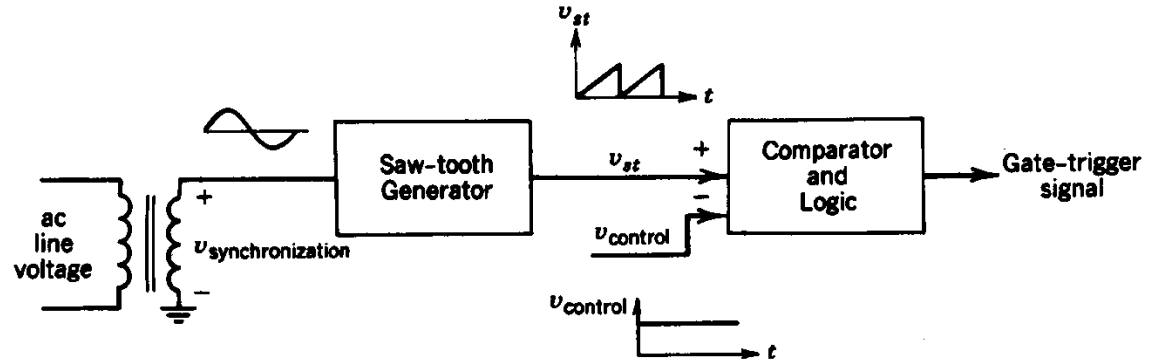


- Two-quadrant conversion

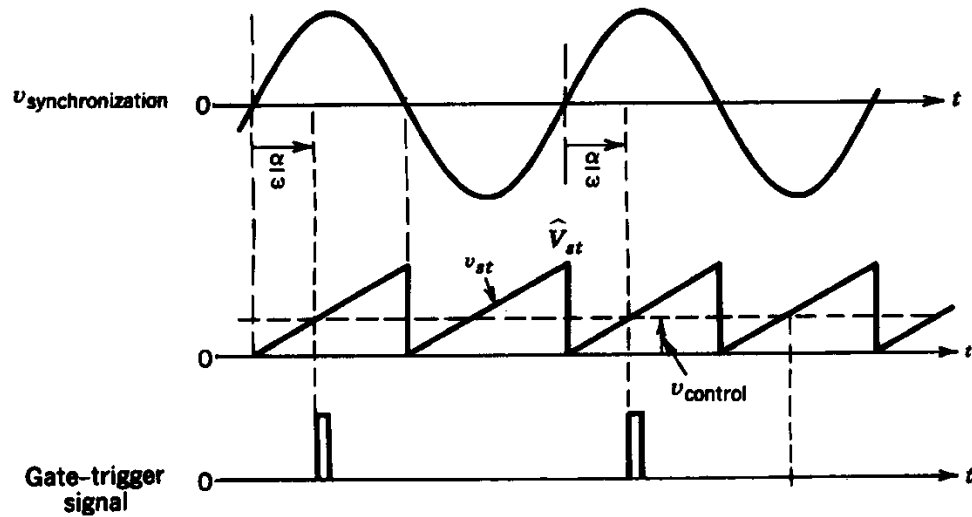
Simple half-wave circuits with thyristors



Thyristor Triggering

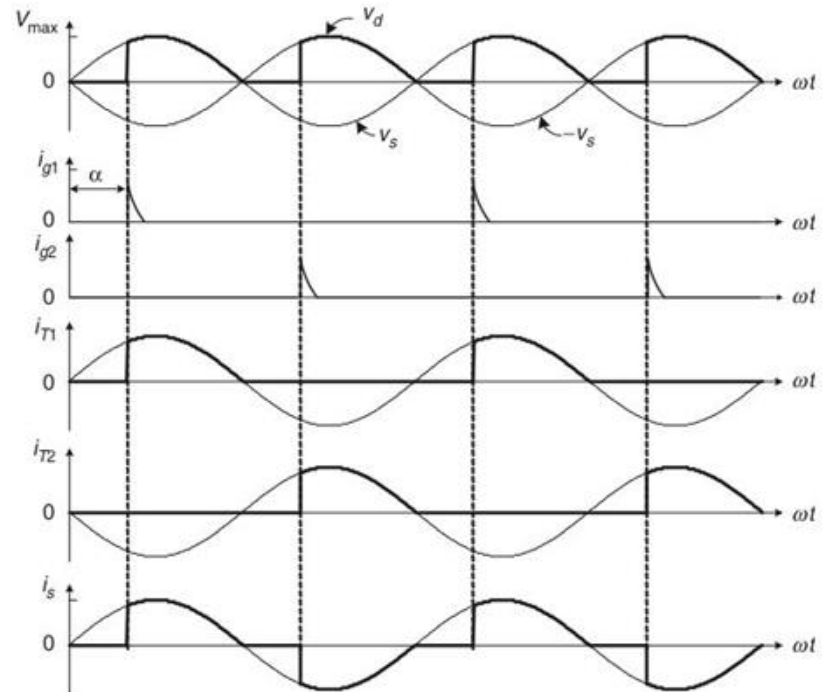
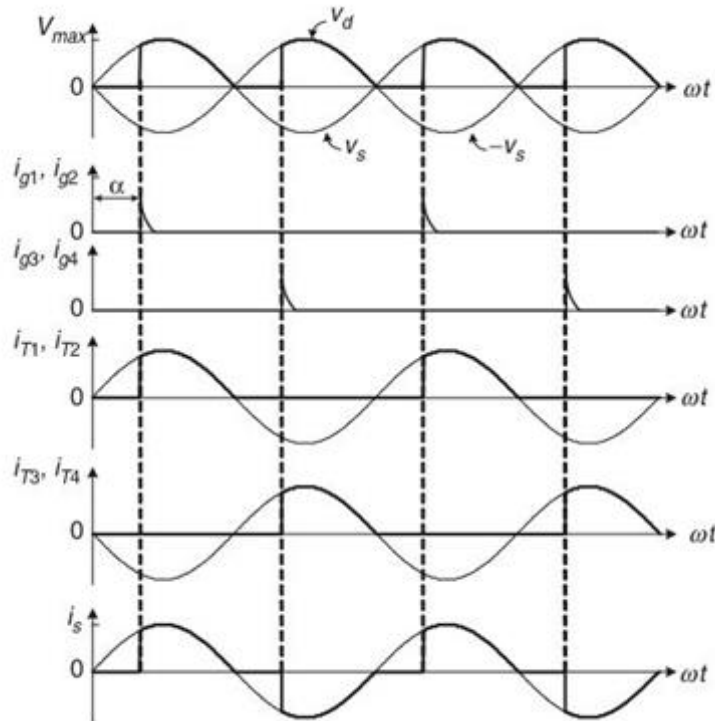
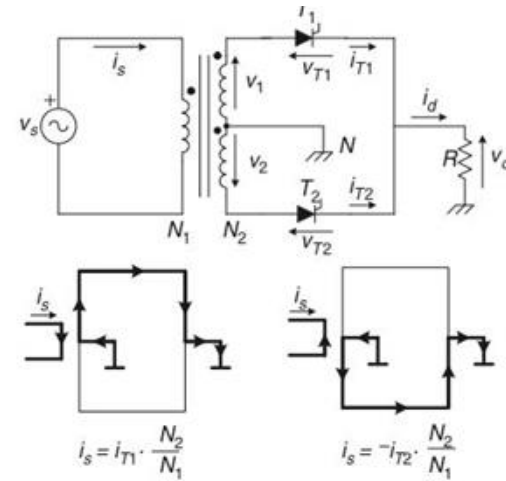
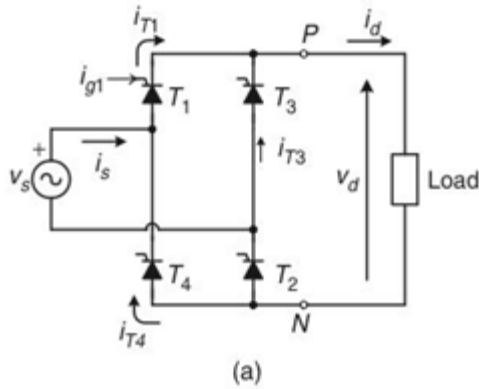


$$\alpha^{\circ} = 180^{\circ} \frac{v_{\text{control}}}{\hat{V}_{st}}$$

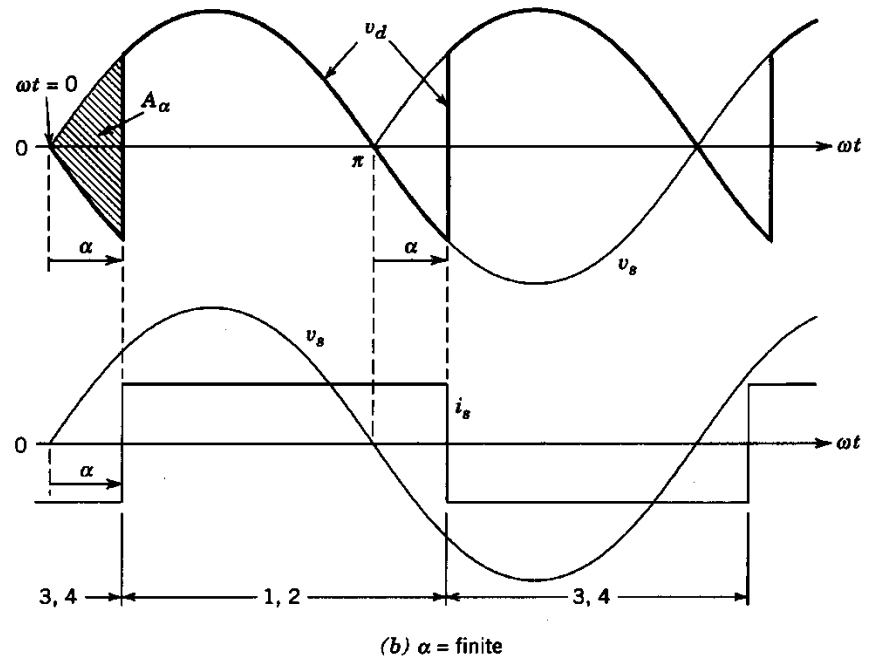
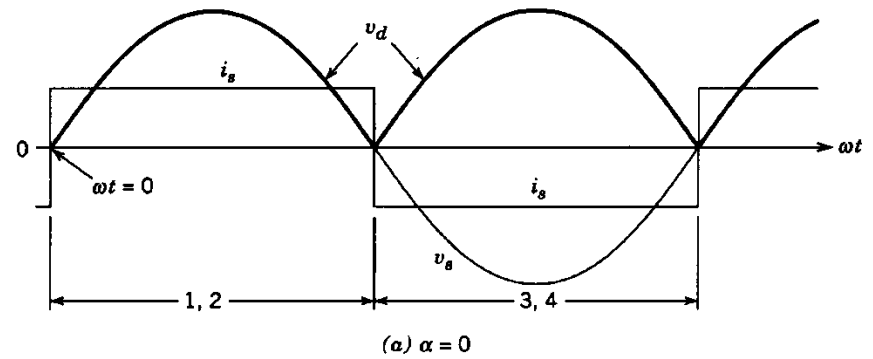
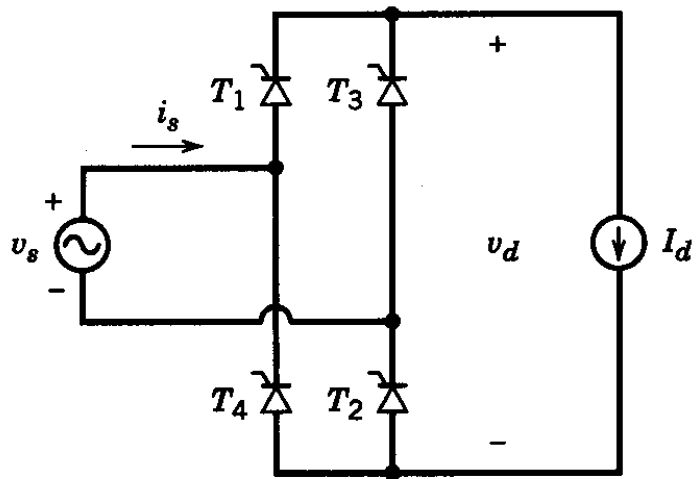


- ICs available

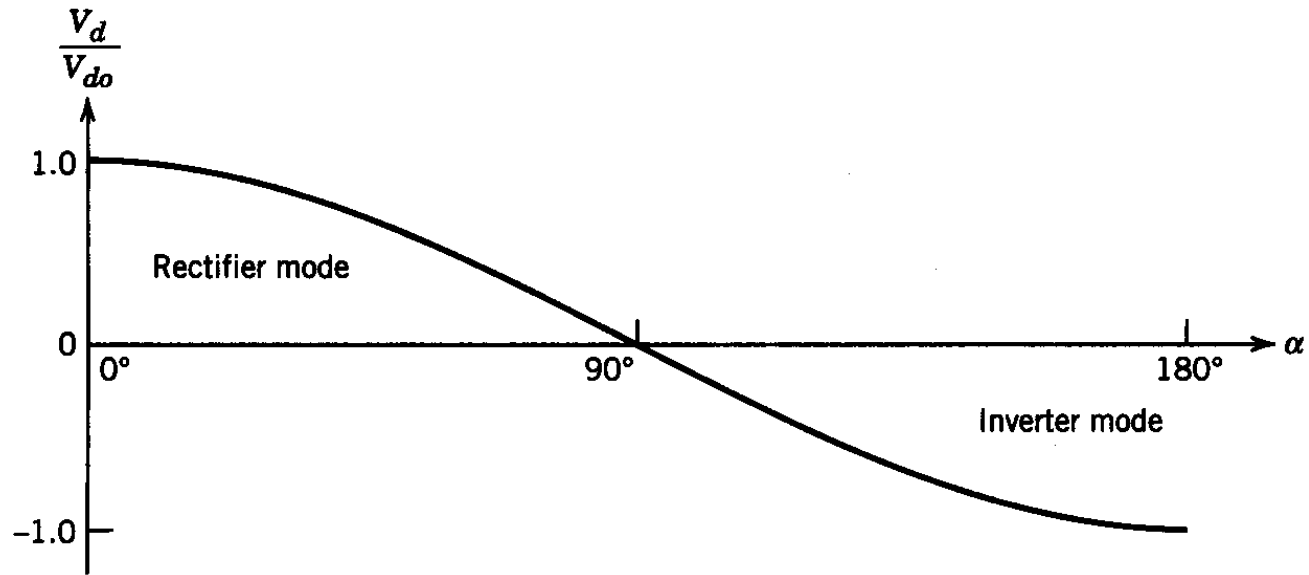
Case of Pure Resistive Load



Full-Bridge Thyristor Converters – Constant DC Current



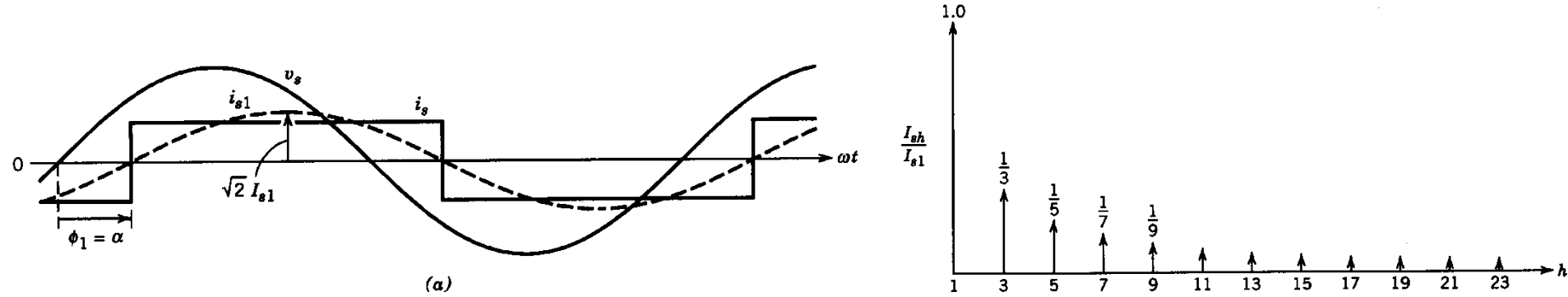
DC-Side Voltage



Average DC voltage: $V_{d\alpha} = V_{do} \cos \alpha$

where $V_{do} = 0.9V_s$

AC-Side Current



RMS value of source current

$$I_s = I_d$$

RMS value of fundamental current

$$I_{s1} = (2\sqrt{2} / \pi) I_d \approx 0.9 I_d$$

RMS value of harmonic current

$$I_{sh} = I_{s1} / h, \quad h = 3, 5, 7, \dots$$

Current THD

$$THD = 100\sqrt{(\pi^2 / 8) - 1} = 48.43\%$$

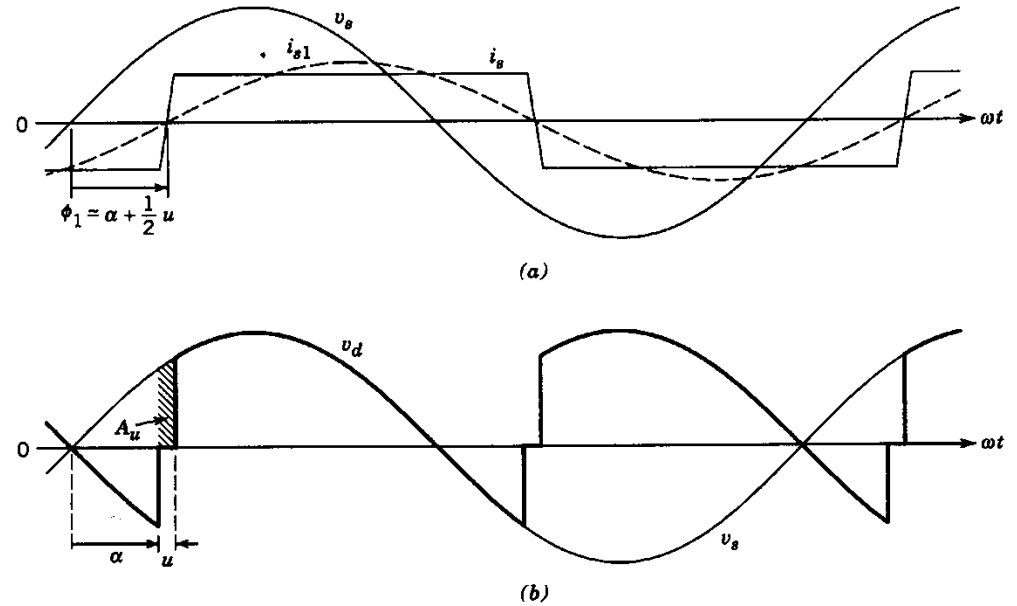
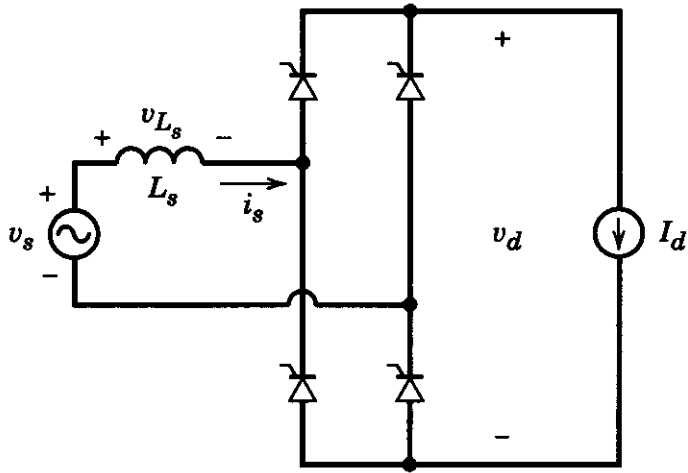
Displacement Power Factor

$$DPF = \cos \alpha$$

Power Factor

$$PF = 0.9 \cos \alpha$$

Effect of Source Inductance



Commutation angle:

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

Average of DC-side voltage:

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

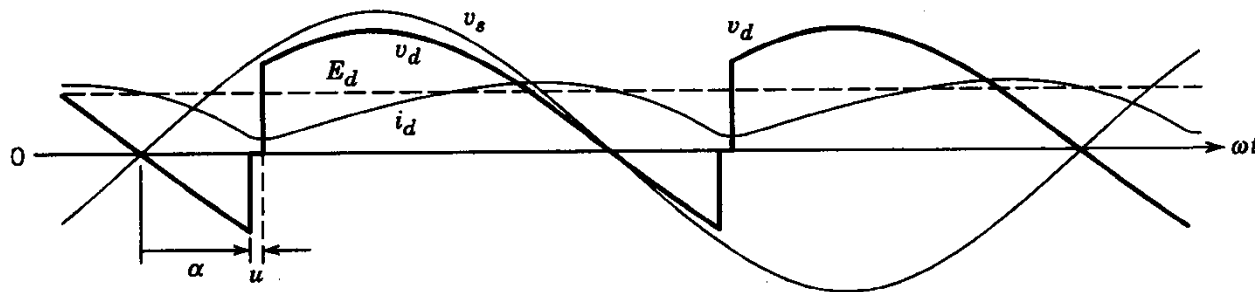
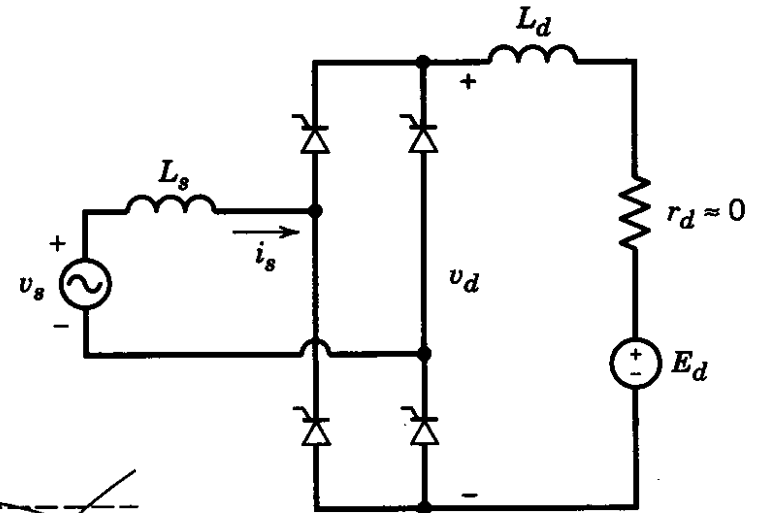
Displacement Power Factor

$$DPF \approx \cos(\alpha + 0.5\mu)$$

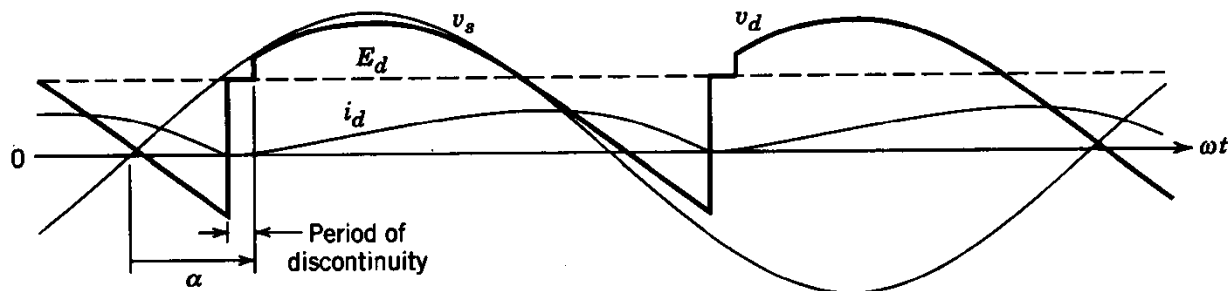
RMS fundamental current

$$I_{s1} = \frac{V_d I_d}{V_s DPF} \approx \frac{0.9V_s I_d \cos \alpha - (2/\pi)\omega L_s I_d^2}{V_s \cos(\alpha + 0.5\mu)}$$

Thyristor Converter with DC Source



Continuous current conduction mode



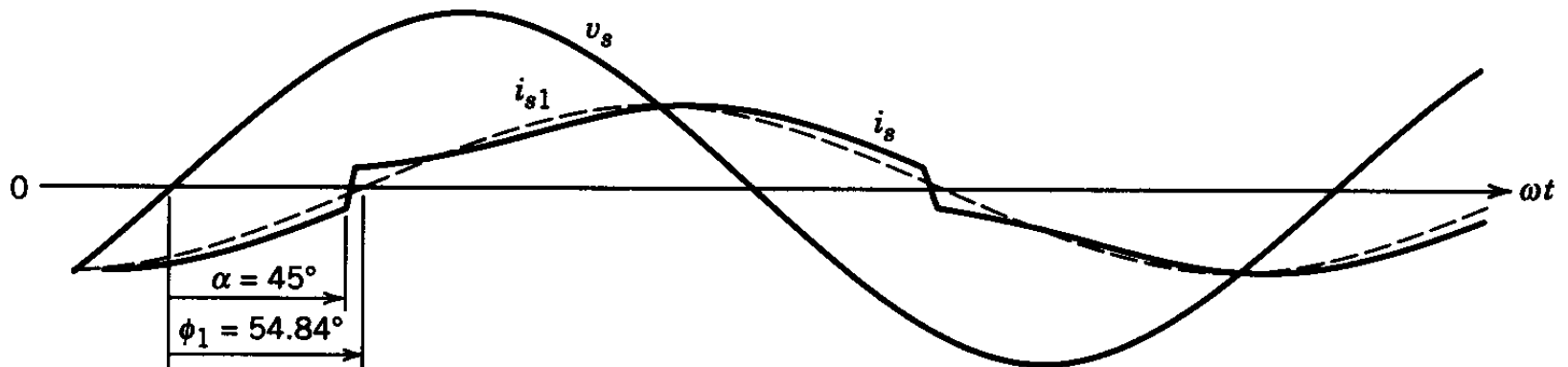
Discontinuous current conduction mode

AC-Side Current Waveform

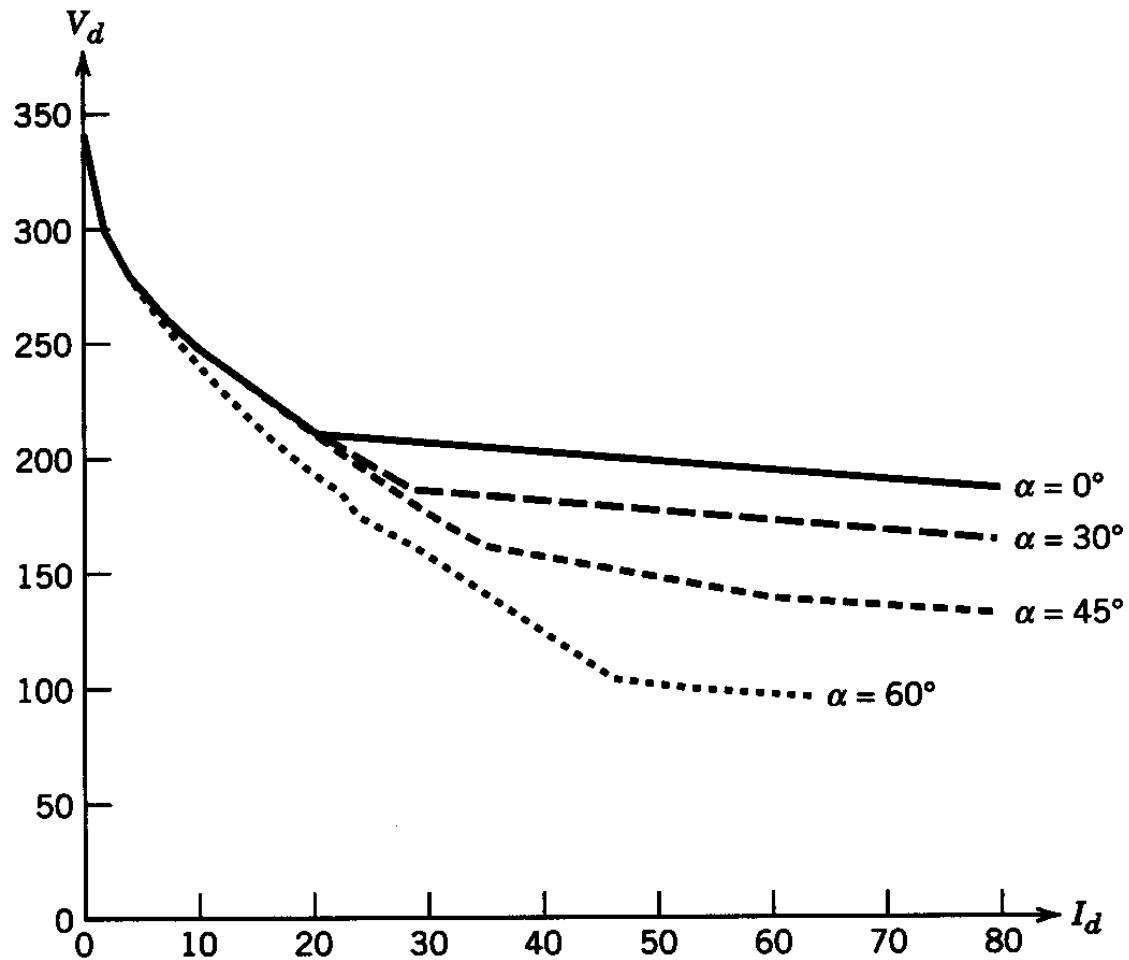
(continuous conduction mode)

PSpice-based simulation example: $V_s = 240$ V, $f = 60$ Hz,
 $L_s = 1.4$ mH, $\alpha = 45$ deg., $L_d = 9$ mH, $E_d = 145$ V.

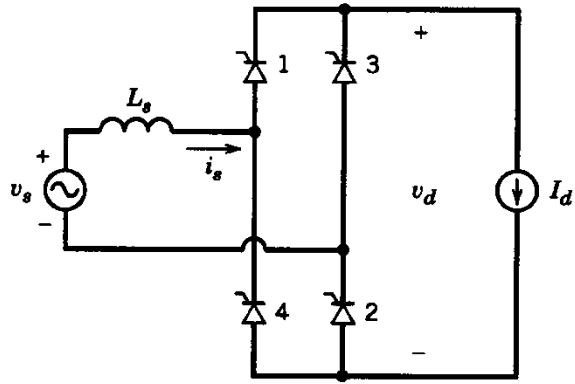
Solution: $I_s = 60.1$ A, $I_{s1} = 59.7$ A, DPF = 0.576, PF =
0.572, THD = 12.3%



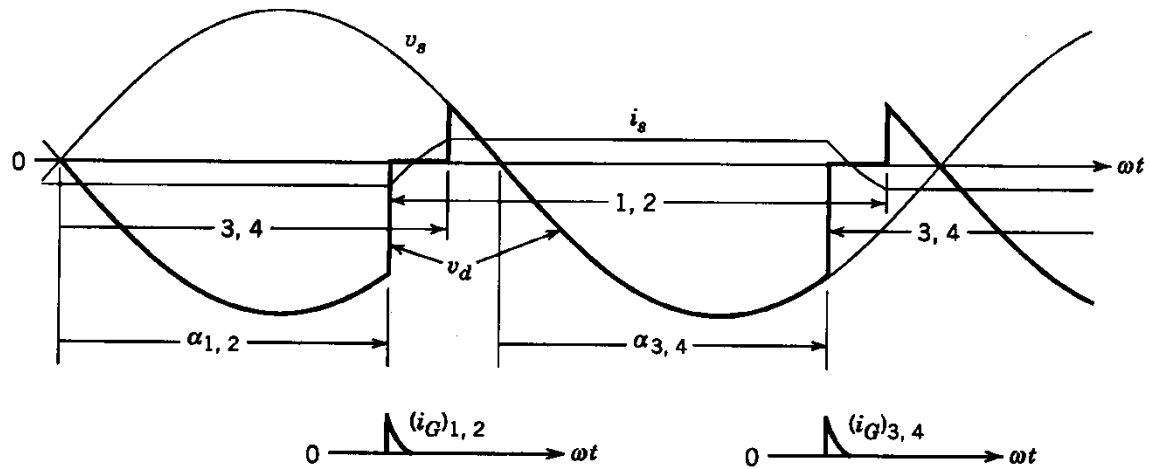
DC Voltage versus Load Current



Inverter Mode ($\alpha > 90^\circ$)

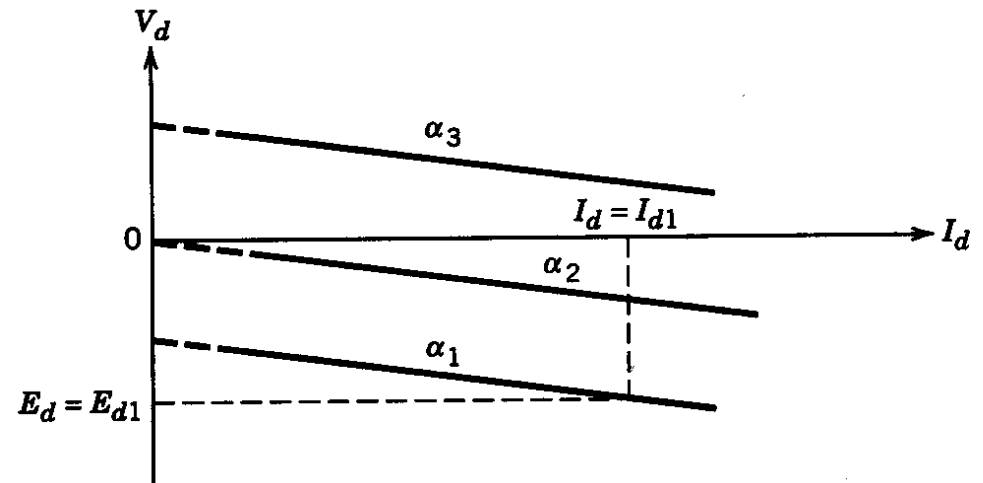
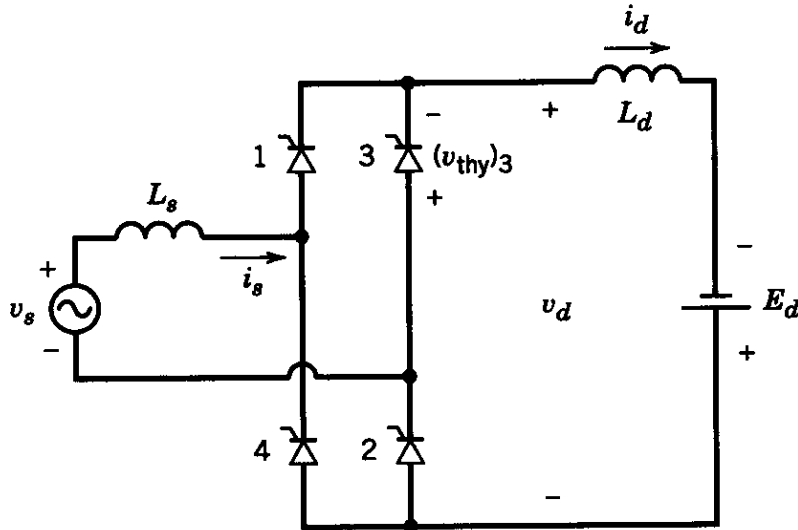


(a)



(b)

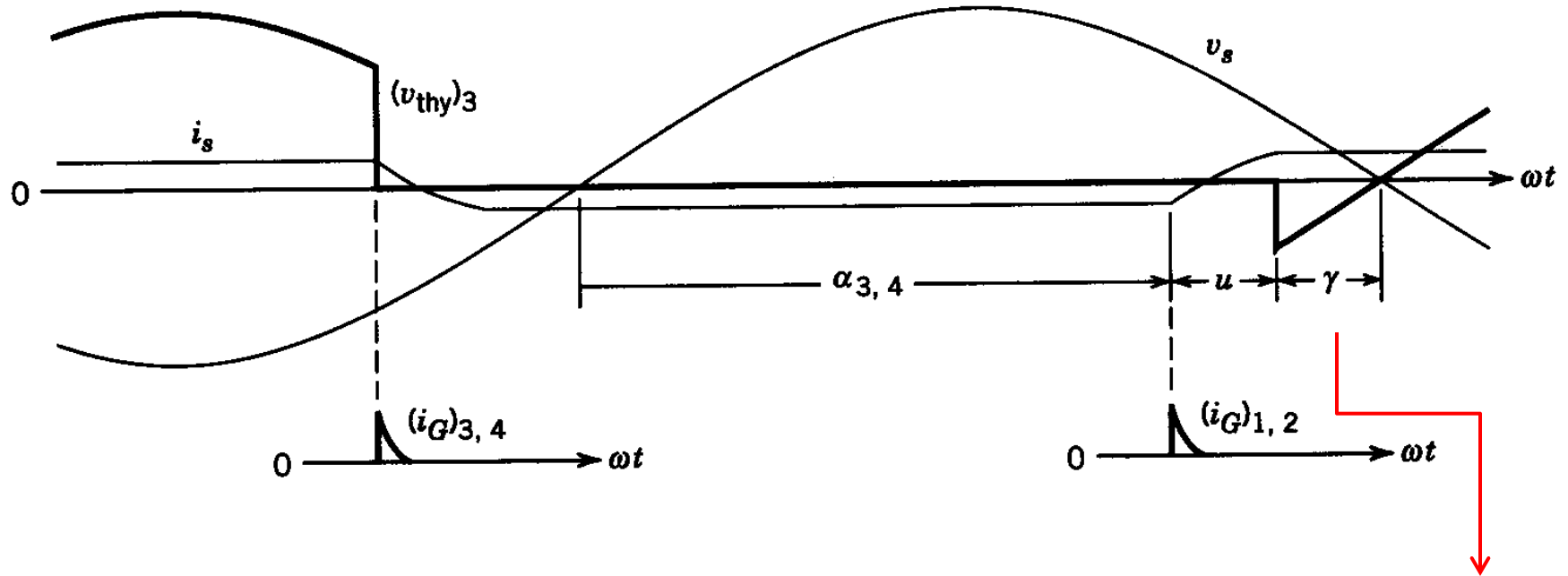
Inverter Mode with DC Voltage Source



- For a large value of L_d , i_d can be assumed constant ($= I_d$), then

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

Inverter Mode: Extinction Angle

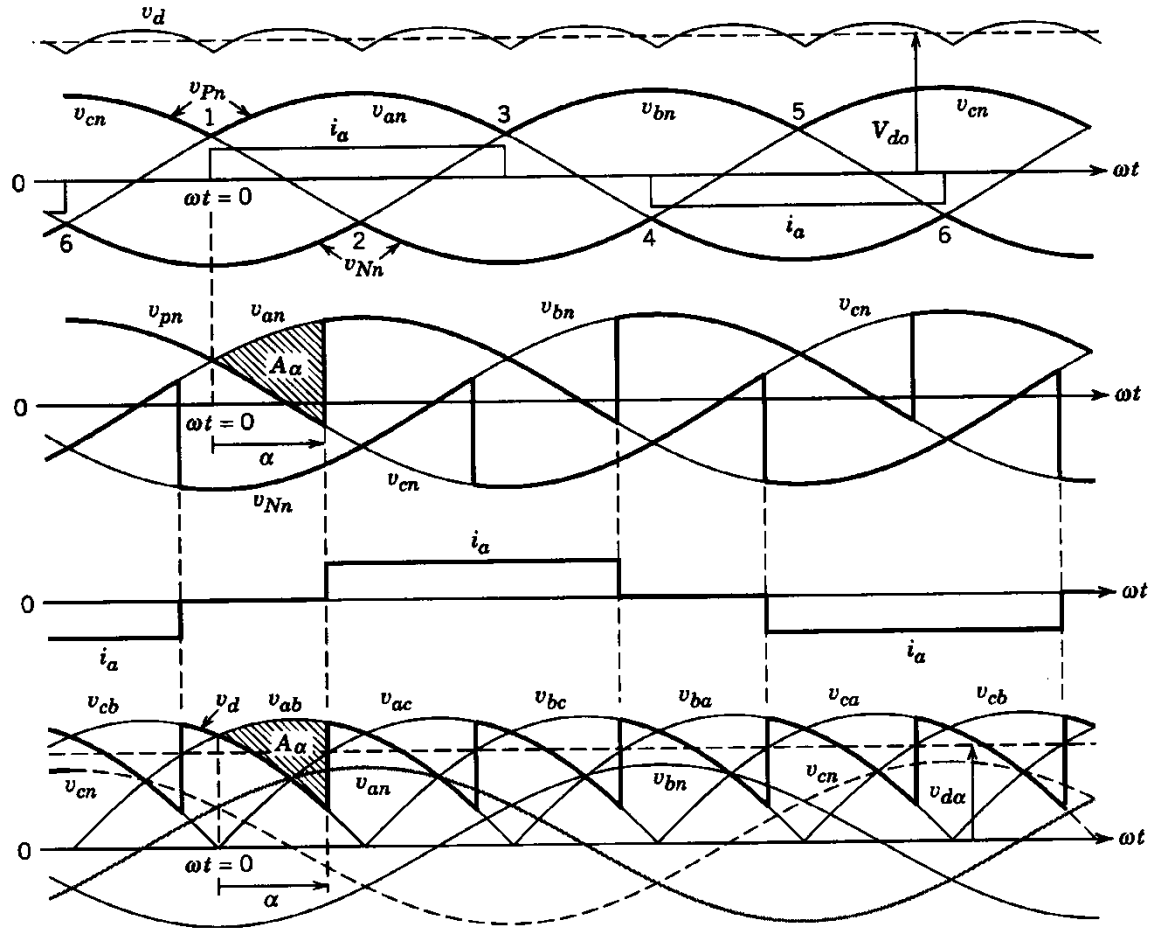
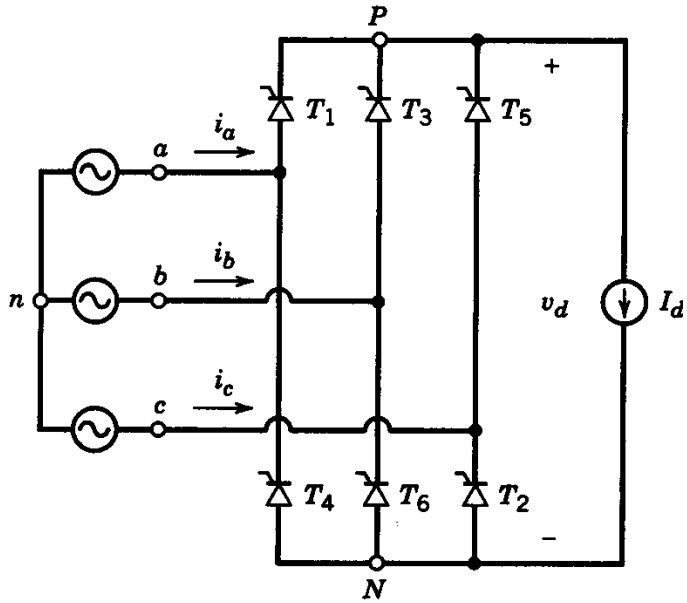


$$\gamma = 180^\circ - (\alpha + \mu)$$

Importance of extinction angle in inverter mode: The extinction time interval should be greater than the thyristor turn-off time:

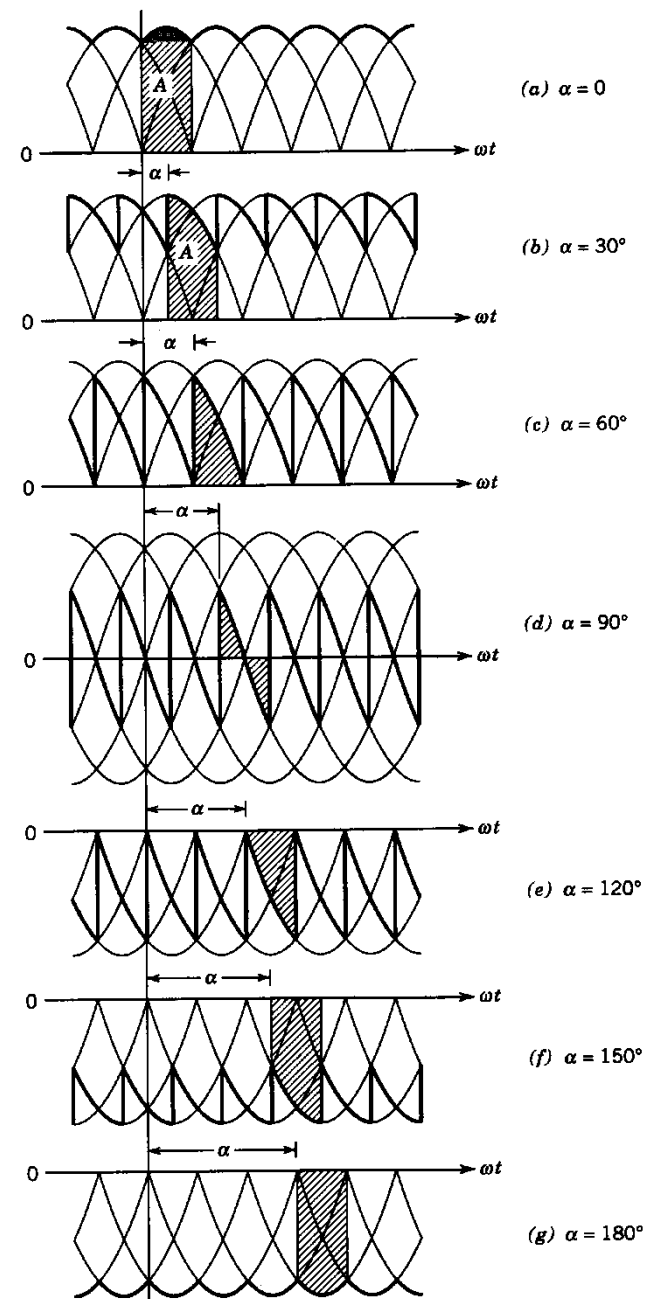
$$t_\gamma = \frac{\gamma}{\omega} > t_q$$

3-Phase Thyristor Converters: Simplified Case

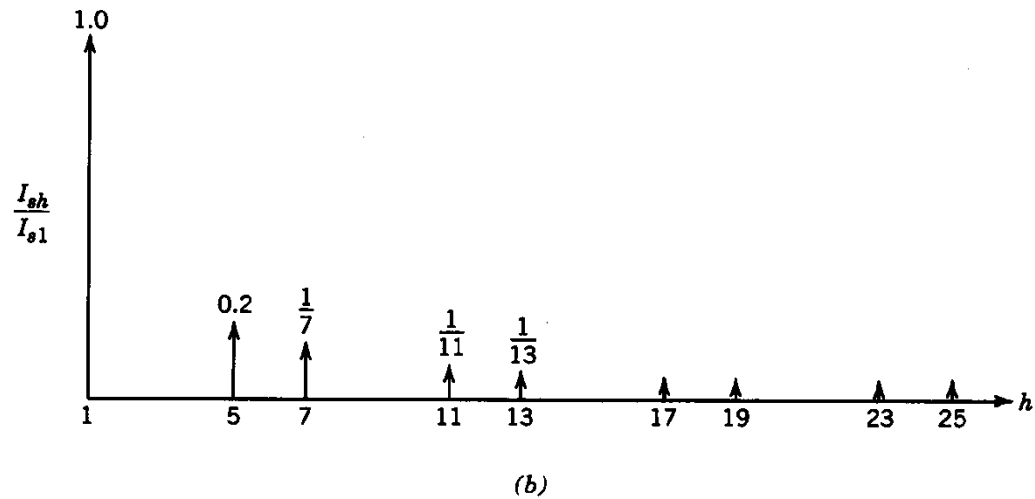
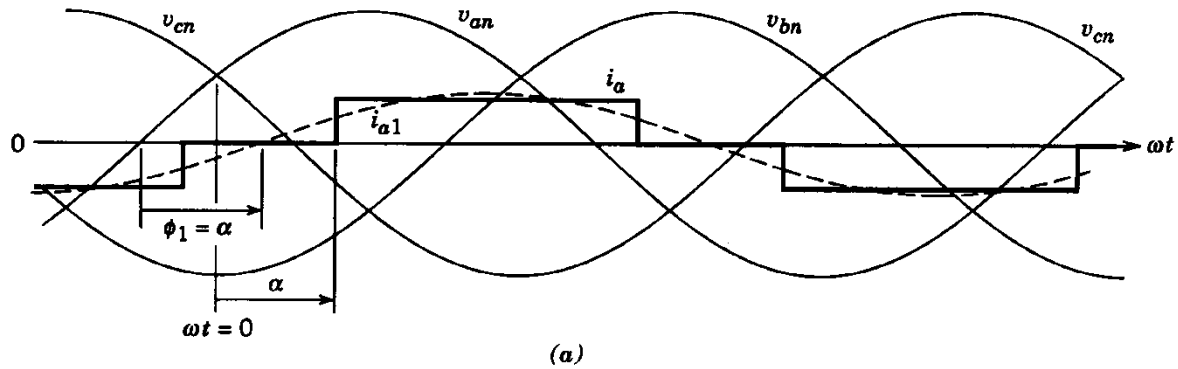


DC-side voltage waveforms assuming zero ac-side inductance

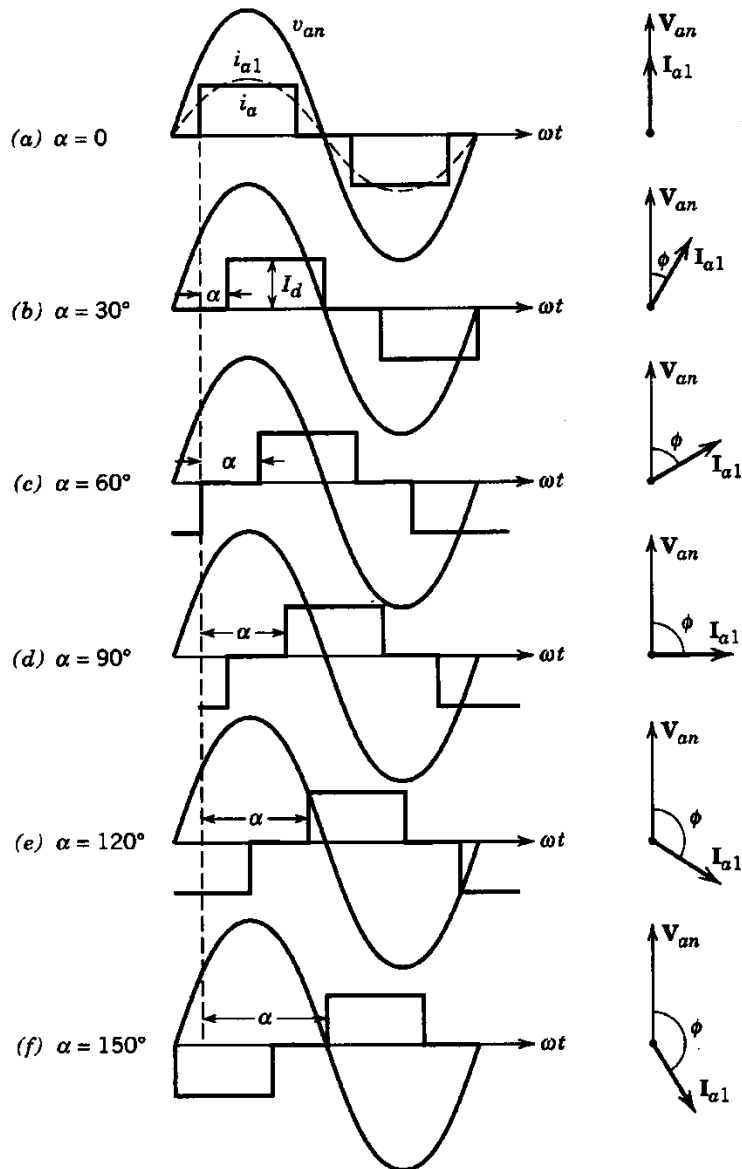
$$\begin{aligned}
 V_d &= V_{do} \cos \alpha \\
 &= \frac{3}{\pi} \sqrt{2} V_{LL} \cos \alpha \\
 &= 1.35 V_{LL} \cos \alpha
 \end{aligned}$$



Input Line-Current Waveform



Input line-current waveforms assuming zero ac-side inductance



$$I_s = \sqrt{2/3} I_d = 0.816 I_d$$

$$I_{s1} = (\sqrt{6} / \pi) I_d \approx 0.78 I_d$$

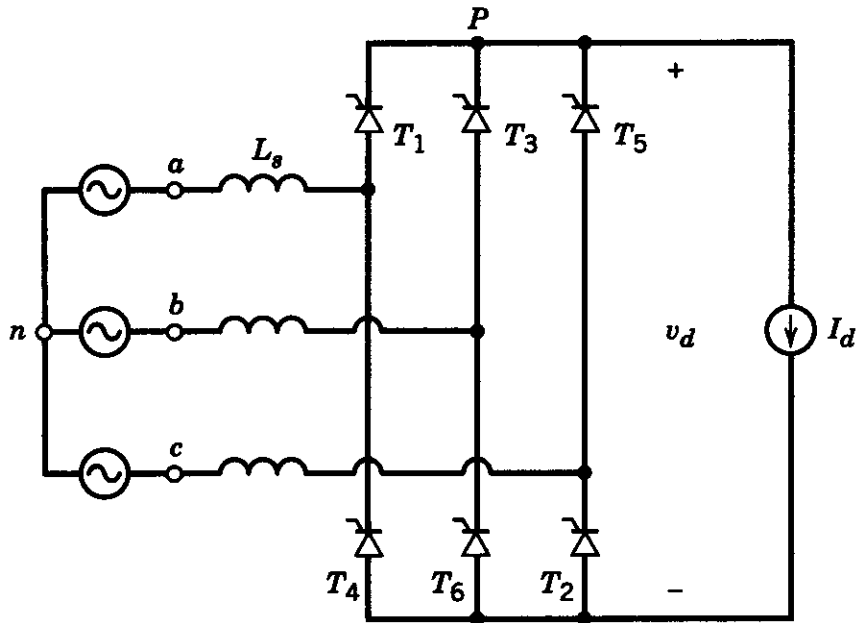
$$I_{sh} = I_{s1} / h, \quad h = 3, 5, 7, \dots$$

$$THD = 100[\sqrt{(\pi^2 / 9) - 1}] = 31\%$$

$$DPF = \cos \alpha$$

$$PF = \frac{3}{\pi} \cos \alpha = 0.955 \cos \alpha$$

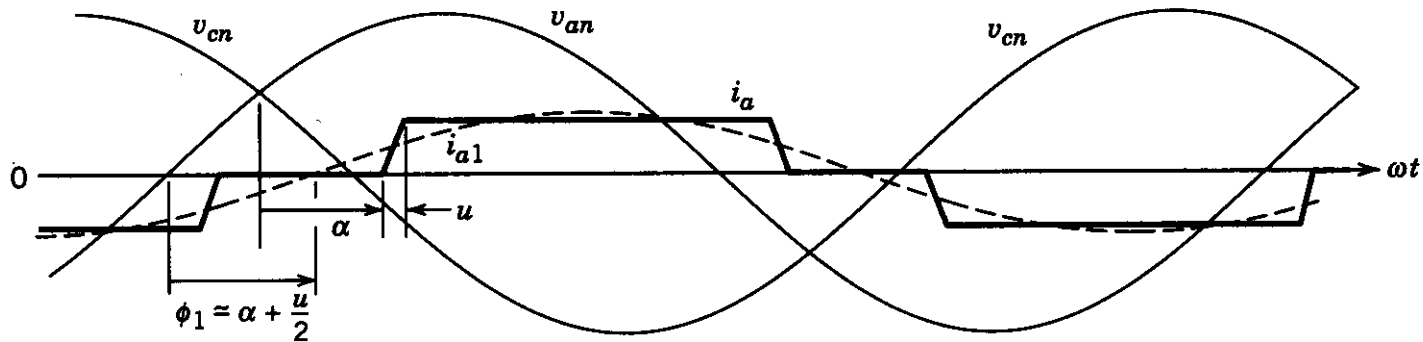
3-Phase Thyristor Converter with AC-side Inductance



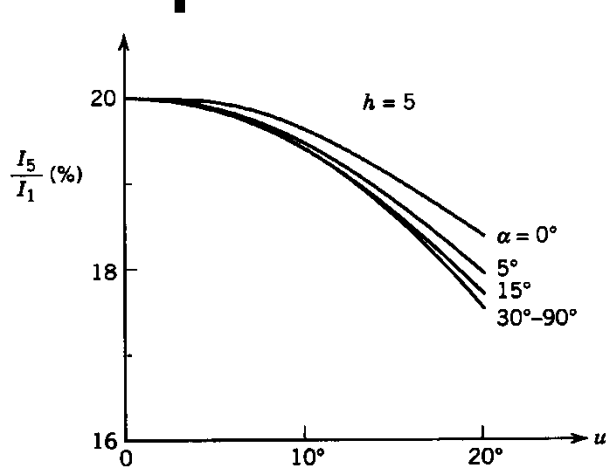
$$\cos(\alpha + \mu) = \cos \alpha - \frac{2\omega L_s I_d}{\sqrt{2}V_{LL}}$$

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

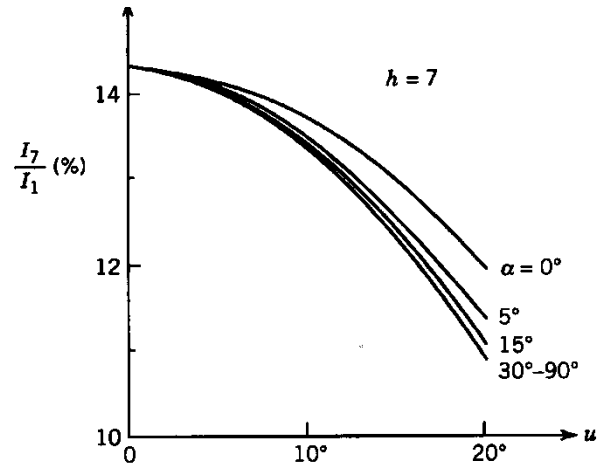
$$DPF \approx \cos(\alpha + 0.5\mu)$$



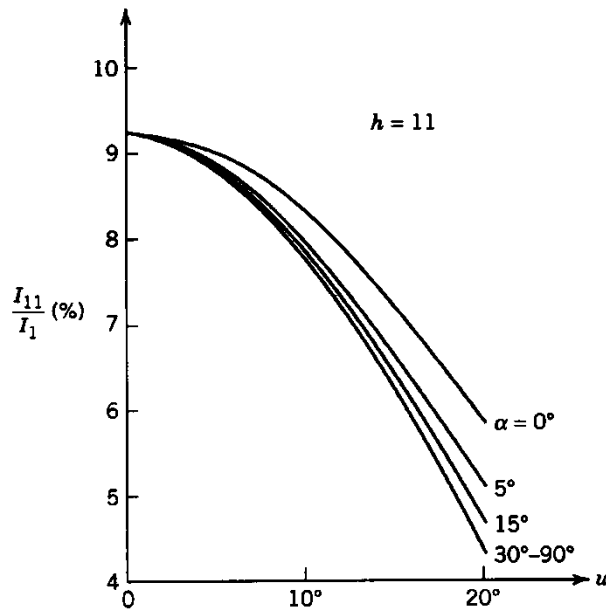
Input Line-Current Harmonics



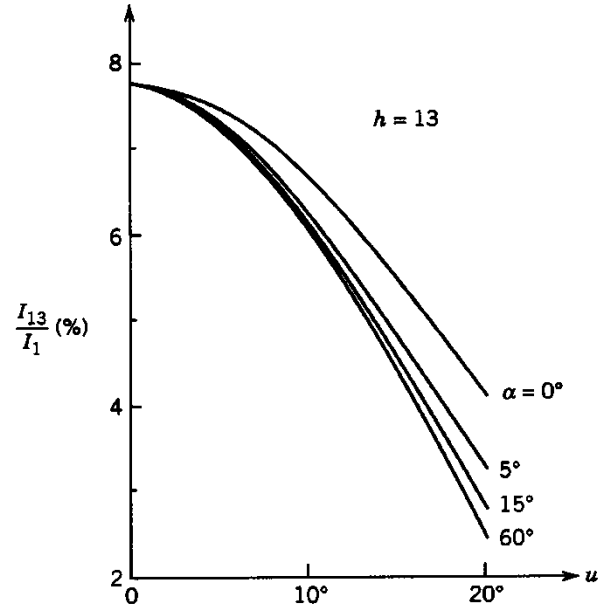
(a)



(b)



(c)



(d)

Input Line-Current Harmonics

	h	5	7	11	13	17	19	23	25
Typical	I_h/I_1	0.17	0.10	0.04	0.03	0.02	0.01	0.01	0.01
Idealized	I_h/I_1	0.20	0.14	0.09	0.07	0.06	0.05	0.04	0.04

Typical Passive Filter Block (for each phase)

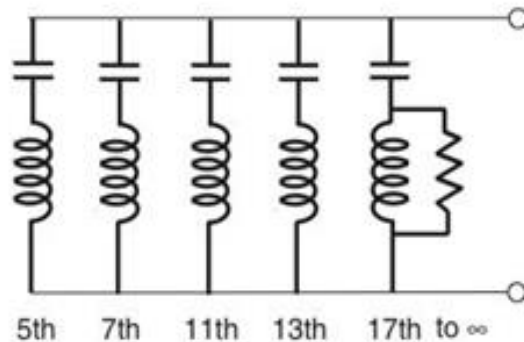
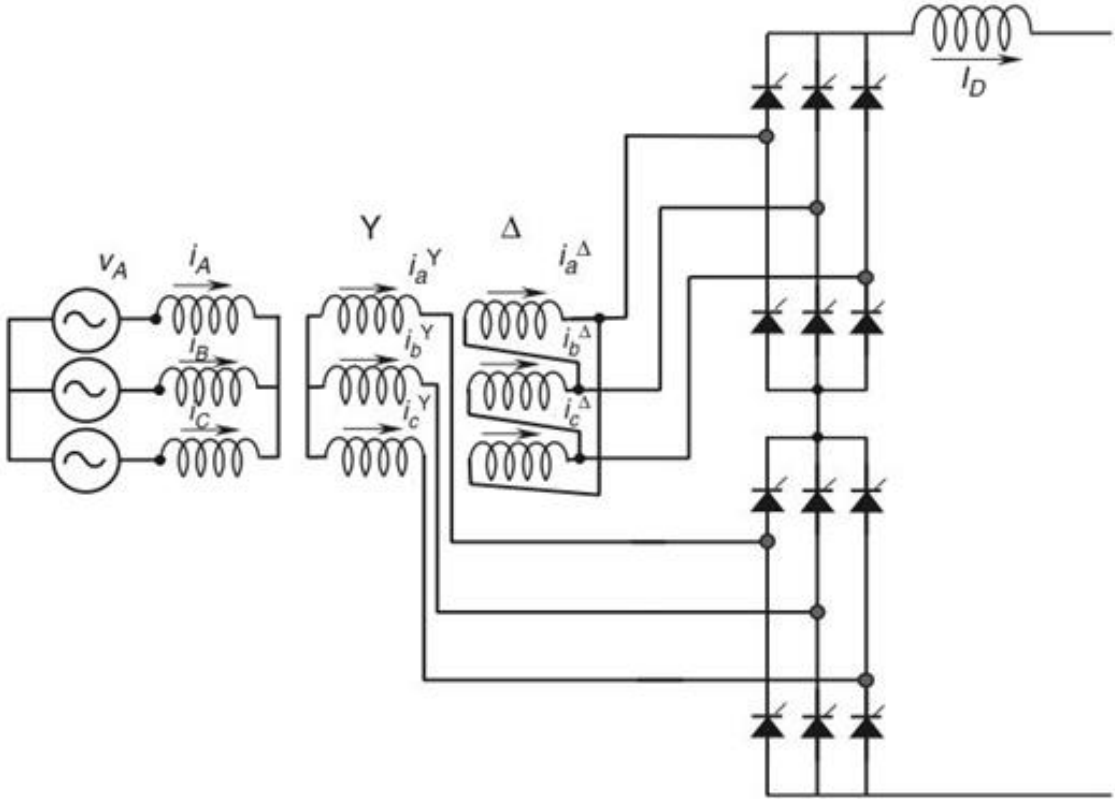


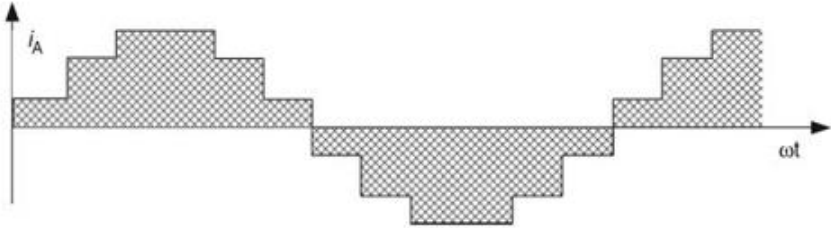
TABLE 12.1 Harmonic current limits in percent of fundamental

Short circuit current (pu)	$h < 11$	$11 < h < 17$	$17 < h < 23$	$23 < h < 35$	$35 < h$	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

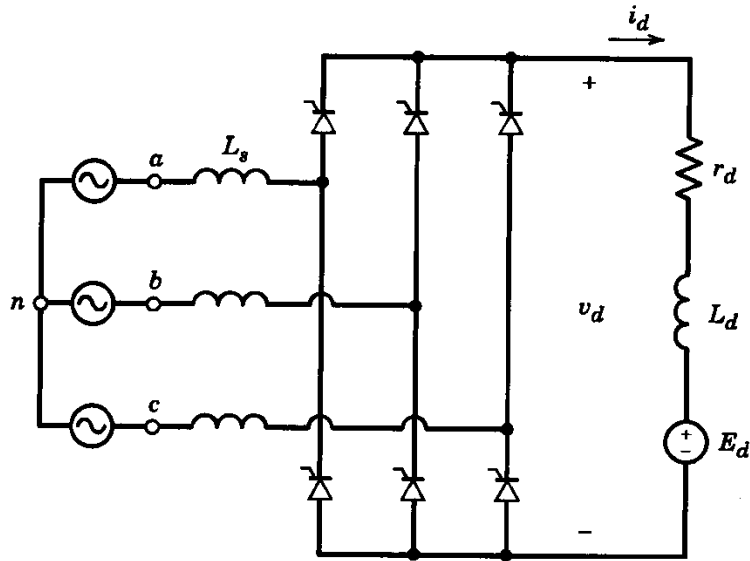
12-Phase Phase Controlled Rectifier



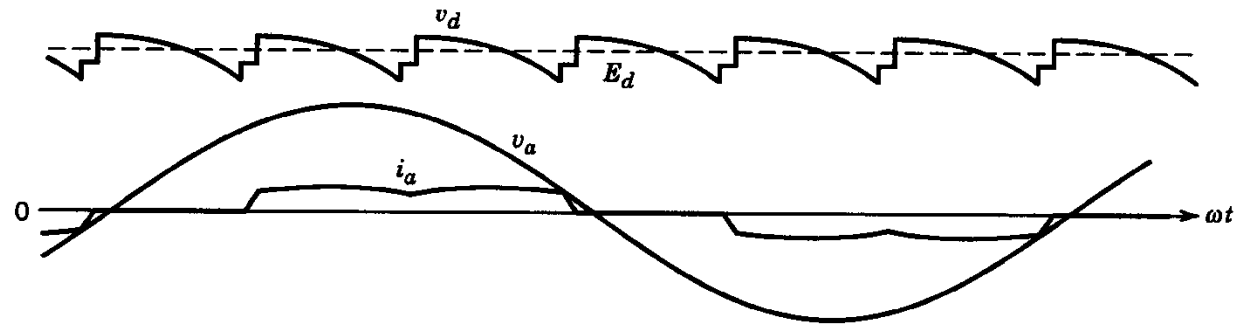
Harmonic Order: 1, 11, 13, 23, 25, ...



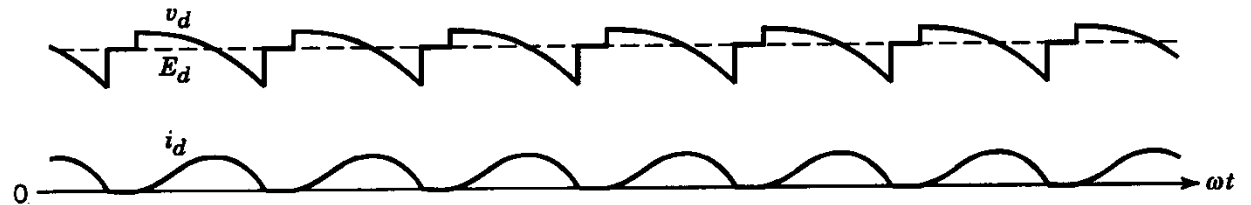
3-Phase Thyristor Converter with Realistic Load



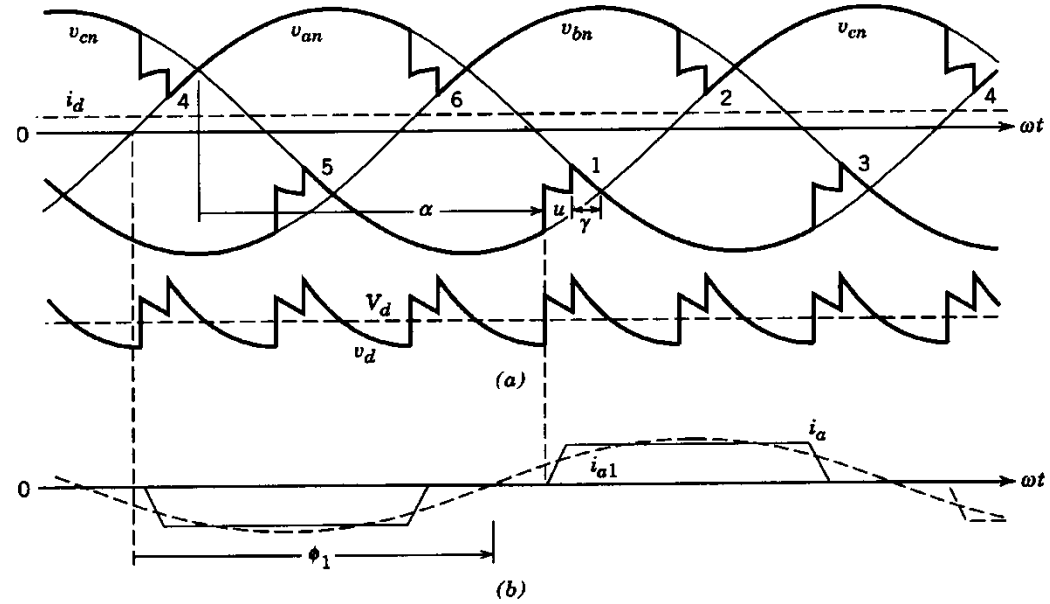
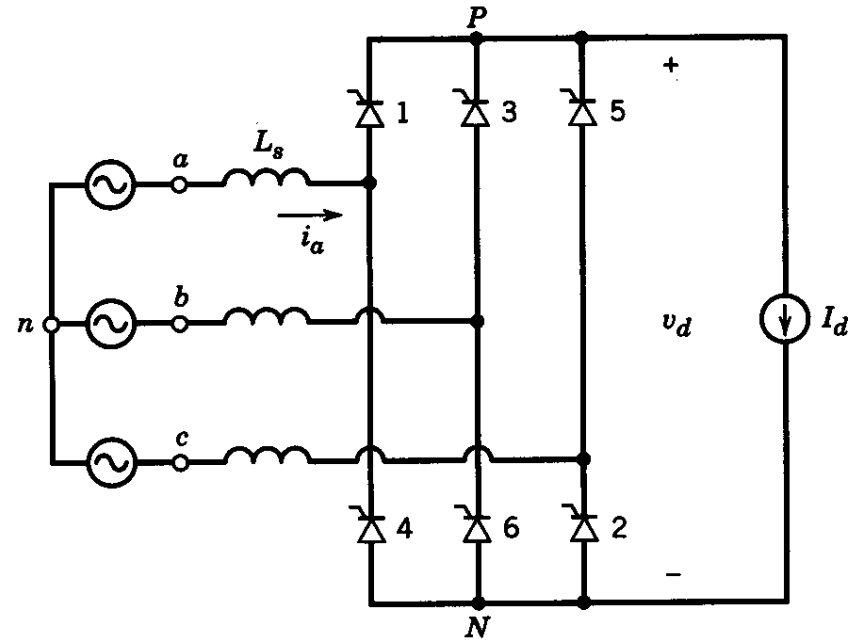
Continuous conduction Mode



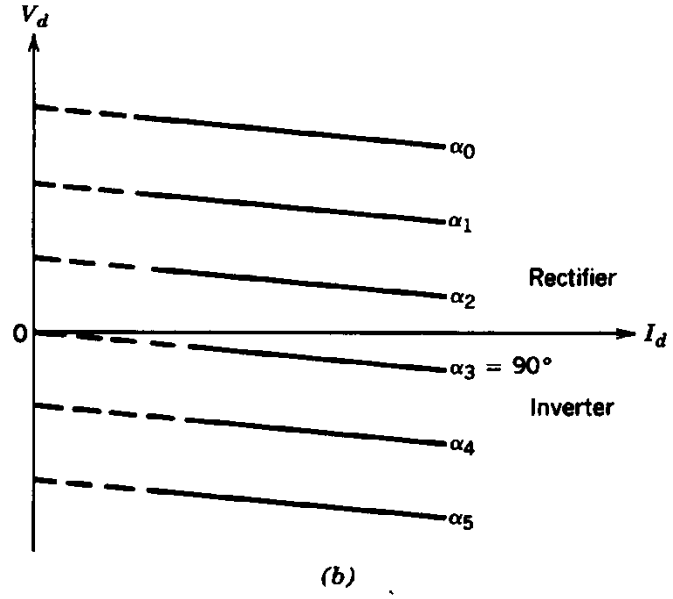
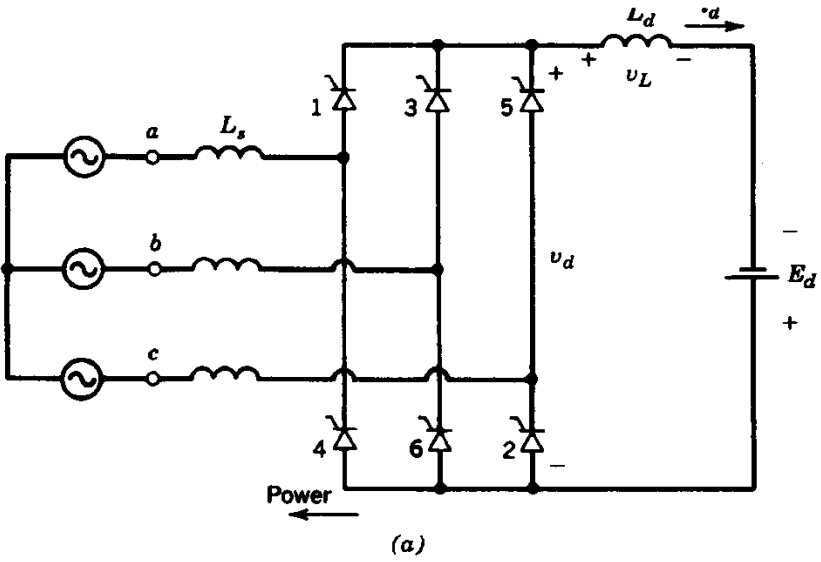
Discontinuous conduction mode



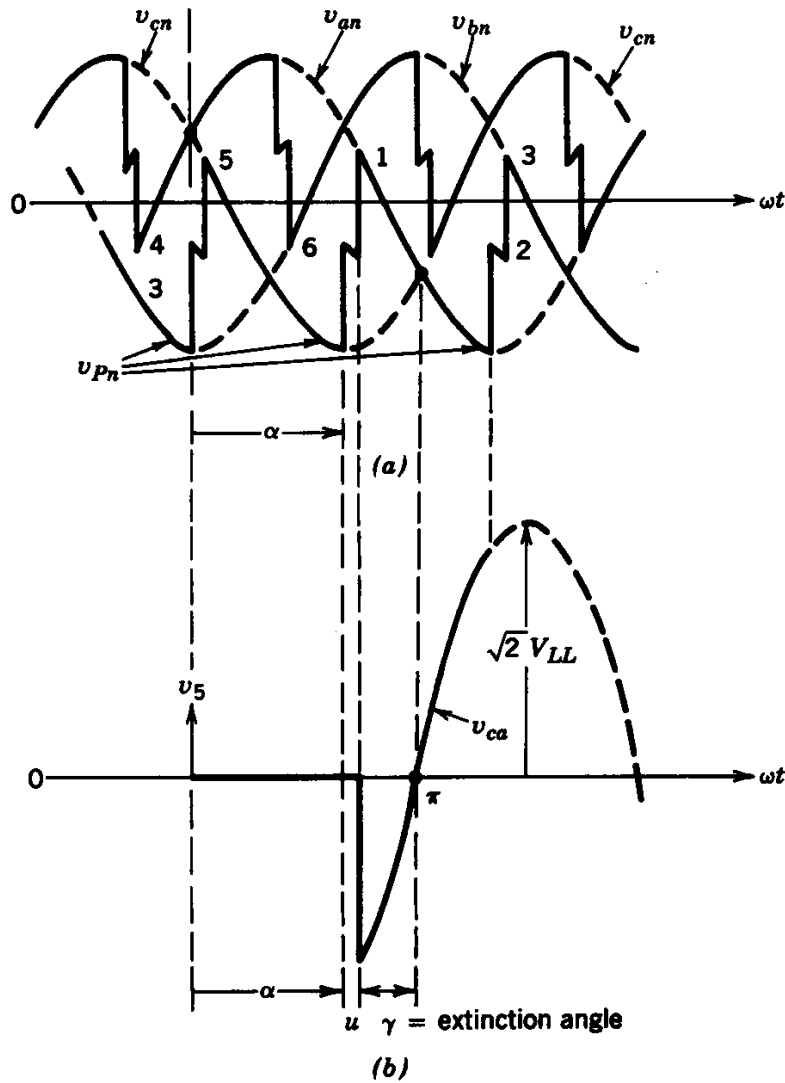
3-Phase Thyristor Inverter – Constant Current



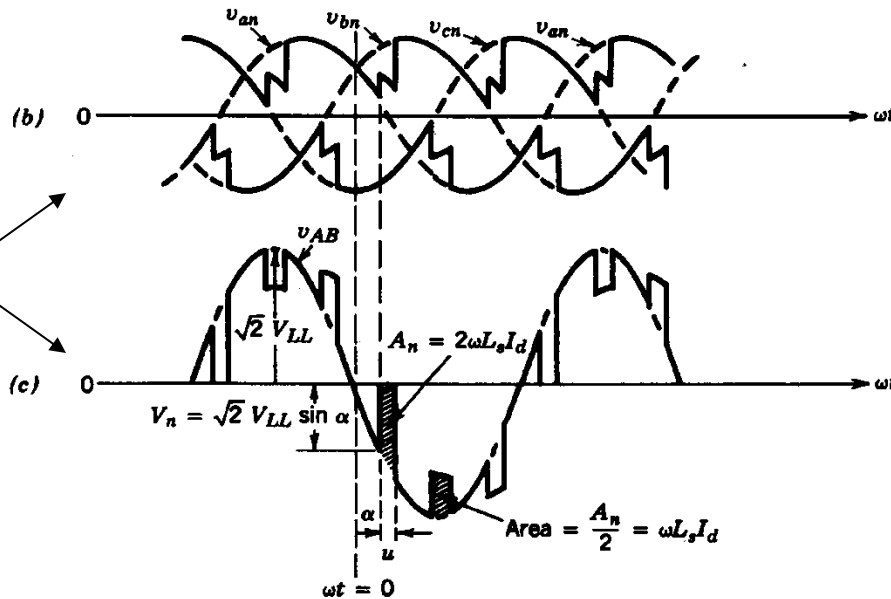
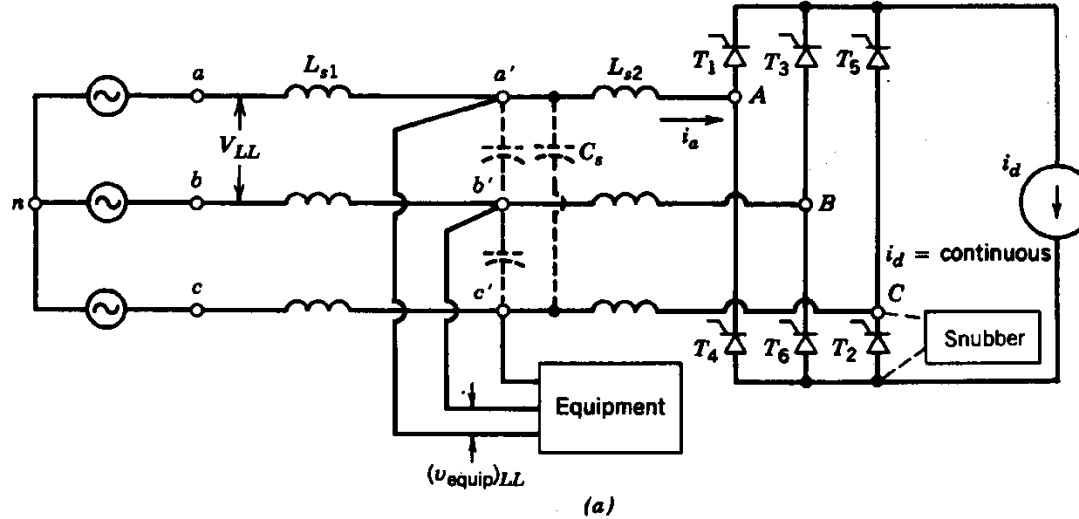
Thyristor Inverter – Constant Voltage & Current



Thyristor Inverter Operation: Extinction Angle



Thyristor Converters: Voltage Notching



$$L_{s1} = L_s$$

$$L_{s2} = 0$$

Depth: $V_n = \sqrt{2}V_{LL} \sin \alpha$

Area: $A_n = 2\omega L_s I_d$

Width: $\mu \approx \frac{2\omega L_s I_d}{\sqrt{2}V_{LL} \sin \alpha}$

Limits on Notching and Distortion

In practice, the notch depth at PCC depends on L_{s1} relative to L_{s2} . Let depth factor be defined by

$$\rho = \frac{L_{s1}}{L_{s1} + L_{s2}}$$

Given L_{s1} , a higher value of L_{s2} results in a smaller notch.

<i>Class</i>	<i>Line Notch Depth</i> $\rho(\%)$	<i>Line Notch Area</i> $(V \cdot \mu s)$	<i>Voltage Total</i> <i>Harmonic Distortion</i> $(\%)$
Special applications	10	16,400	3
General system	20	22,800	5
Dedicated system	50	36,500	10