Chapter 1

Power Devices

a power device ~ a switch

Switch States:

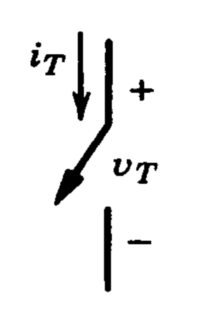
on state (static) i ratings (RMS)

off state (static) v ratings (forward and reverse peak)

commutation states (dynamic) switching t or f ratings

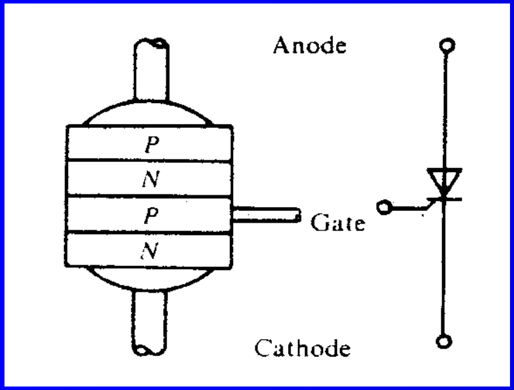
A Power Switching Device

* i flow in one direction only
* can withstand a forward v (except diodes)
* can be turned on or off (except diodes) by a relatively small controlling i or v

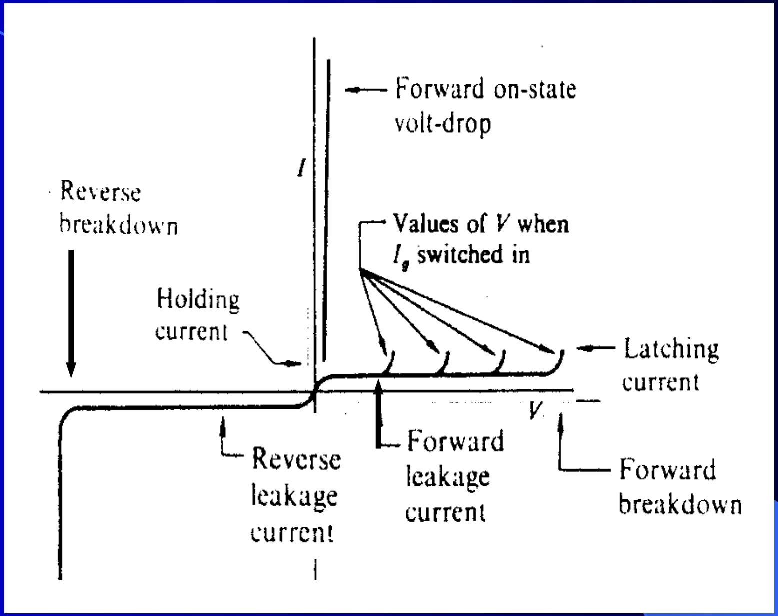


Idealized semiconductor switch symbol

Thyristor (SCR)



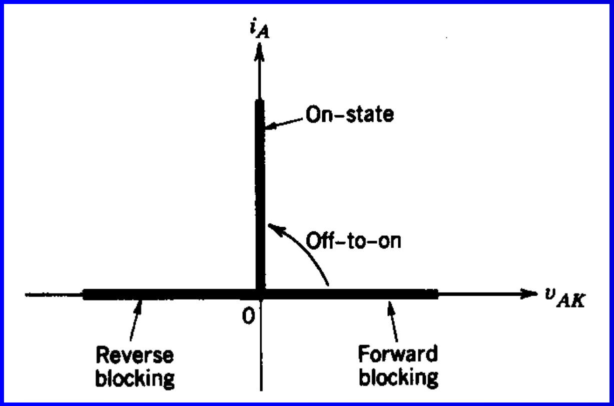
Structure and symbol



Thyristor Characteristics

$V_{on\text{-}state}$ ~ 1-3V

forward breakdown *v* ~ reverse breakdown *v*

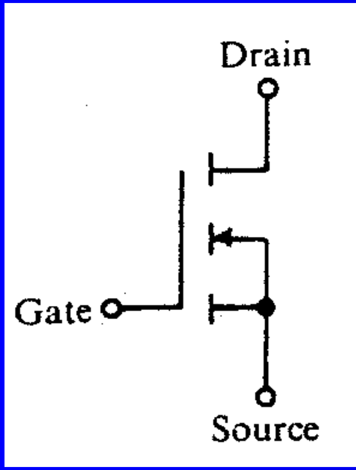


Idealized Characteristics

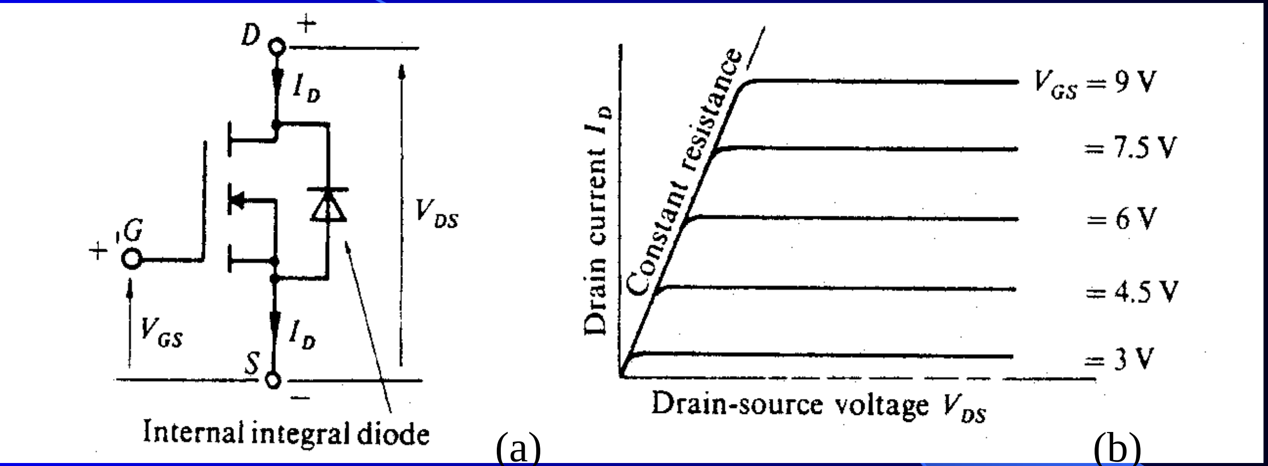
Semi-controlled device

- Turns on by a gate-*i* pulse if forward biased
- Turns off if *i* tries to reverse like the diode

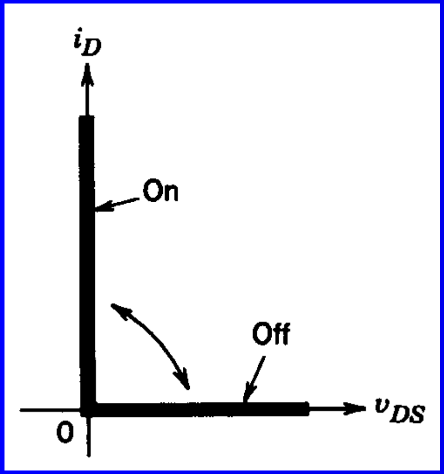
Power MOSFET



Symbol



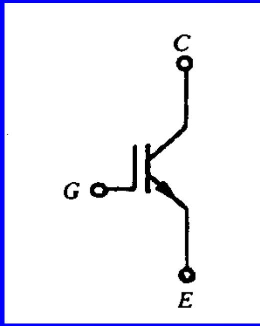
(a) Electrical circuit. (b) Output characteristic.



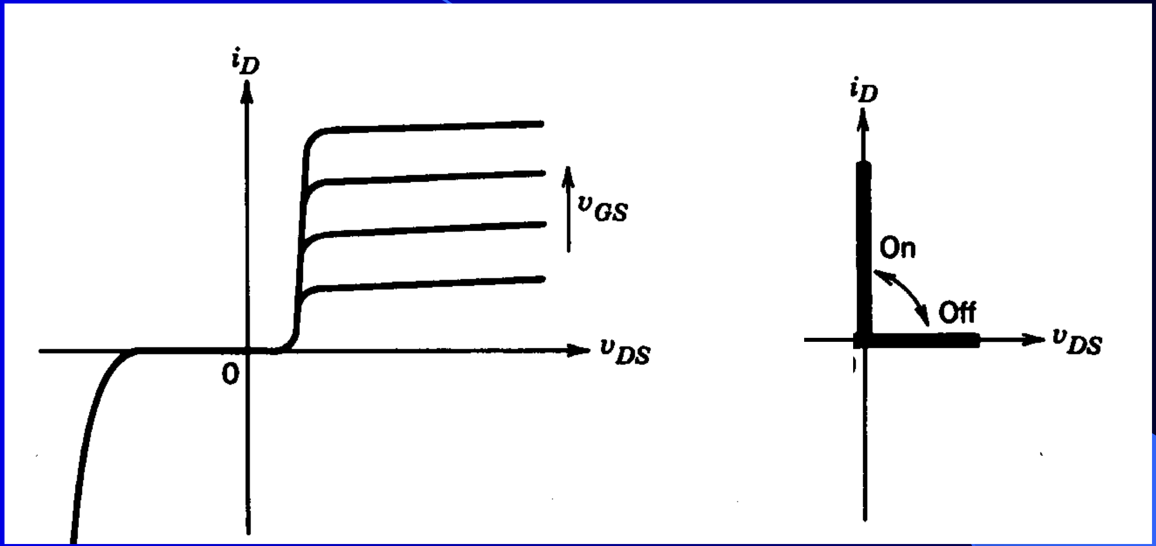
Idealized Characteristics

- Unipolar power semiconductor
- Easy gate control — voltage controlled
- High switching f — without stored charge
- High on-state resistance
  — a concern at high voltage ratings

IGBT (Insulated Gate Bipolar Transistor)



Symbol



i-v Characteristic. Idealized Characteristics

The collector-emitter characteristics are similar to those of the BJT but the control features are those of the MOSFET.

used most widely nowadays in low and medium power applications.

Device Comparisons

Based on the ideal characteristics:

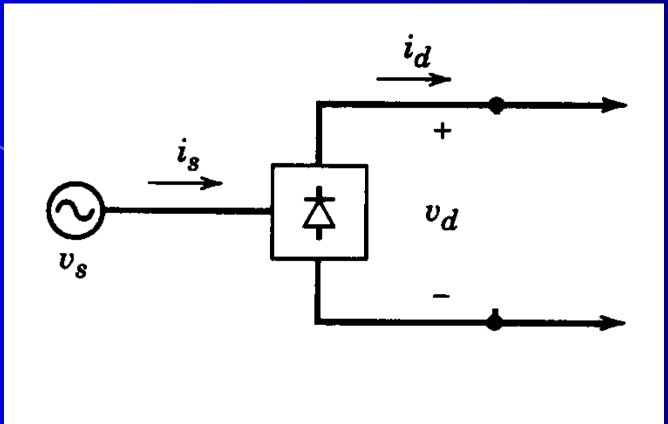
1. Controlled turn-on & –off	voltage-controlled:	MOSFET、IGBT
	current-controlled:	SCR (semi-controlled)
2. Unlimited voltage & current ratings	high:	SCR
	medium:	IGBT
	low:	MOSFET
3. Zero conduction loss	low :	SCR
	medium:	IGBT
	high :	MOSFET
4. Instant turn-on and –off times	high:	MOSFET
	medium:	IGBT
	low:	SCR
5. Zero gate firing power requirement	low :	MOSFET、IGBT
	medium:	SCR

Chapter 2

Diode Rectifiers

a line-frequency diode rectifier:

a line-frequency AC voltage $\rightarrow$ an uncontrolled DC voltage



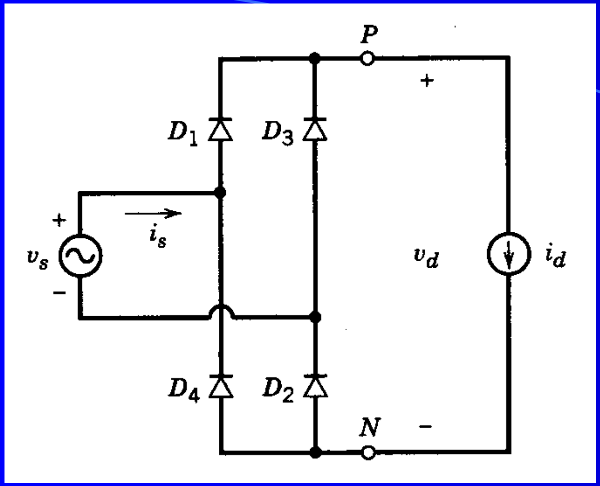
Uncontrolled utility interface (AC to DC)

DC voltages: a mean (DC) level + *an alternating ripple*

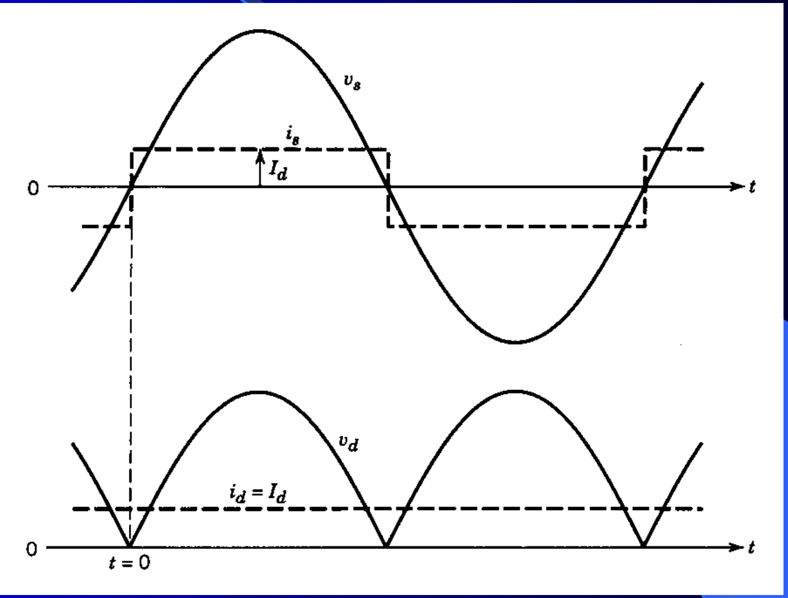
AC currents: non-sinusoidal

$\gamma_f = f_{R(rms)} / f_{mean}$ — ripple factor (DC voltage)

$\xi_f = f_{1(rms)} / f_{rms}$ — distortion factor (AC current)



Inductive Load (R-L)



Load: idealized inductive

$$V_d = 2V_{smax}/\pi$$

$$I_{s1} = 0.9I_d$$

PF (power factor) = 0.9

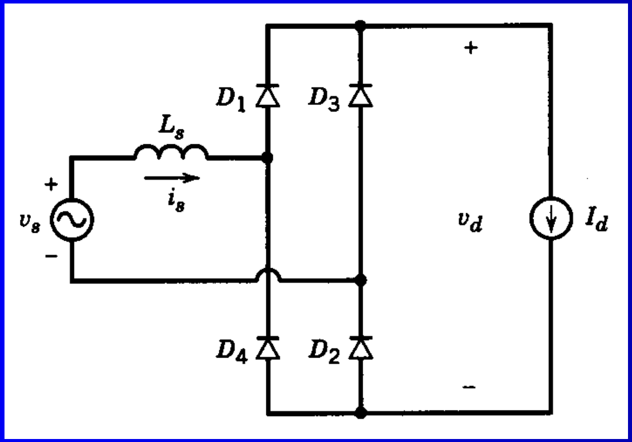
DC output: voltage, current waveforms (v_d, i_d)

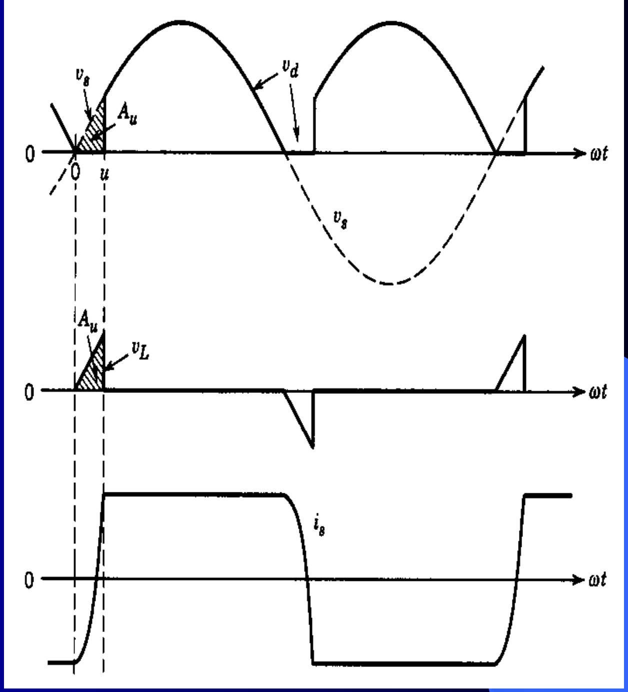
AC input: current waveforms (v_s, i_s)

Devices: current, voltage waveforms (v_{diode}, i_{diode})

Circuit analysis with ac-side inductance

Understanding current commutation



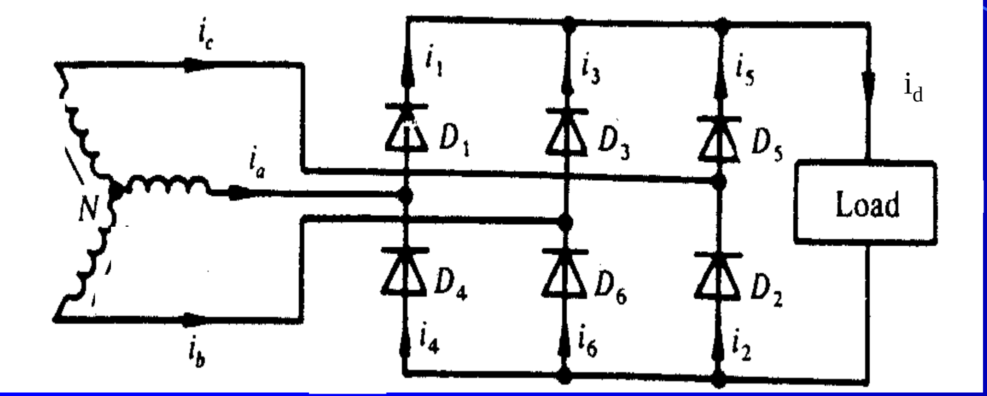


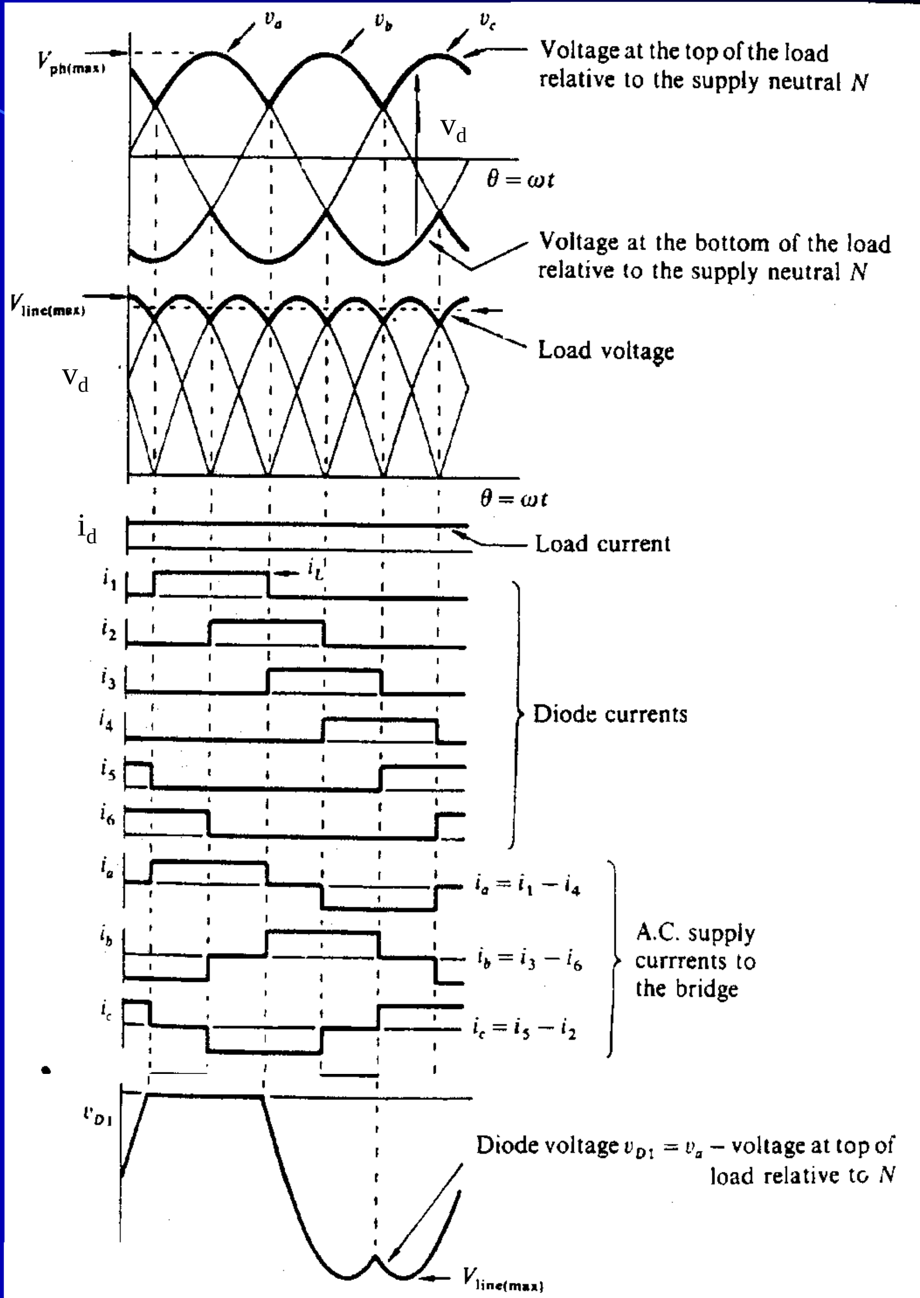
$$i_s = V_{smax}/(\omega L_s) \bullet (1 - \cos\omega t) - I_d$$

u (overlap angle)

$$\cos u = 1 - 2\omega L_s I_d / V_{smax}$$

Three-phase bridge





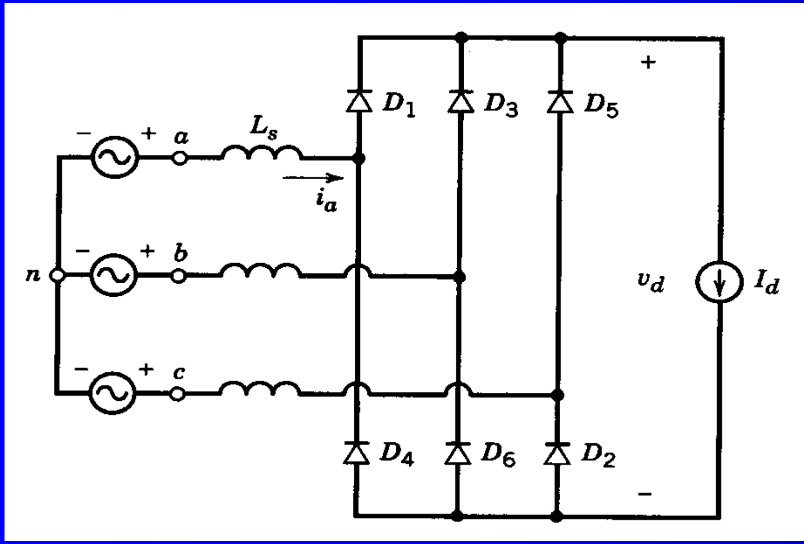
$$V_d = 3/\pi \ V_{line(max)}$$

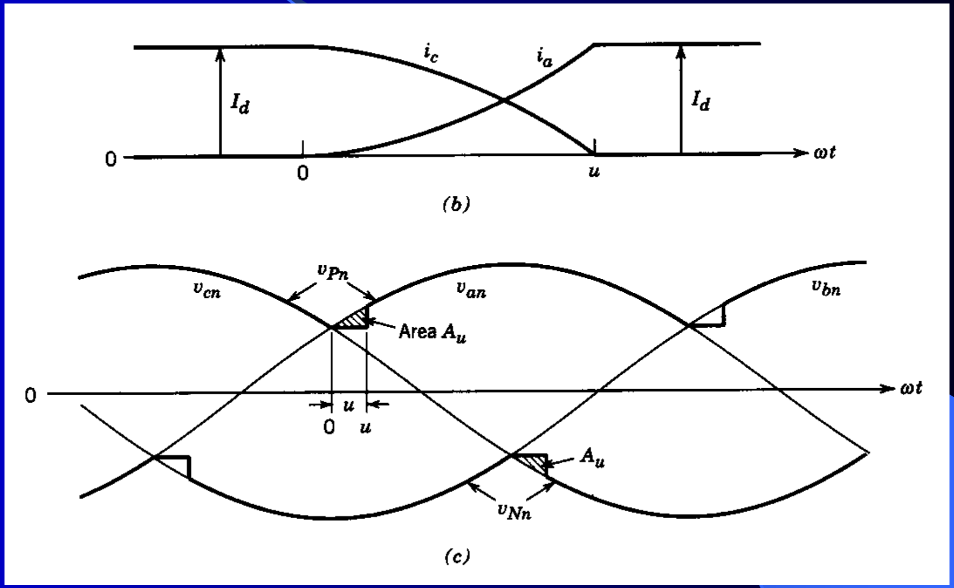
$$I_{s1} = 0.78 I_d$$

PF (power factor) = 0.955

Circuit analysis with ac-side inductance

Understanding current commutation





$$i_a = V_{line(max)}/(2\omega L_s) \bullet (1 - \cos\omega t)$$

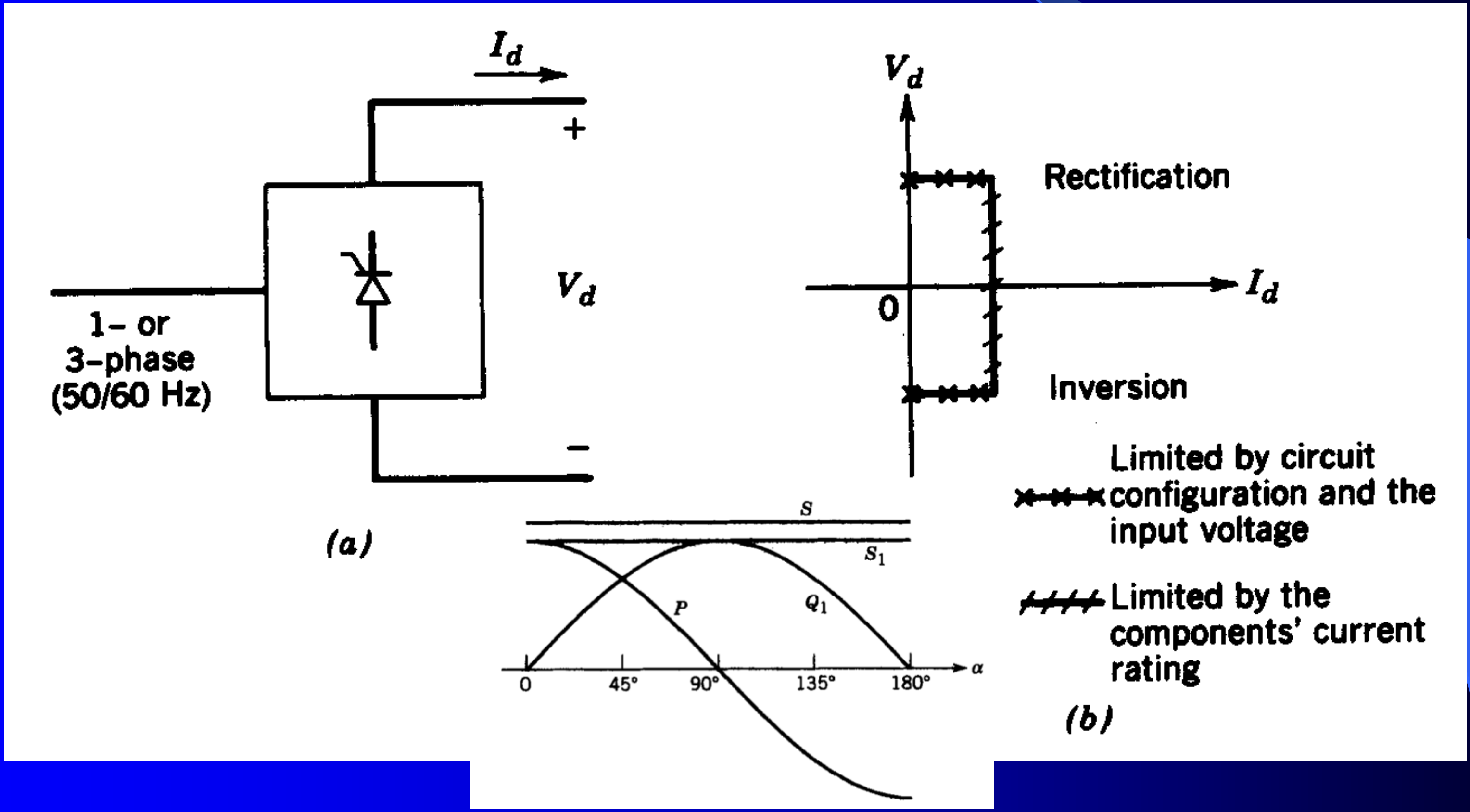
$$\cos u = 1\text{-}2XI_d/V_{line(max)}$$

Chapter 3

Thyristor
AC-DC Converters

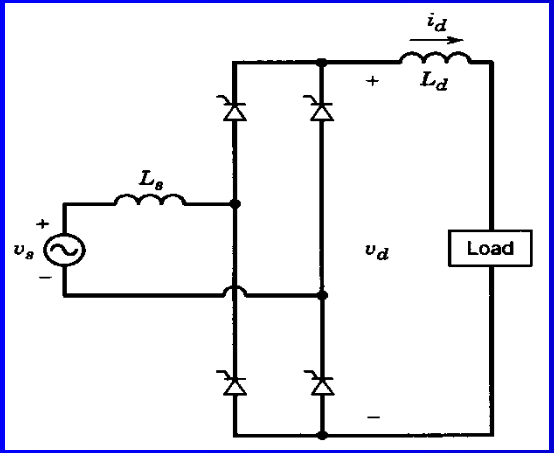
an AC voltage source— **an AC-DC converter** — DC

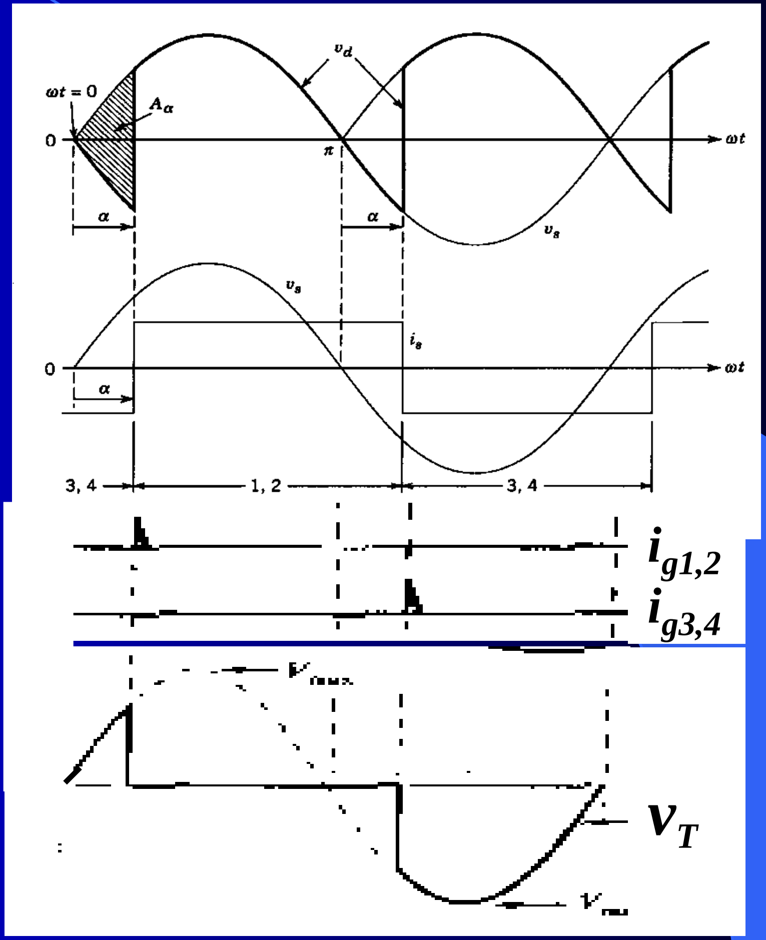
AC/DC Conversion: rectifying mode & inverting mode



Thyristor Converter - two-quadrant converter

Single-phase Bridge



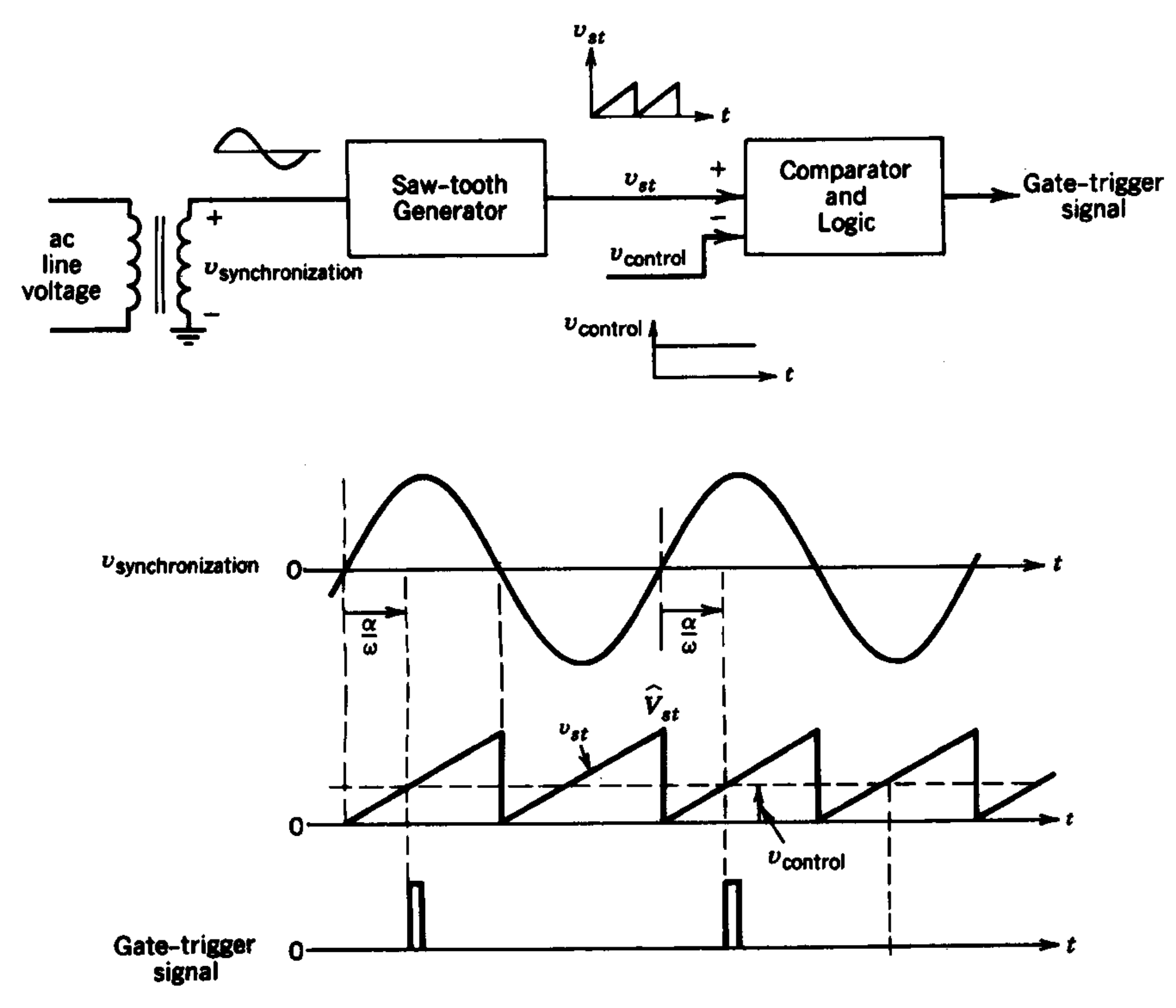


$$V_d = 2V_{smax}/\pi \bullet \cos\alpha$$

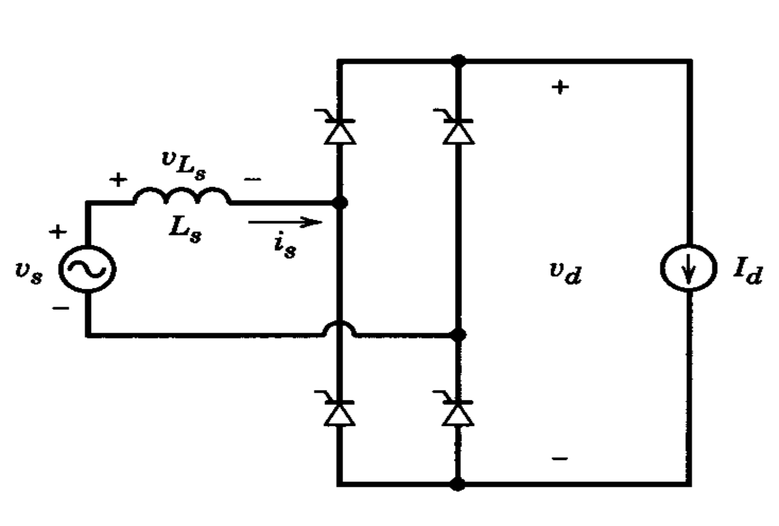
$$I_{s1} = 0.9I_d$$

$$PF = 0.9\cos\alpha$$

Thyristor Triggering



- ICs available

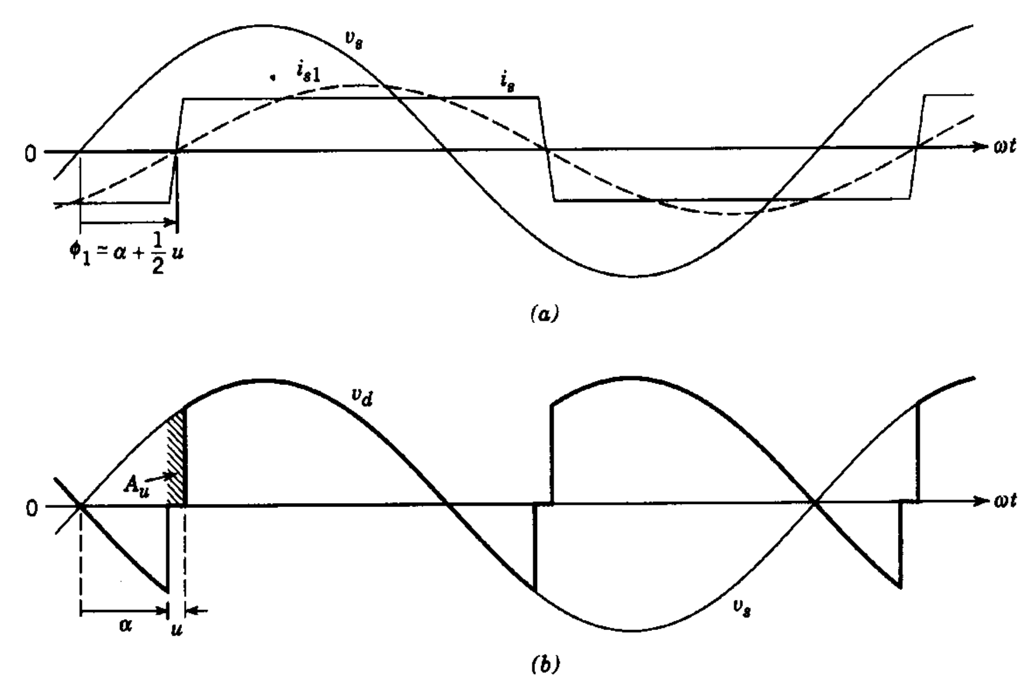


Finite ac-side inductance

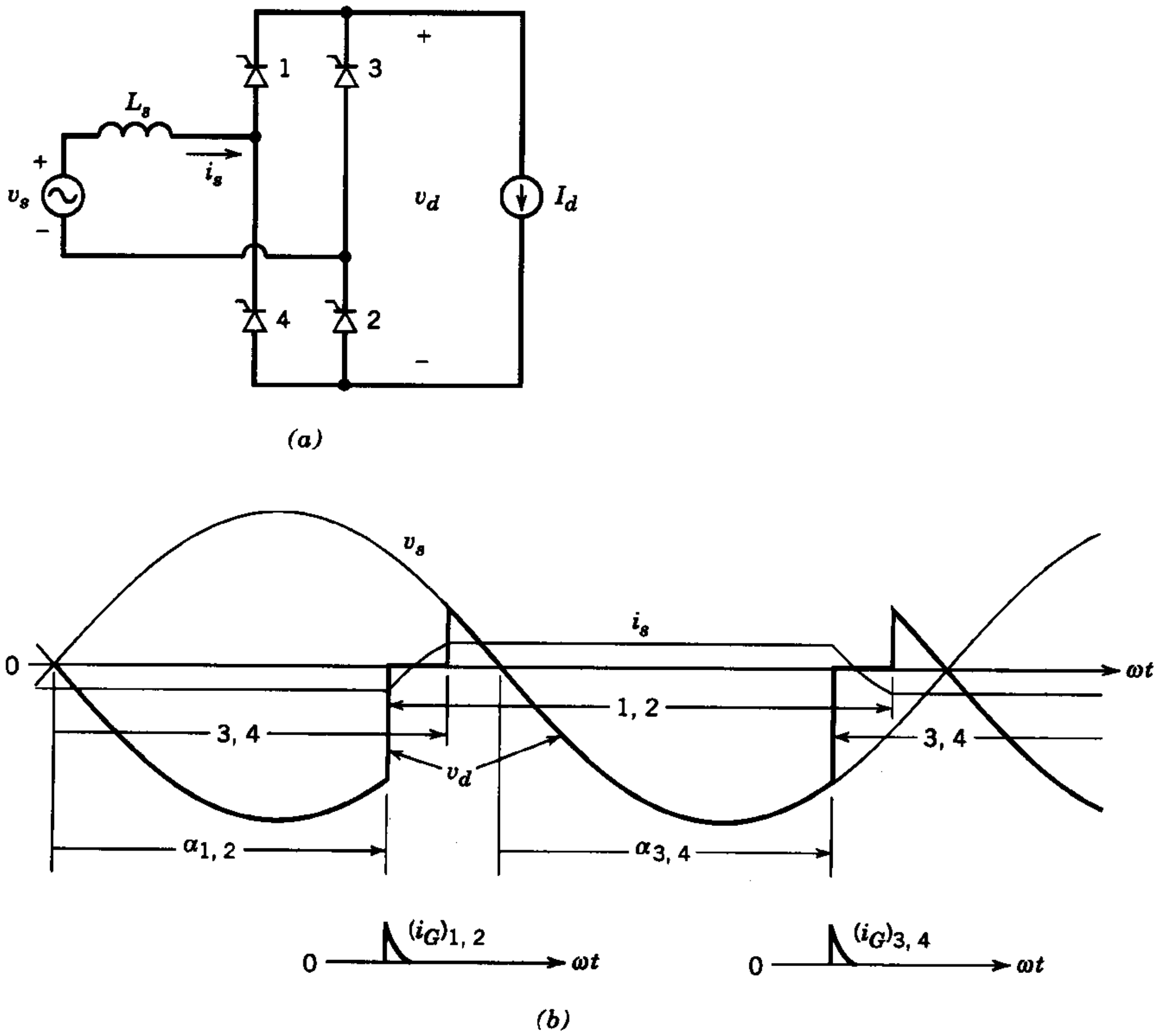
$$v_s = V_{smax}\sin(\omega t+\alpha) = L_s\, di_s/dt$$

$$[t = 0,\quad i_s = -I_d]$$

$$[\omega t = \boldsymbol{u},\quad i_s = I_d]$$



Inverting Mode (α > 90°)



extinction angle δ

$\delta = 180 - \alpha - u$

$\delta_{min} > 5°$

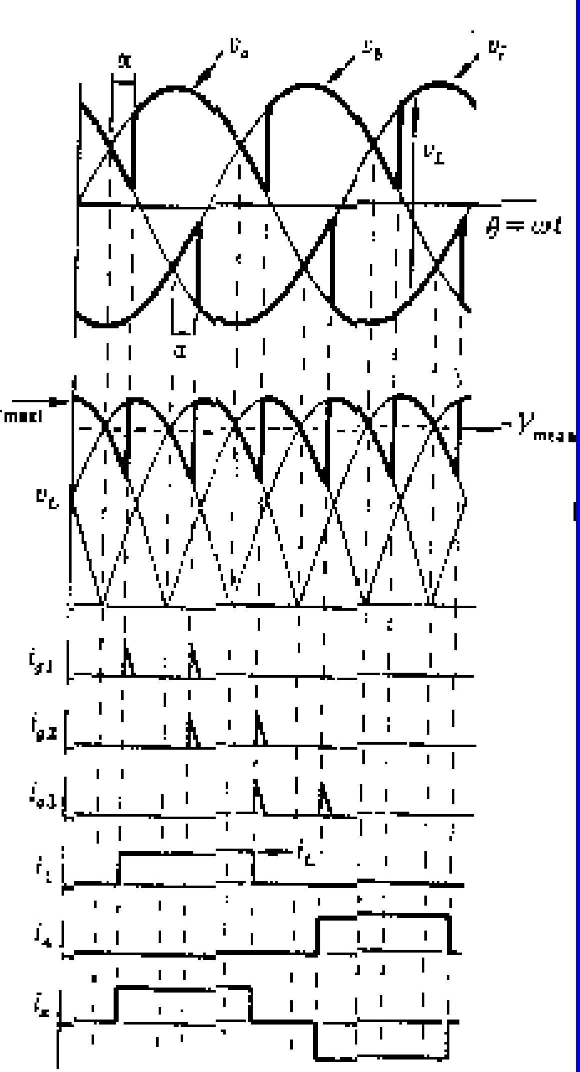
Rectifying mode:

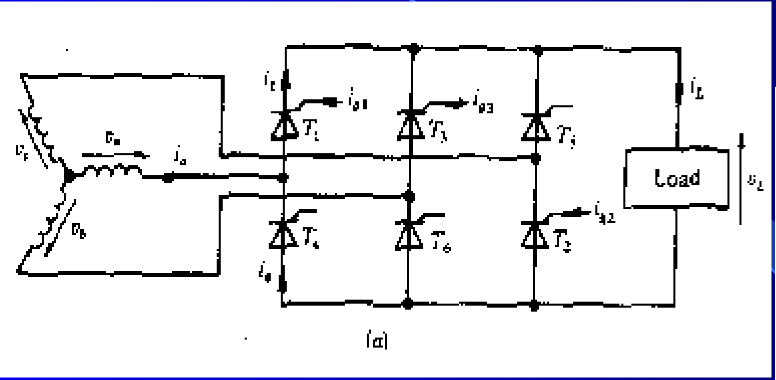
$\alpha < 90$

Inverting mode:

α: $90 \sim 180 - \delta_{min}$

Three-phase Bridge



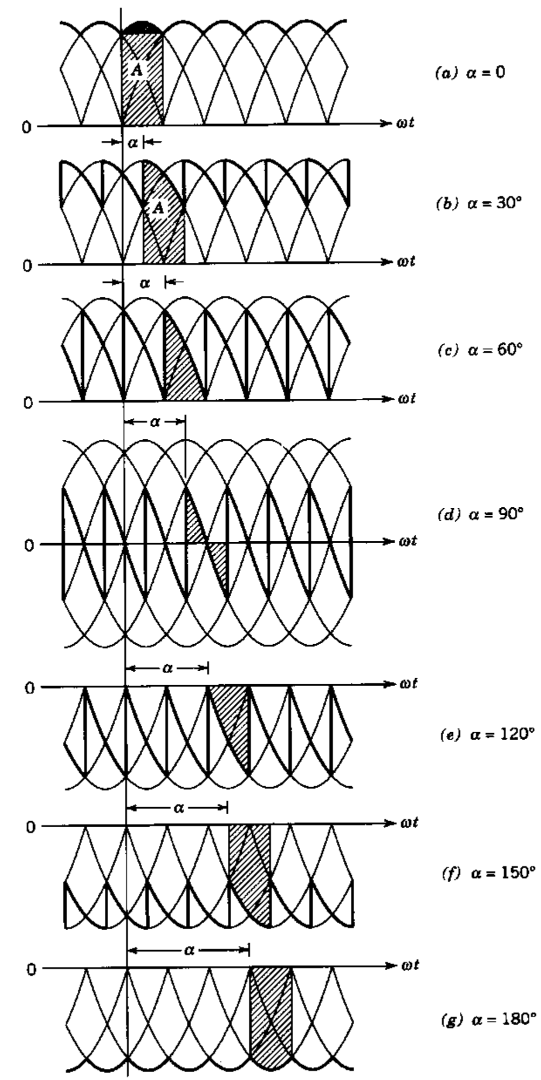


$$\mathbf{V_d} = 3/\pi \, V_{line(max)} \bullet \cos\alpha$$

$$I_{s1} = 0.78 I_d$$

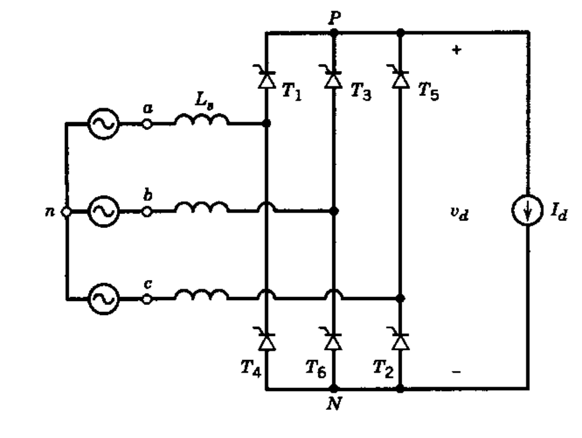
$$PF = 0.955 \cos\alpha$$

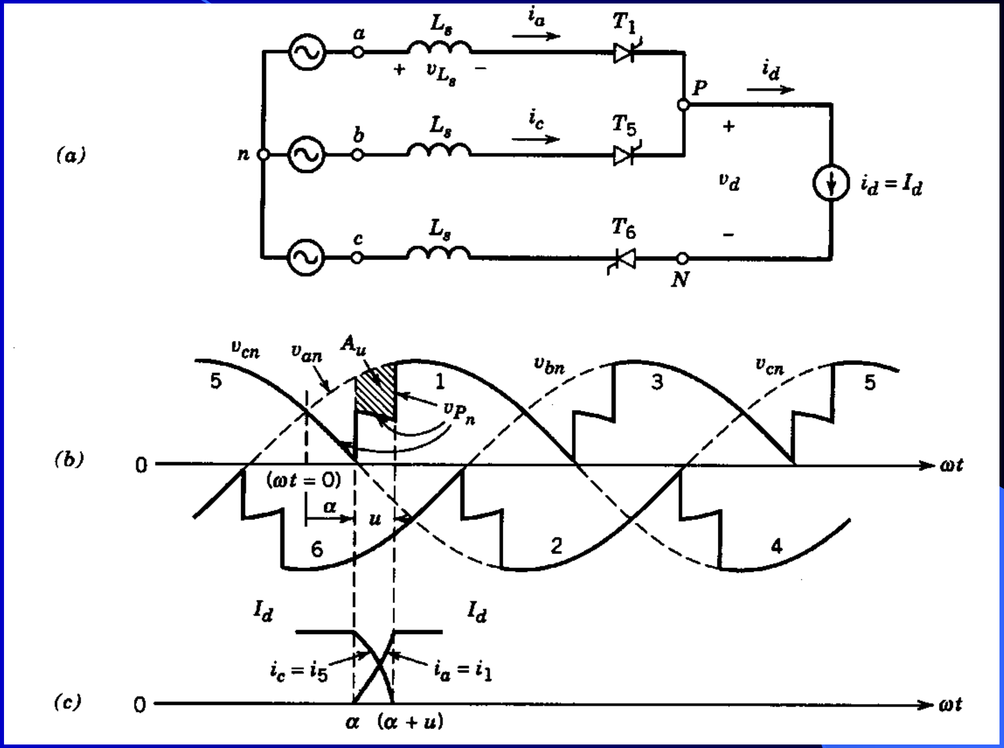
Starting problem



AC-side inductance included

Current Commutation Waveforms





$$v_a - v_c = V_{line(max)} \sin(\omega t + \alpha) = 2L_s di_a/dt$$

$$[\ t = 0, \quad i_a = 0\ ]$$

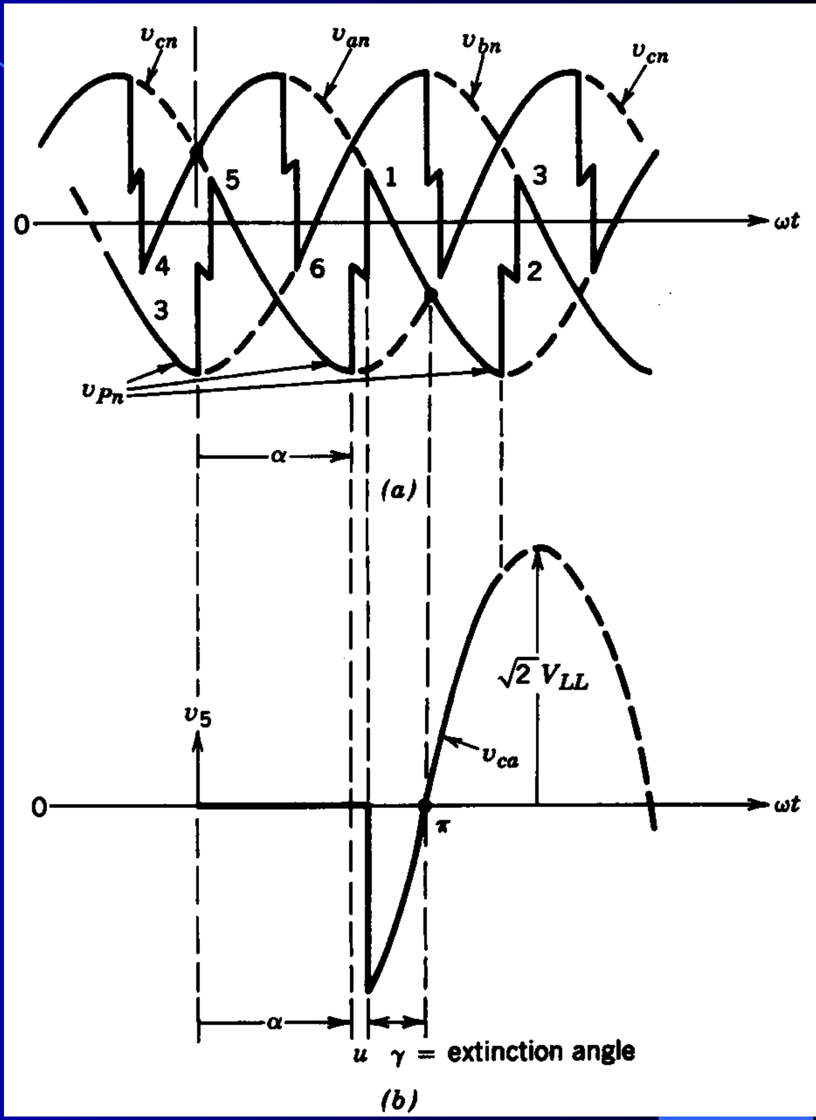
$$[\ \omega t = \boldsymbol{u}\ , \quad i_a = I_d\ ]$$

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

extinction angle δ

$\delta = 180 - \alpha - u$

$\delta_{min} > 5^\circ$

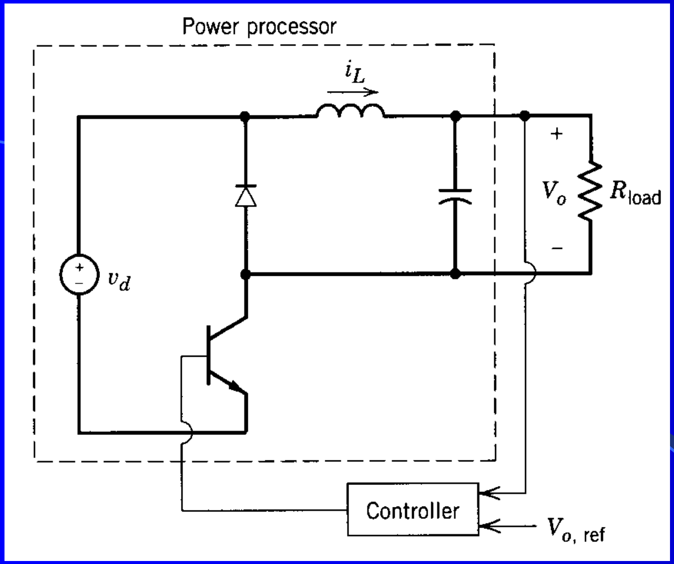


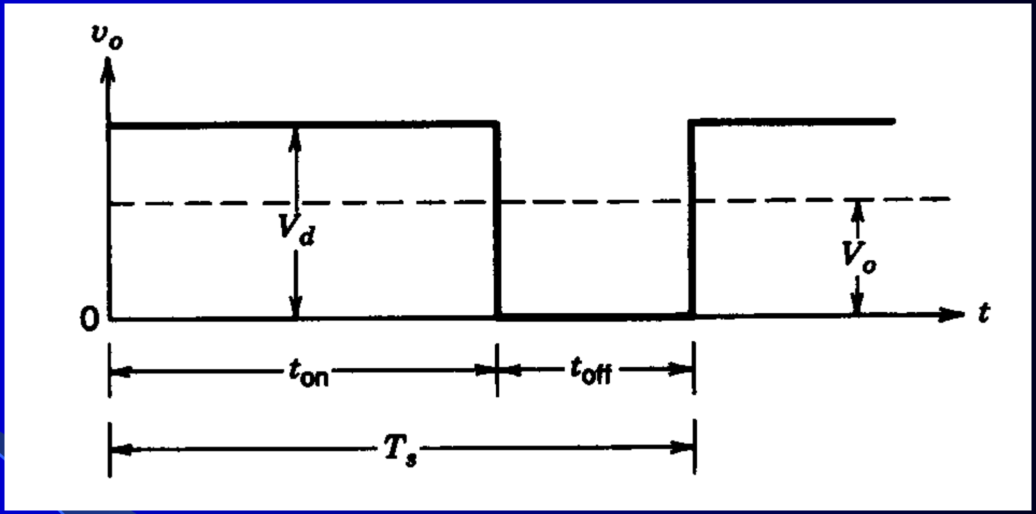
Chapter 4

DC-DC Converters

(DC Choppers)

Basic Principle





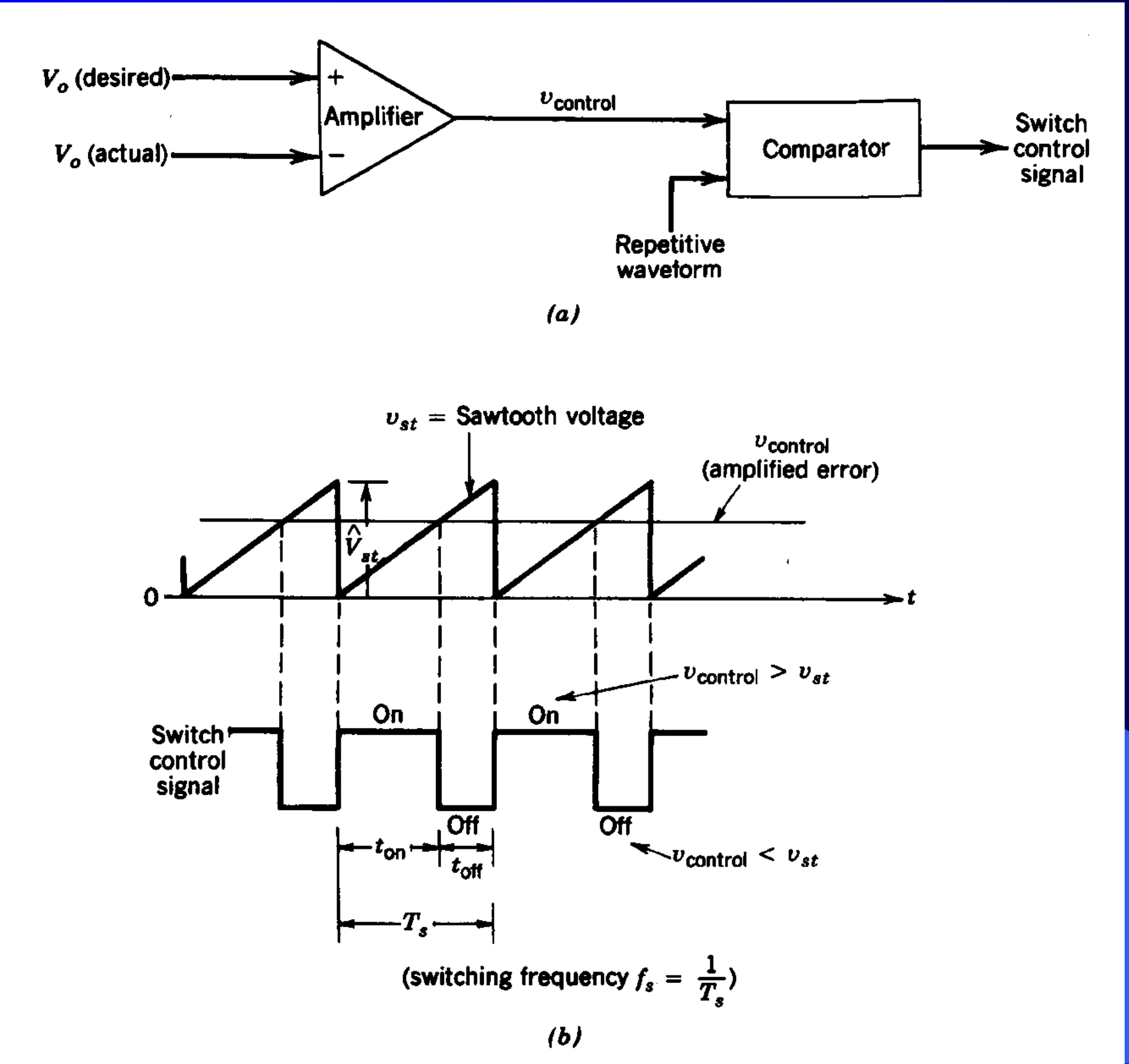
$$V_o = \frac{1}{T_s}\int_0^{t_{on}} v_0\,dt = \frac{t_{on}}{T_s}V_d = f_s t_{on} V_d = DV_d$$

D – duty ratio

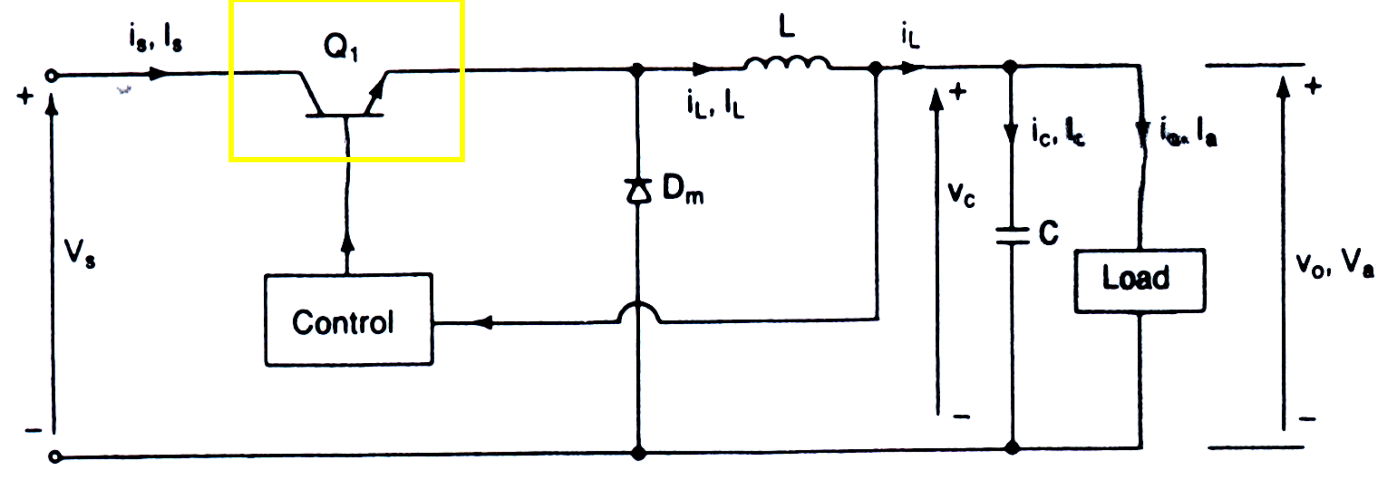
2 methods to control the output voltage:

1) **frequency fixed, on-duration adjusted -- PWM**
2) *Both frequency and on-duration adjusted.*

Control of DC-DC converters by PWM



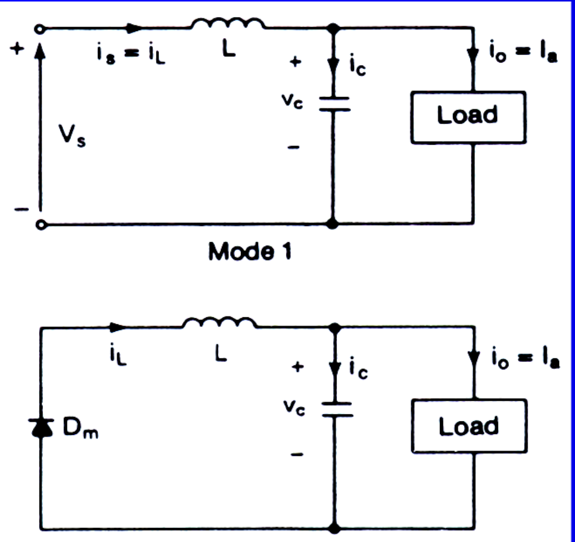
Buck Regulators



(a) Circuit diagram

$$V_a = kV_s$$

$$I_s = kI_a$$



(b) Equivalent circuits

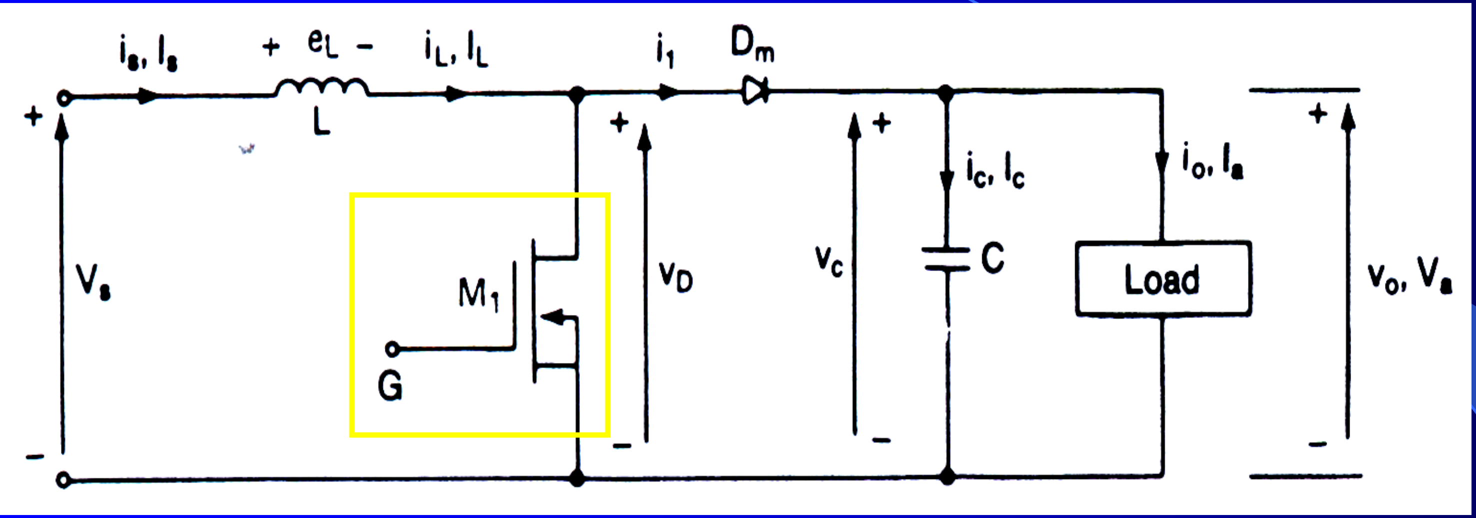
$$\Delta I = \frac{V_s k(1-k)}{fL} \qquad \Delta V_c = \frac{V_s k(1-k)}{8LCf^2}$$

Boundary between continuous and discontinuous

$$I_{LB} = I_{aB} = 0.5\Delta I$$

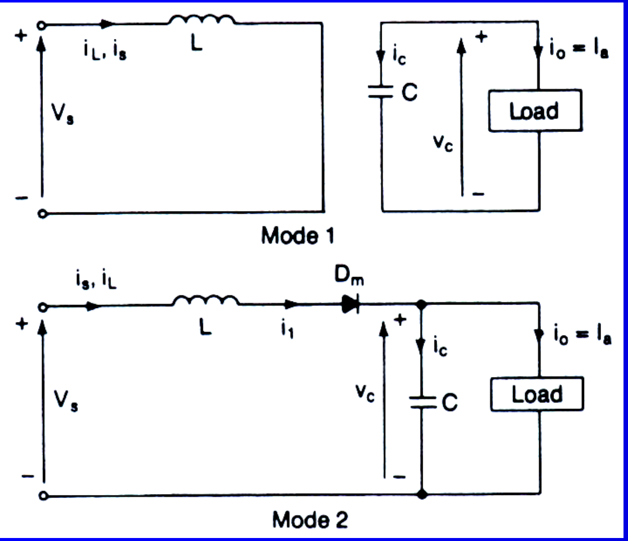
In steady state, the average inductor *v* must be 0.

Boost Regulators



$$V_a = \frac{V_s}{1-k}$$

$$I_s = \frac{I_a}{1-k}$$



$$\Delta I = \frac{V_s k}{fL}$$

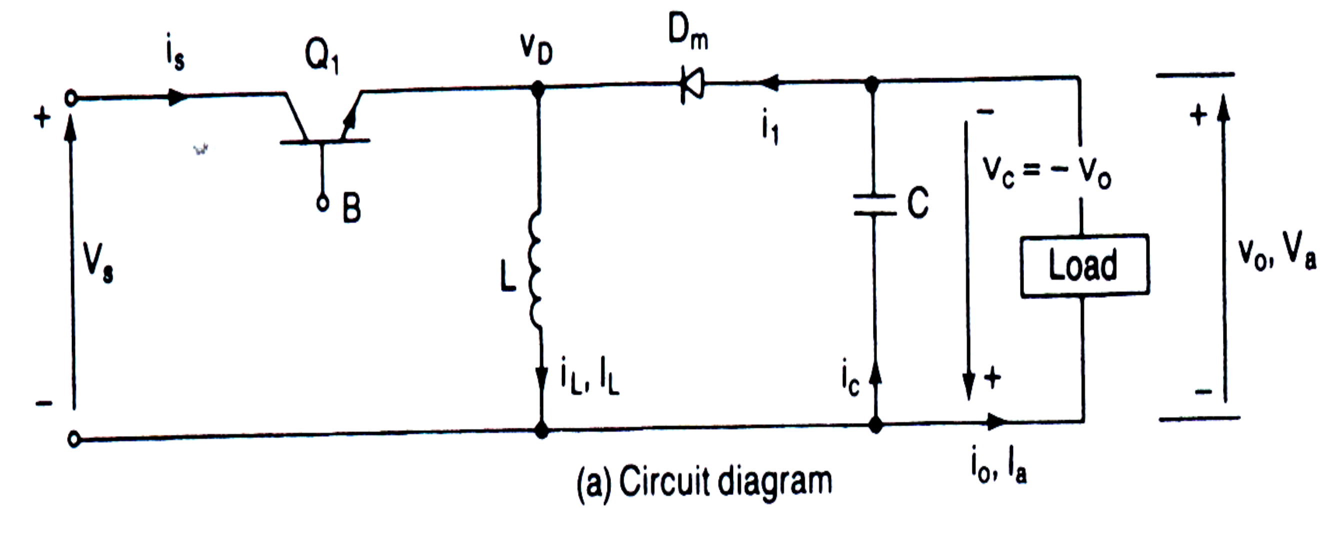
$$\Delta V_c = \frac{I_a k}{fC}$$

Boundary between continuous and discontinuous

$I_{LB} = 0.5\Delta I$ $\quad$ $I_{aB} = I_{LB}(1\text{-}k)$

In steady state, the average inductor *v* must be 0.

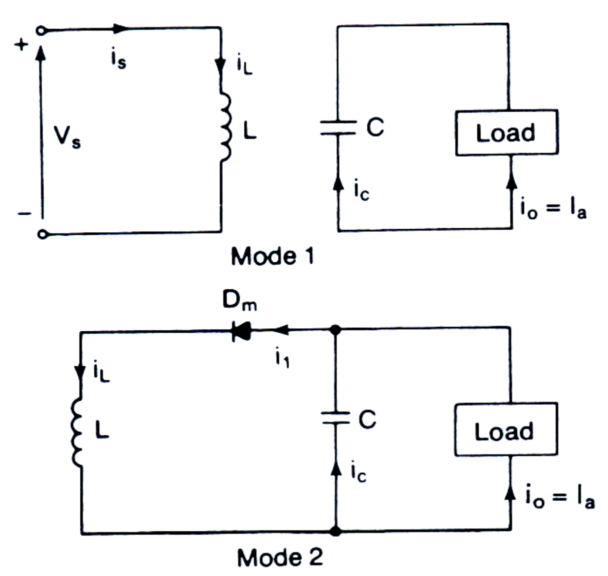
Buck-Boost Regulators



(a) Circuit diagram

$$V_a = -\frac{V_s k}{1-k}$$

$$I_s = \frac{I_a k}{1-k}$$



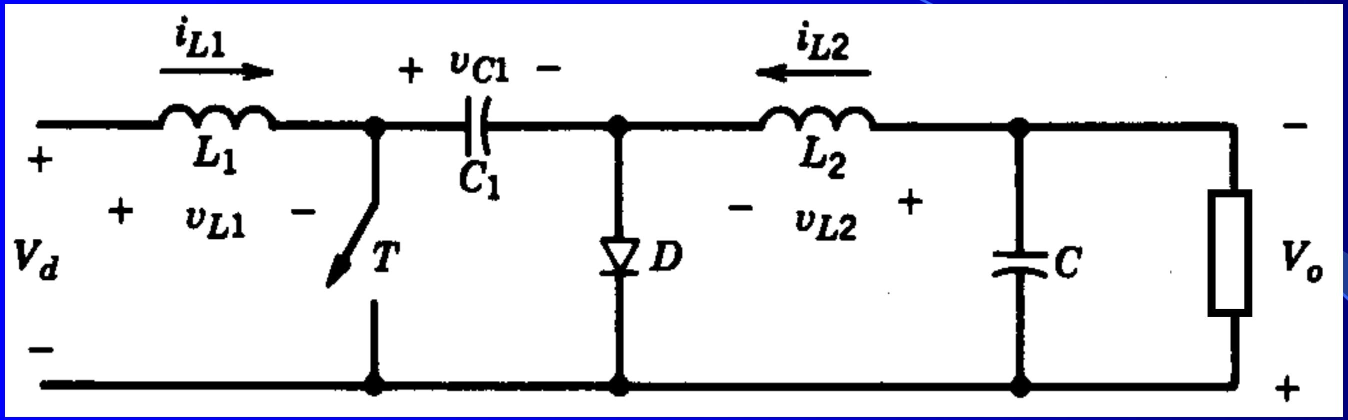
$$\Delta I = \frac{V_s k}{fL} \qquad \Delta V_c = \frac{I_a k}{fC}$$

Boundary between continuous and discontinuous

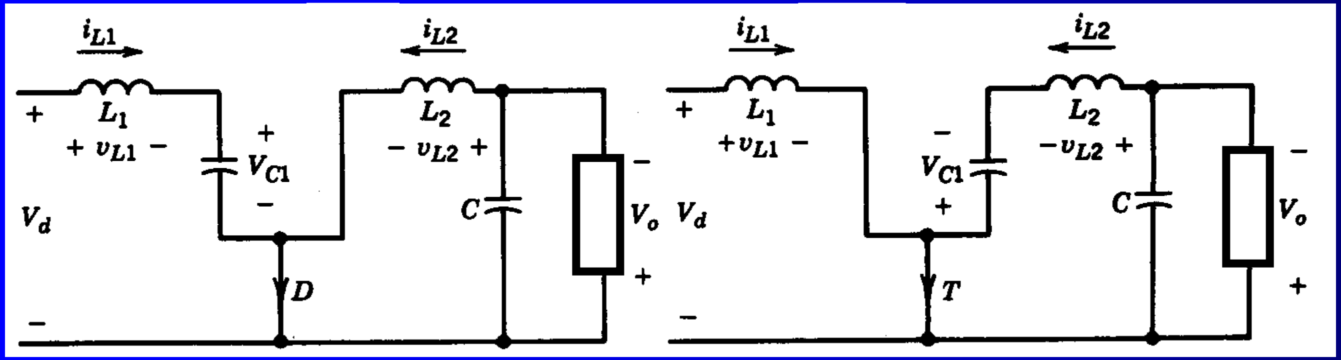
$I_{LB} = 0.5\Delta I \qquad I_{aB} = I_{LB}(1\text{-}k)/k$

In steady state, the average inductor v must be 0.

Cuk Regulators



$$V_o = -\frac{DV_d}{1-D}$$



$$I_d = \frac{DI_o}{1-D}$$

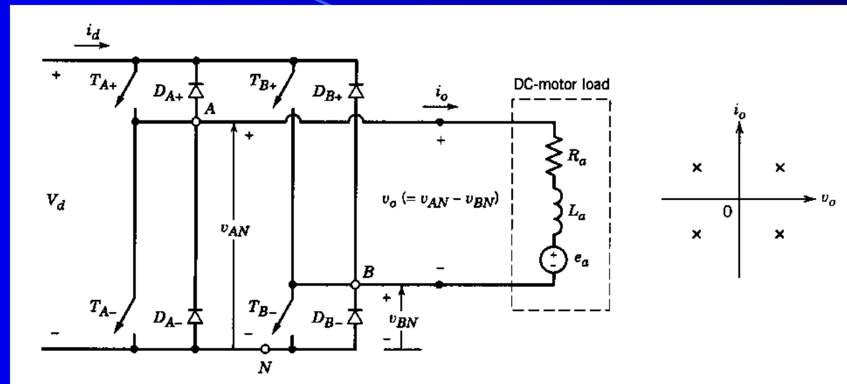
Mode 1 — off

Mode 2 — on

$$\Delta I_{L1} = \frac{DV_d}{f_s L_1} \qquad \Delta I_{L2} = \frac{DV_d}{f_s L_2} \qquad \Delta V_{c1} = \frac{I_d(1-D)}{f_s C_1} \qquad \Delta V_{c2} = \frac{DV_d}{8C_2 L_2 f_s^{\,2}}$$

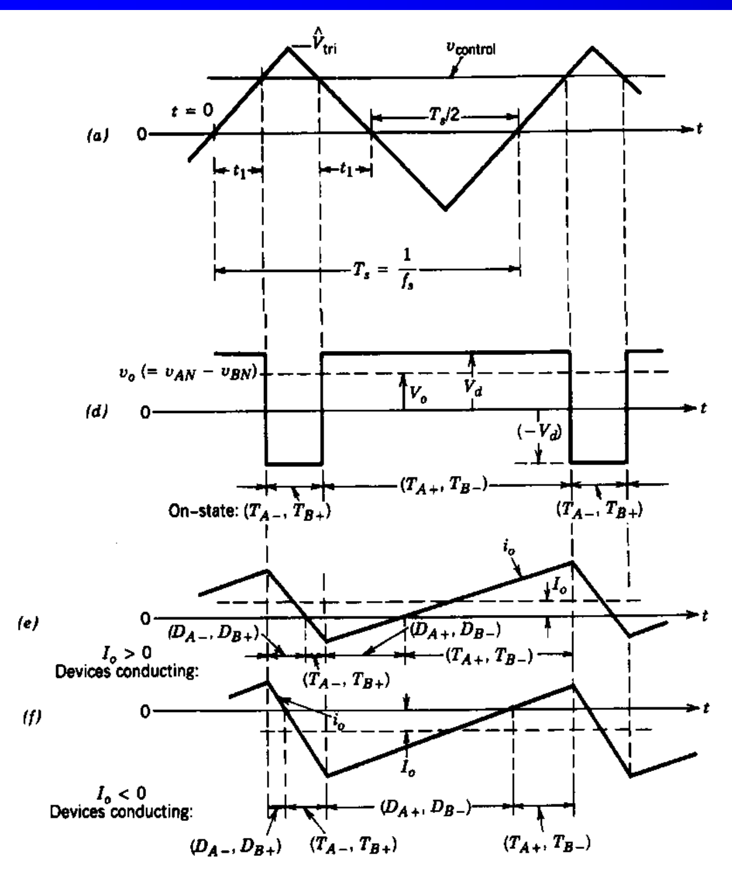
Full-bridge Regulators

DC-DC Choppers

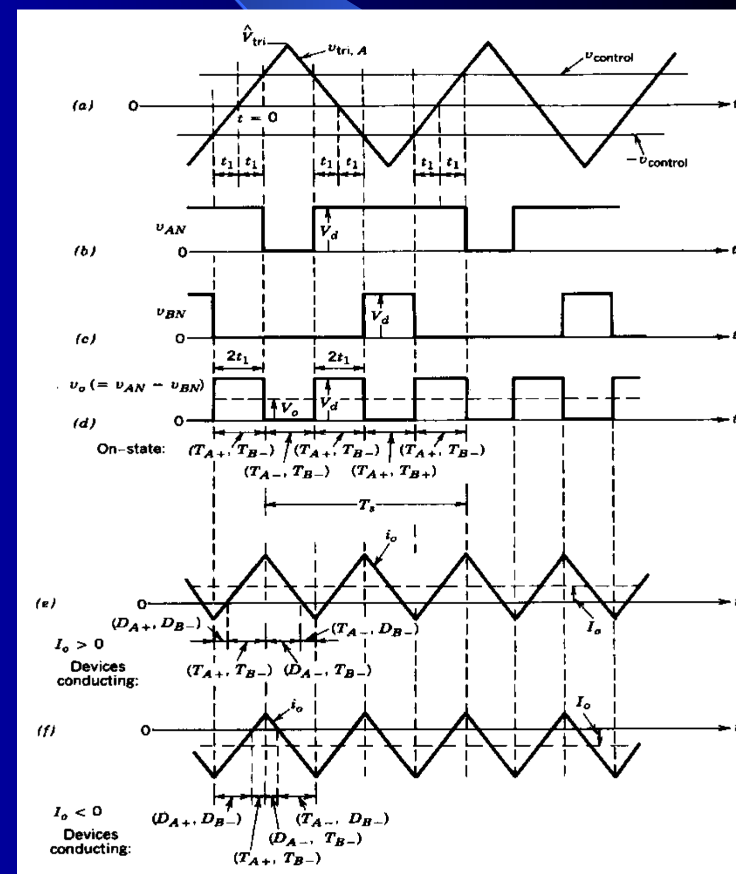


PWM-Bipolar

PWM - Unipolar



blanking time



Chapter 5

DC-AC Inverters

DC power source – DC-AC Inverters – an AC load

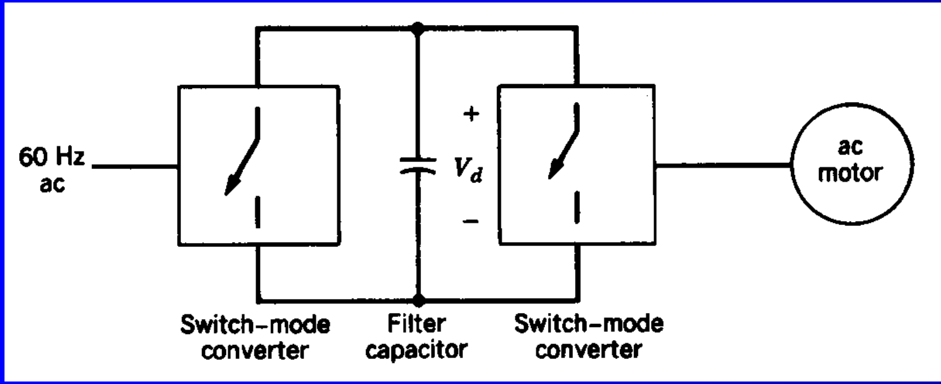
DC Voltage converted to Sinusoidal AC Voltage

* Switch-mode using fast switching devices, anti diode (GTO, IGBT, power MOSFET, etc.)

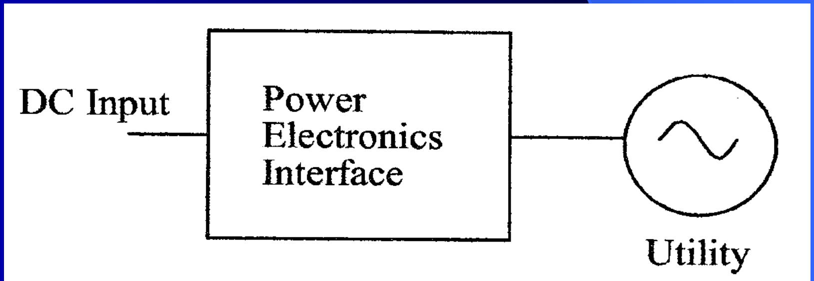
* Constant DC voltage source in DC side

* both output amplitude and frequency variable

* applications: AC motor drives and grid inverter

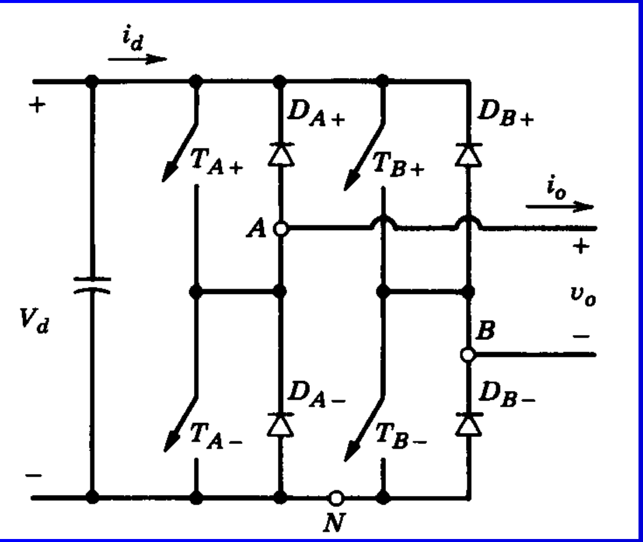


power flow bi-directional ac motor



Photovoltaic Systems

5-1. Single-phase Bridge Inverters

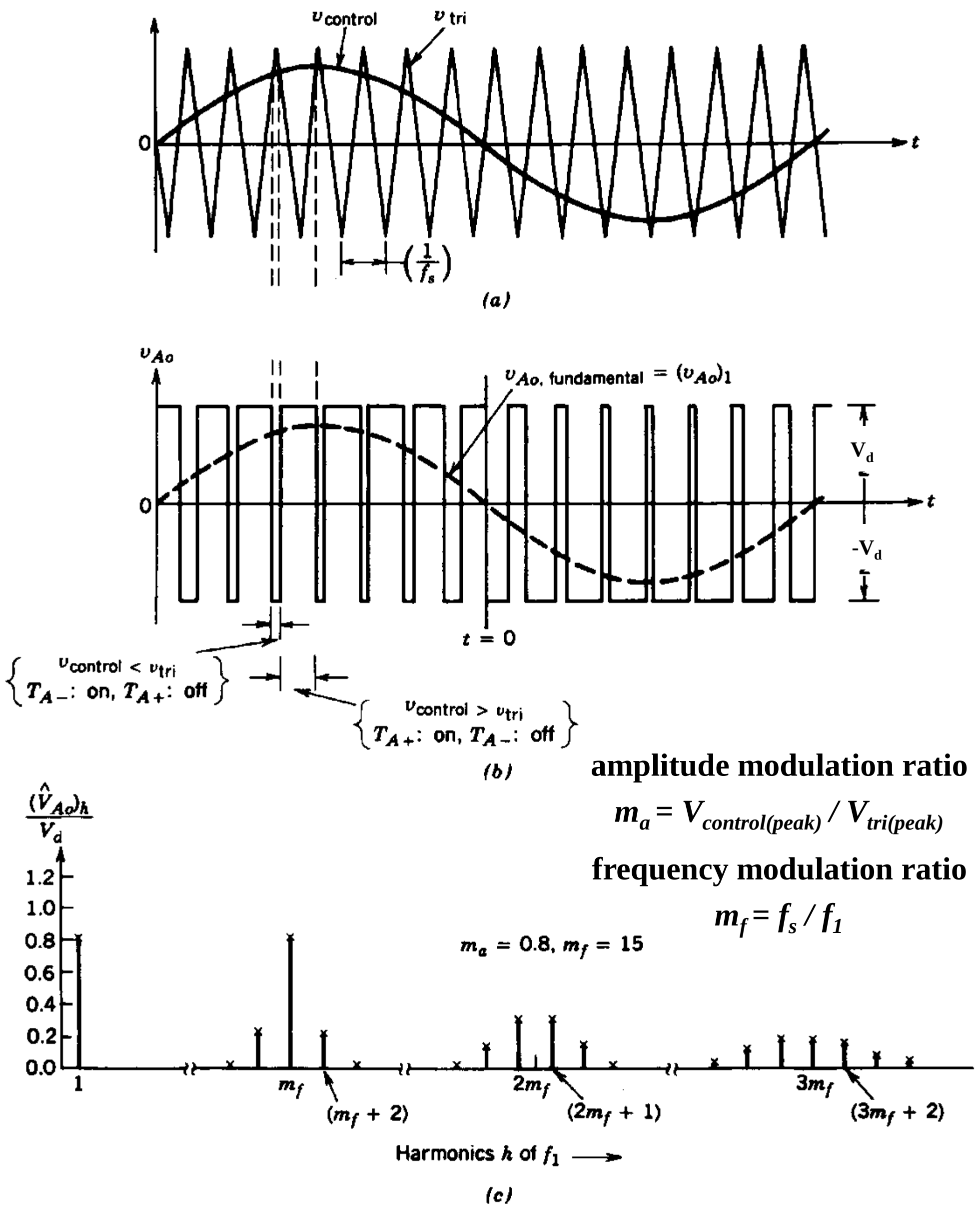


blanking time

Four combinations of switch states and the corresponding voltage levels:

1. T_{A+}, T_{B-} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A-}, T_{B+} off) $\boldsymbol{v_o} = \boldsymbol{V_d}$
2. T_{A-}, T_{B+} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A+}, T_{B-} off) $\boldsymbol{v_o} = -\boldsymbol{V_d}$
3. T_{A+}, T_{B+} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A-}, T_{B-} off) $\boldsymbol{v_o} = 0$
4. T_{A-}, T_{B-} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A+}, T_{B+} off) $\boldsymbol{v_o} = 0$

PWM - Bipolar



amplitude modulation ratio

$$m_a = V_{control(peak)} / V_{tri(peak)}$$

frequency modulation ratio

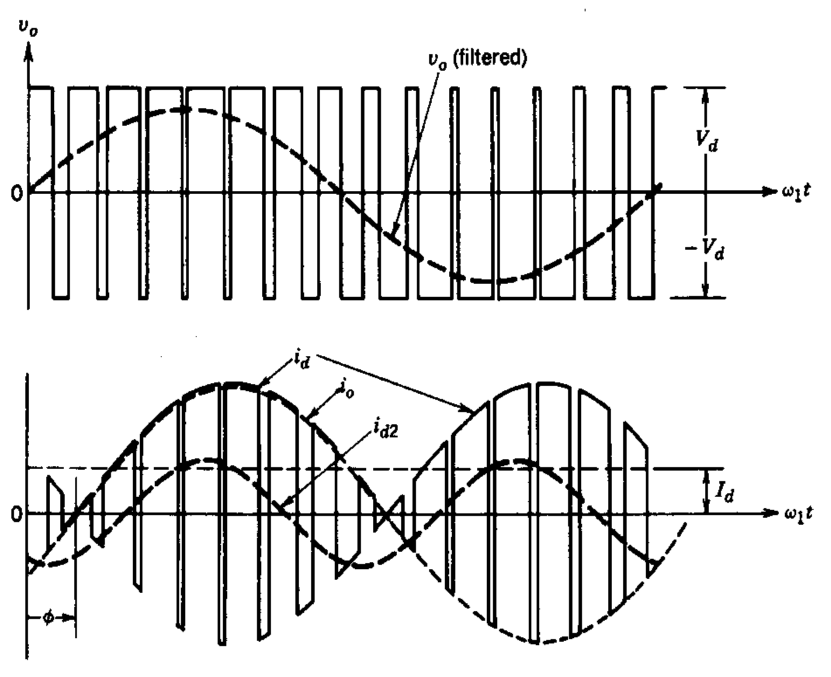
$$m_f = f_s / f_1$$

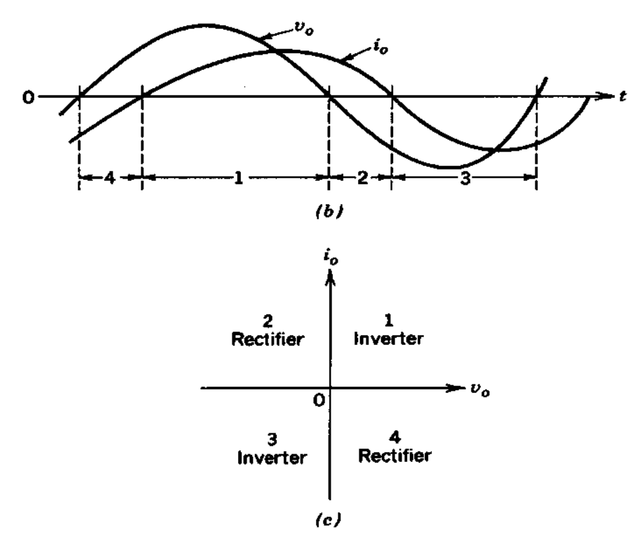
1. synchronous PWM – no subharmonics;

2. m_f an odd integer – no even harmonics;

3. harmonics – appearing as sidebands around m_f and its multiples.

PWM - Bipolar





1. T_{A+}, T_{B-} on: $v_{AN} = V_d$, $v_{BN} = 0$;
   (T_{A-}, T_{B+} off) $v_o = V_d$

   $i_o > 0$ T_{A+}, T_{B-} conduct; $i_d = i_o$
   $i_o < 0$ D_{A+}, D_{B-} conduct; $i_d = i_o$

2. T_{A-}, T_{B+} on: $v_{AN} = 0$, $v_{BN} = V_d$;
   (T_{A+}, T_{B-} off) $v_o = -V_d$

   $i_o < 0$ T_{A-}, T_{B+} conduct; $i_d = -i_o$
   $i_o > 0$ D_{A-}, D_{B+} conduct; $i_d = -i_o$

PWM with Bipolar Voltage Switching

Linear $V_{o1max} = m_a V_d$

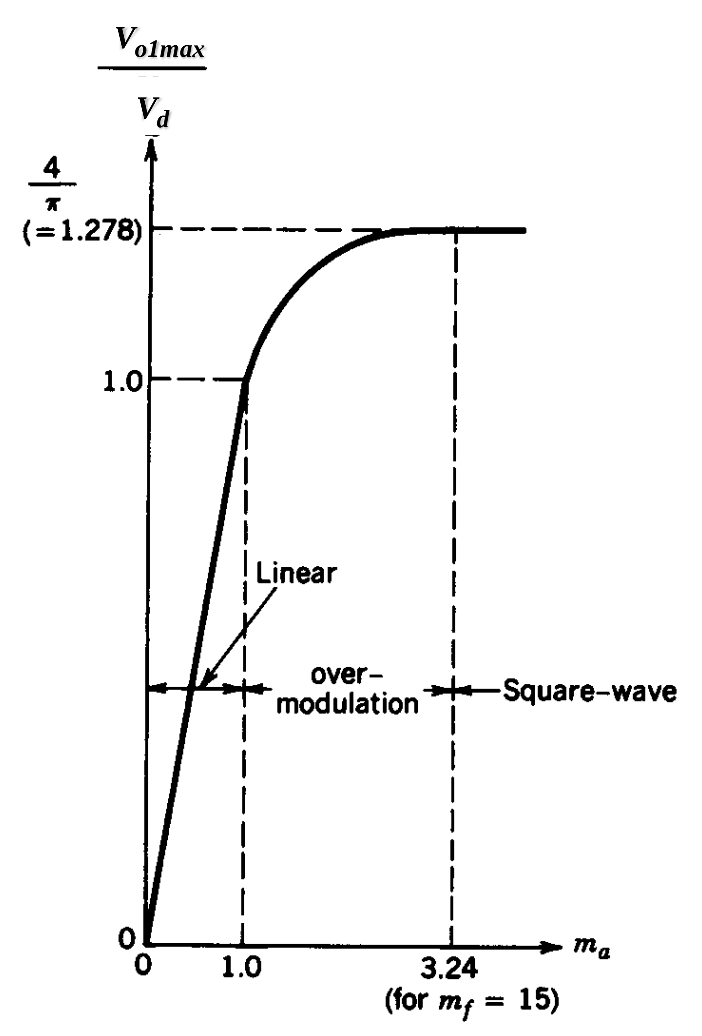
$m_a \le 1$

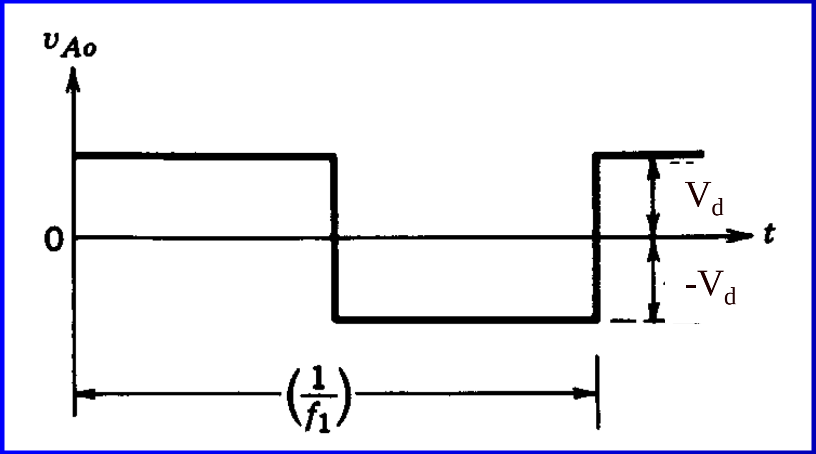
Over-modulation $V_d < V_{o1max} < 4/\pi \, V_d$

$m_a > 1$

Square-wave operation $V_{o1max} = 4/\pi \, V_d$

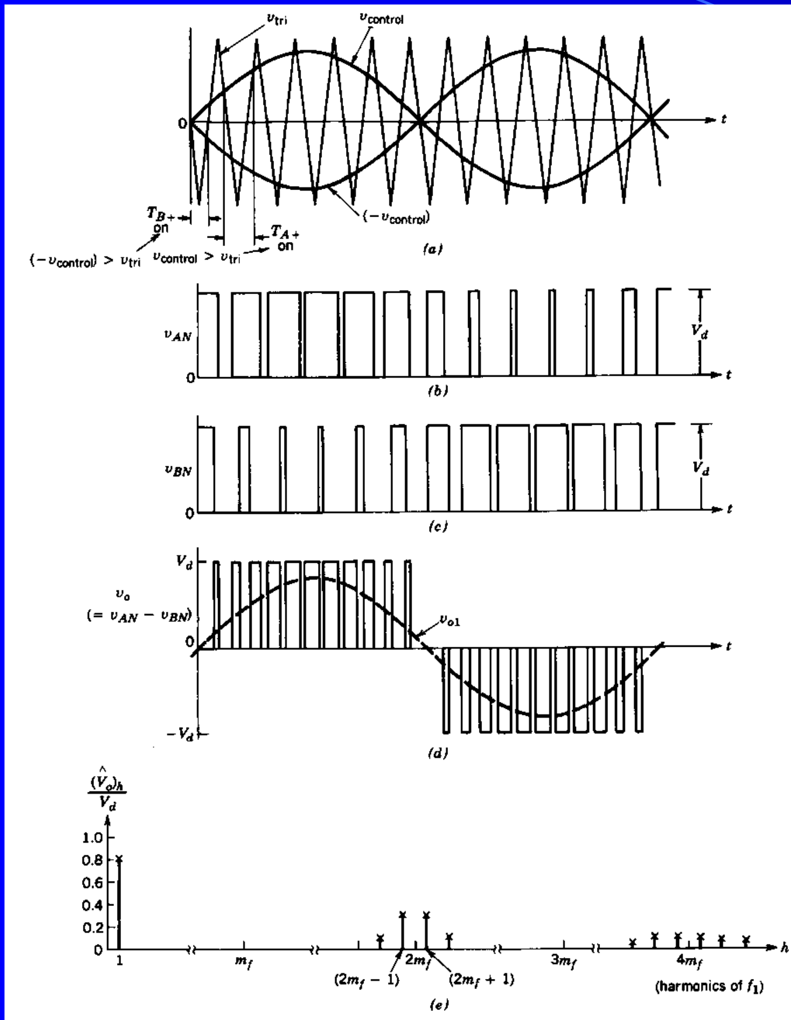
Output voltage Fundamental as a Function of m_a

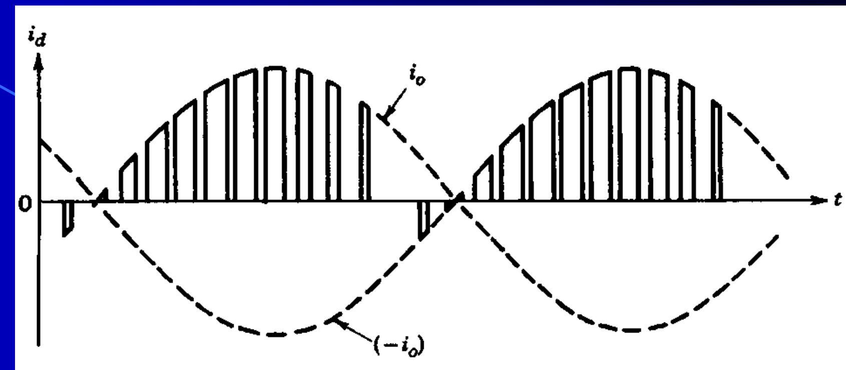




Square-Wave Mode of Operation

PWM - Unipolar





1. Leg A:

   T_{A+} on $\quad i_o > 0 \quad T_{A+}$ conducts; $\quad i_d = i_o$

   $\qquad\quad\ i_o < 0 \quad D_{A+}$ conducts; $\quad i_d = i_o$

   T_{A-} on $\quad i_o < 0 \quad T_{A-}$ conducts; $\quad i_d = -i_o$

   $\qquad\quad\ i_o > 0 \quad D_{A-}$ conducts; $\quad i_d = -i_o$

2. Leg B:

   T_{B+} on $\quad i_o < 0 \quad T_{B+}$ conducts; $\quad i_d = -i_o$

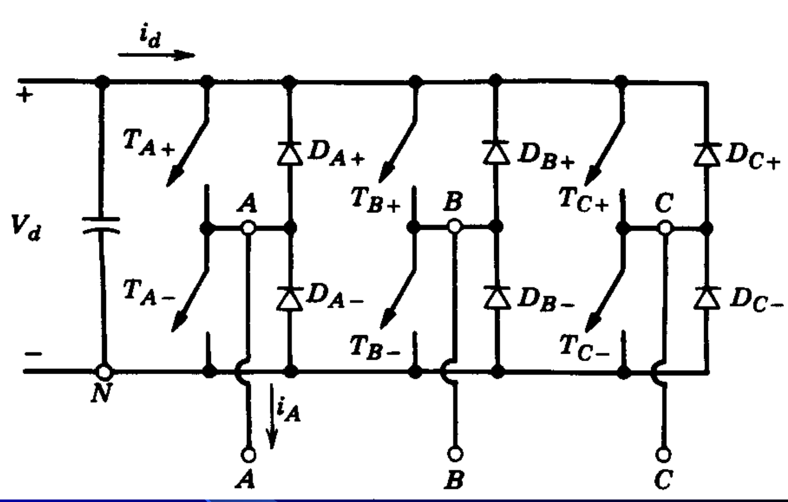
   $\qquad\quad\ i_o > 0 \quad D_{B+}$ conducts; $\quad i_d = -i_o$

   T_{B-} on $\quad i_o > 0 \quad T_{B-}$ conducts; $\quad i_d = i_o$

   $\qquad\quad\ i_o < 0 \quad D_{B-}$ conducts; $\quad i_d = i_o$

- "effectively" doubling f_s
- harmonic components around f_s are absent

5-2. Three-phase Bridge Inverters



switch states

and the corresponding voltage levels

$[T_{A+}, T_{B+}, T_{C+}, T_{A-}, T_{B-}, T_{C-}]$

= [0, 0, 0, 1, 1, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, 0, 0]$

= [1, 0, 0, 0, 1, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [V_d, 0, -V_d]$

= [0, 1, 0, 1, 0, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [-V_d, V_d, 0]$

= [1, 1, 0, 0, 0, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, V_d, -V_d]$

= [0, 0, 1, 1, 1, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, -V_d, V_d]$

= [1, 0, 1, 0, 1, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [V_d, -V_d, 0]$

= [0, 1, 1, 1, 0, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [-V_d, 0, V_d]$

= [1, 1, 1, 0, 0, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, 0, 0]$

Three-Phase PWM Waveforms

Leg A:

$v_{control,A} > v_{tri}$ T_{A+} on $v_{AN} = V_d$;

$v_{control,A} < v_{tri}$ T_{A-} on $v_{AN} = 0$;

Leg B:

$v_{control,B} > v_{tri}$ T_{B+} on $v_{BN} = V_d$;

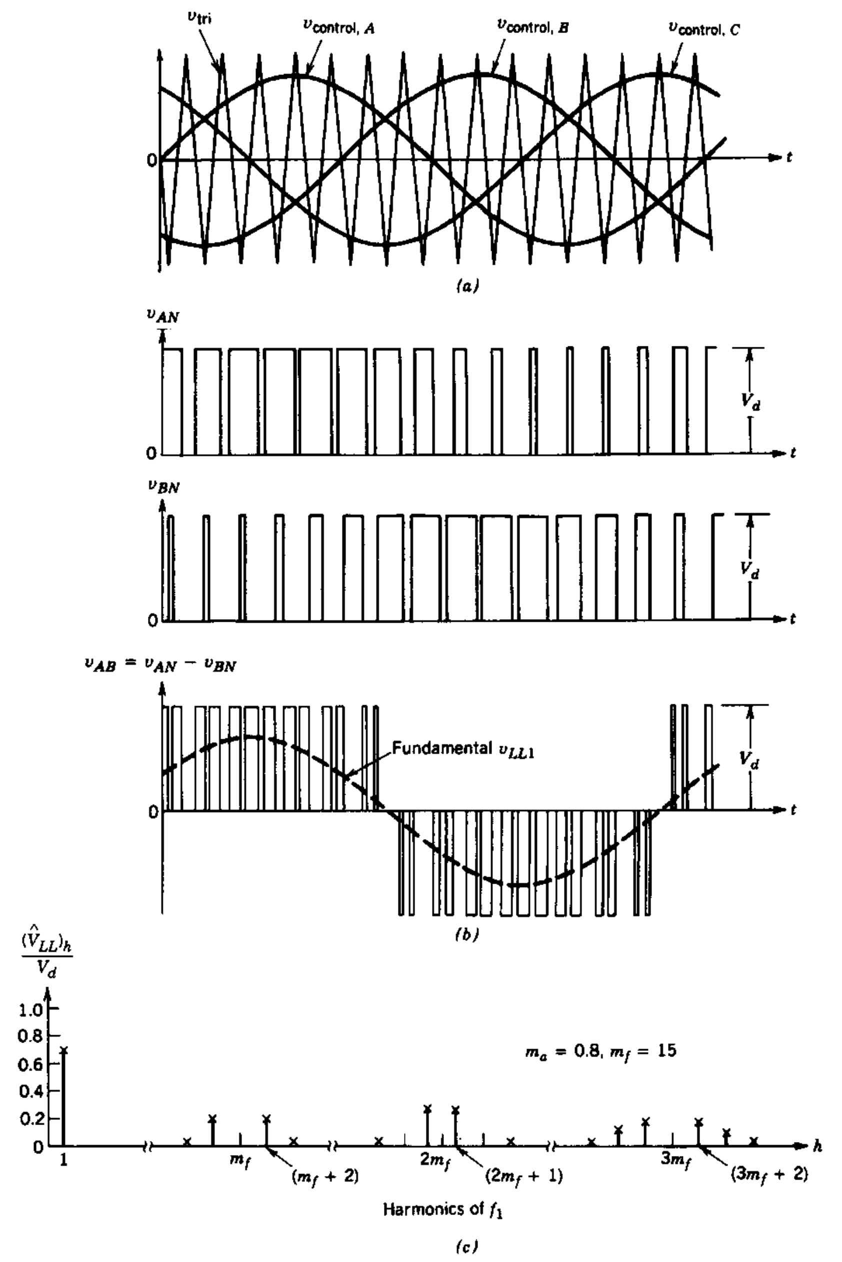
$v_{control,B} < v_{tri}$ T_{B-} on $v_{BN} = 0$;

Leg C:

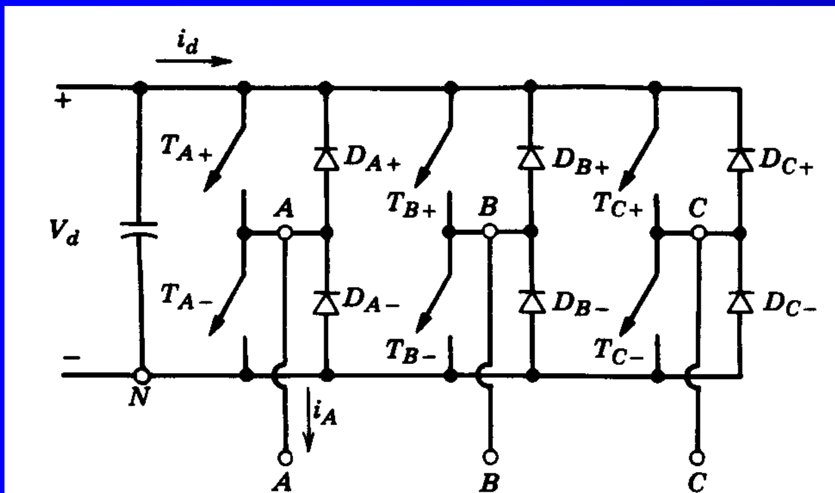
$v_{control,C} > v_{tri}$ T_{C+} on $v_{CN} = V_d$;

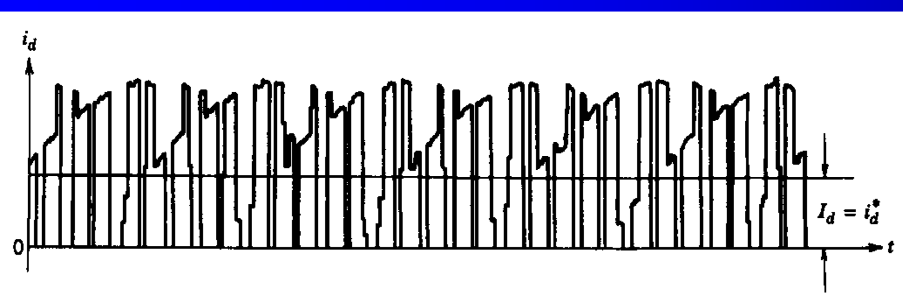
$v_{control,C} < v_{tri}$ T_{C-} on $v_{CN} = 0$;

$$v_{AB} = v_{AN} - v_{BN}$$



Three-Phase PWM Waveforms





The current consists of a DC component and the switching-frequency related harmonics.

Leg A:

T_{A+} on $i_A > 0$ T_{A+} conducts; $i_{d1} = i_A$

$i_A < 0$ D_{A+} conducts; $i_{d1} = i_A$

T_{A-} on $i_A < 0$ T_{A-} conducts; $i_{d1} = 0$

$i_A > 0$ D_{A-} conducts; $i_{d1} = 0$

Leg B:

T_{B+} on $i_B > 0$ T_{B+} conducts; $i_{d2} = i_B$

$i_B < 0$ D_{B+} conducts; $i_{d2} = i_B$

T_{B-} on $i_B < 0$ T_{B-} conducts; $i_{d2} = 0$

$i_B > 0$ D_{B-} conducts; $i_{d2} = 0$

Leg C:

T_{C+} on $i_C > 0$ T_{C+} conducts; $i_{d3} = i_C$

$i_C < 0$ D_{C+} conducts; $i_{d3} = i_C$

T_{C-} on $i_C < 0$ T_{C-} conducts; $i_{d3} = 0$

$i_C > 0$ D_{C-} conducts; $i_{d3} = 0$

$$i_d = i_{d1} + i_{d2} + i_{d3}$$

Three-Phase PWM Waveforms

Linear $V_{LL1rms} = 0.612 m_a V_d$

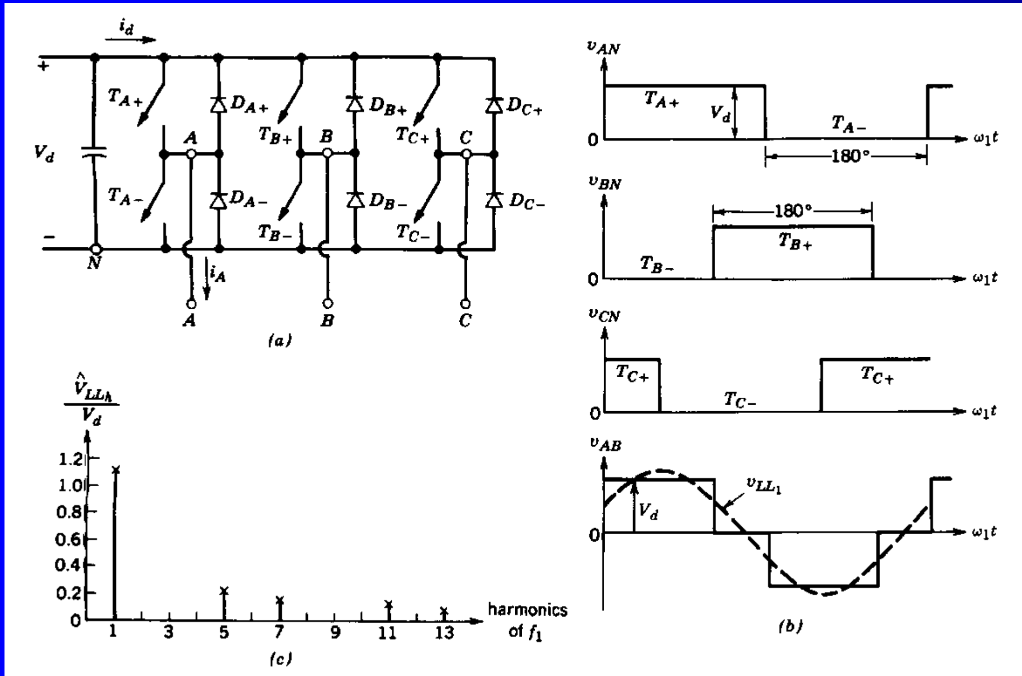
$m_a \leq 1$

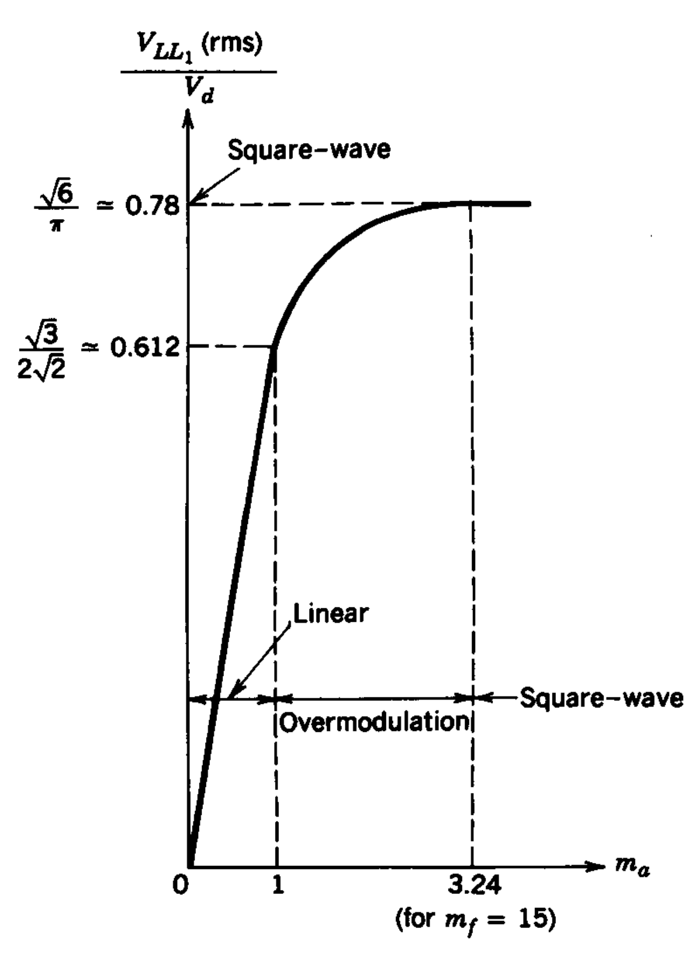
Over-modulation $0.612V_d < V_{LL1rms} < 0.78V_d$

$m_a > 1$

Square-wave operation $V_{LL1rms} = 0.78\ V_d$

Output voltage Fundamental as a Function of m_a





Chapter 6

Gate and Base Drives

Gate and Base Drive Circuits

produce control terminal currents or voltages to cause the devices to switch.

- **Drive circuit**

amplifies logic control signals to levels required to drive power switch,

has significant power capabilities compared to logic level signal processing circuits.

Functionality of Gate/Base Drive Circuits

- **Turn power switch from off-state to on-state**

    Minimize turn-on time

    Provide adequate drive power to keep switch in on-state

- **Turn power switch from on-state to off-state**

    Minimize turn-off time

    Provide bias to insure that switch remains off

- **Control power switch to protect it**

    overvoltages, overcurrents …

    blanking times

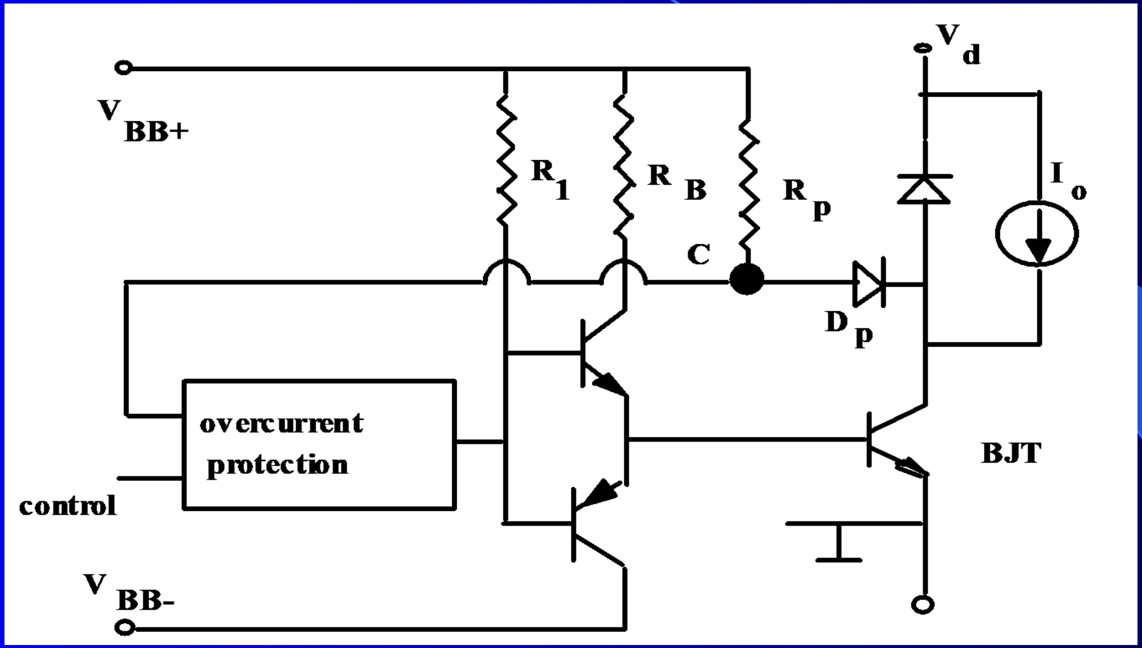
- **Provide electrical isolation**

    between power switch and signal processing circuits

Drive Circuit Design Considerations

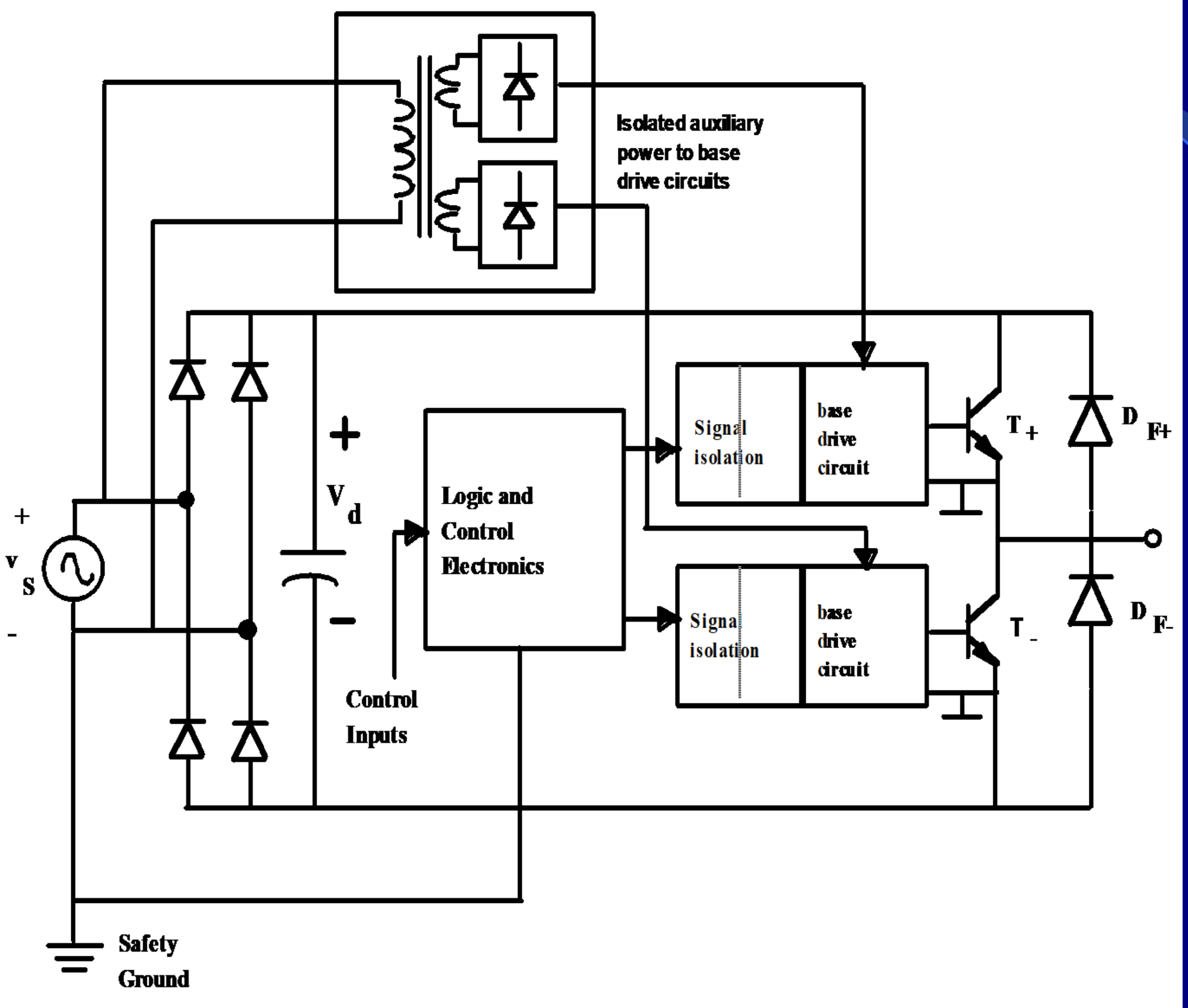
- Output current/voltage magnitude
- Waveshaping to improve switch performance
- Provisions for electrical isolation and power switch protection
- Drive circuit topologies
- Component layout to minimize stray inductance and shielding from switching noise

Overcurrent Protection with Drive Circuits



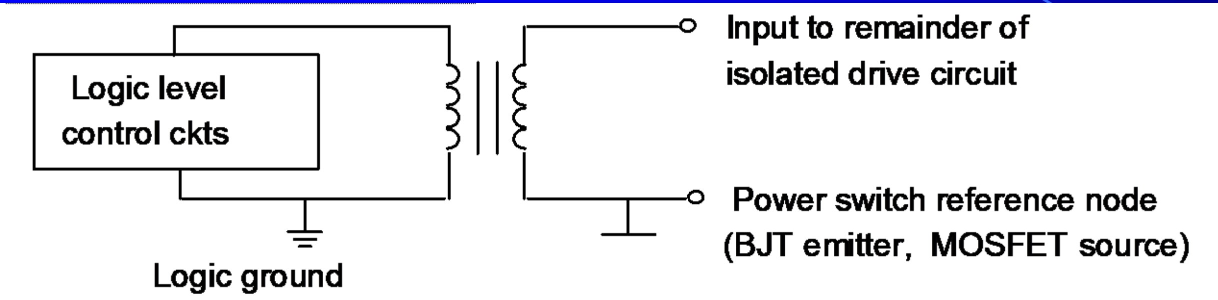
- Point C one diode drop above $V_{CE(sat)}$ when BJT is on. Overcurrent will increase V_{CE} and thus potential at C.
- If C rises above a threshold value and control signal is biasing BJT on, overcurrent protection block will turn off BJT.

Need for Electrical Isolation of Drive Circuits

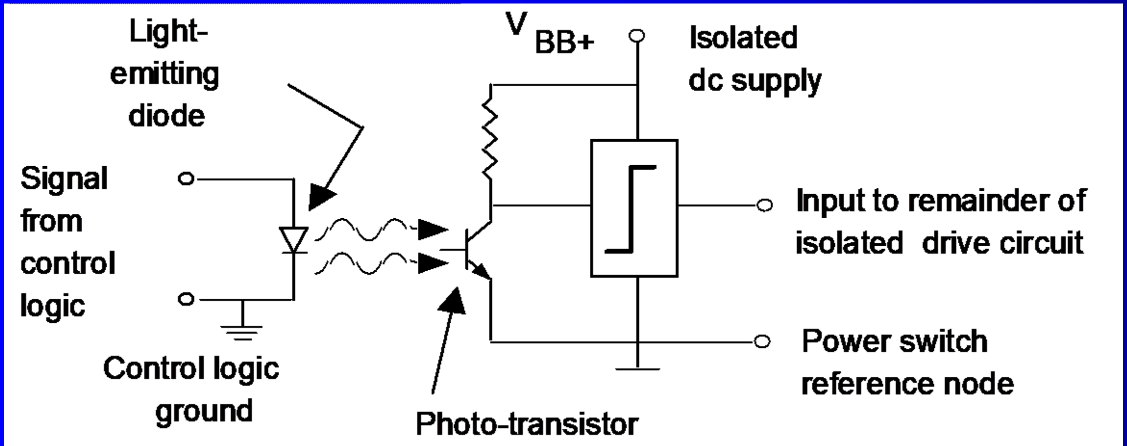


Variation in emitter potentials with respect to safety and logic ground means that electrical isolation of emitters from logic ground is needed.

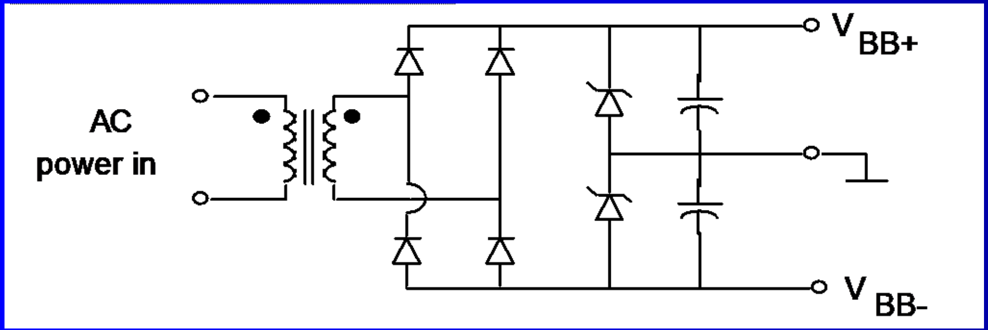
Methods of Control Signal Isolation



Transformer isolation



Opto-coupler isolation

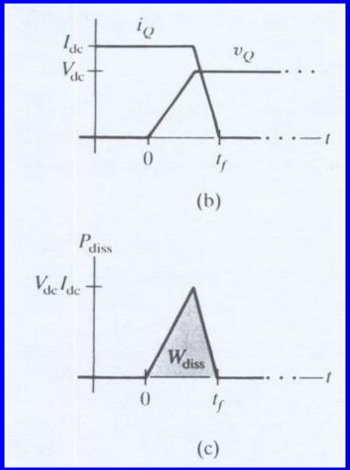


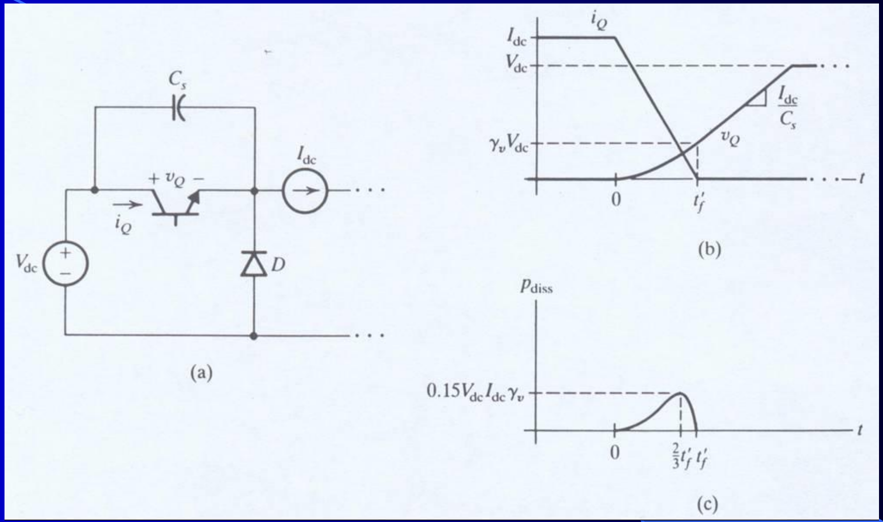
Isolated dc power supplies for drive circuits

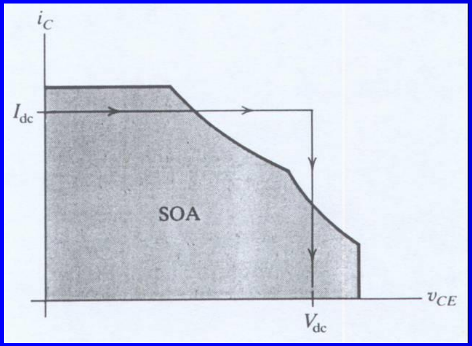
Chapter 7

Snubber Circuits

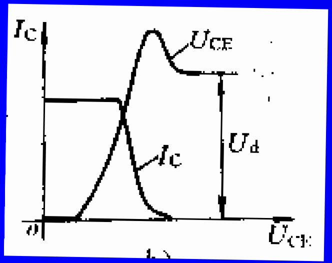
7-1 The Turn-off Snubber

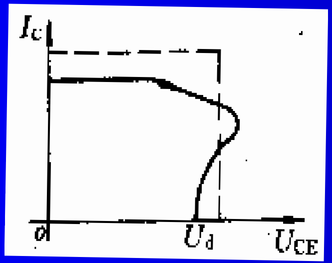


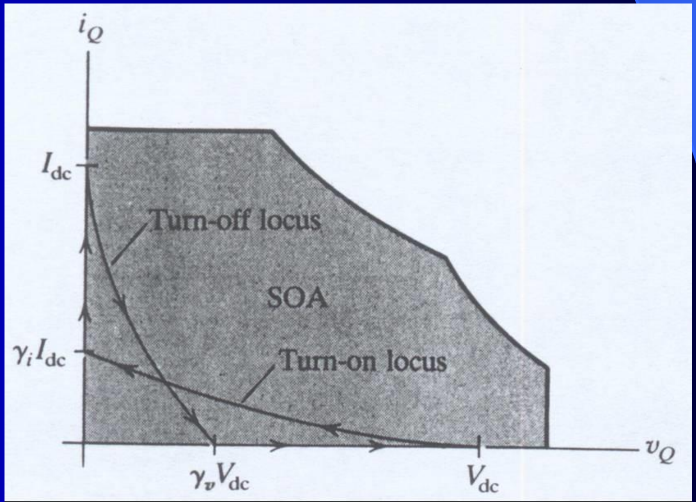




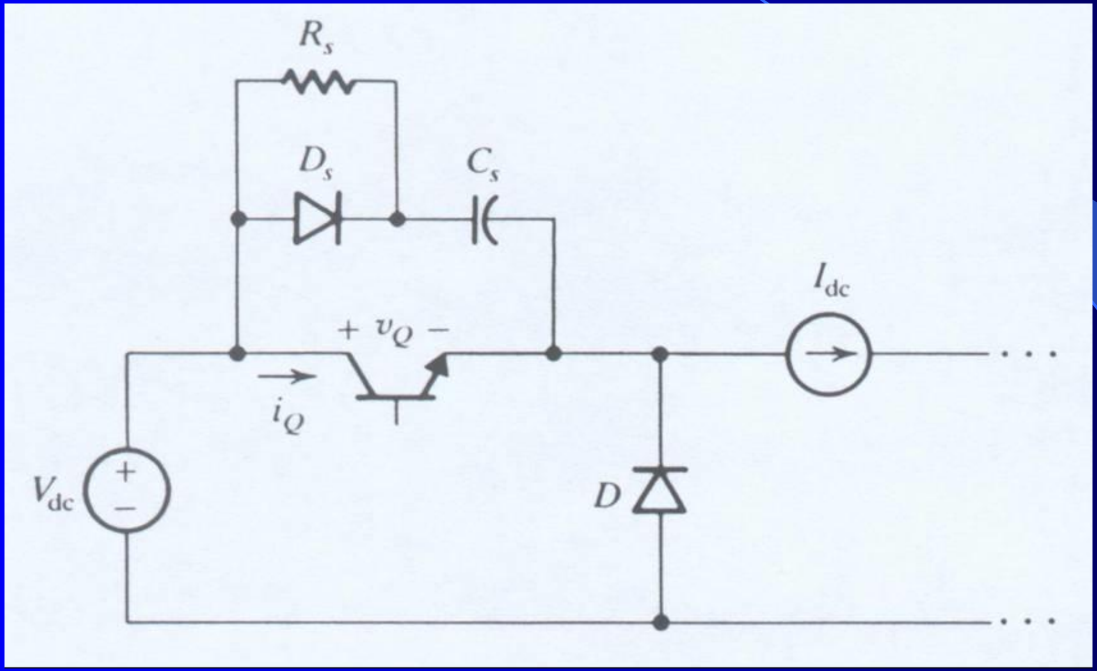
C_S -- to limit the rise rate of the voltage during the turn-off transition.







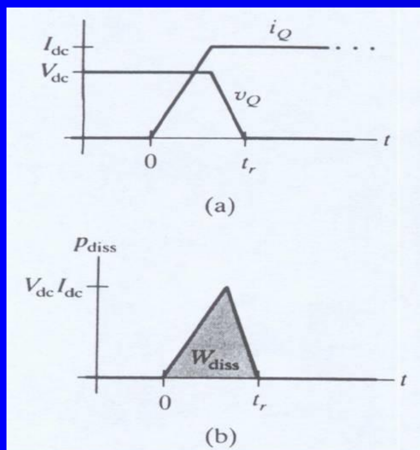
A More Practical Snubber

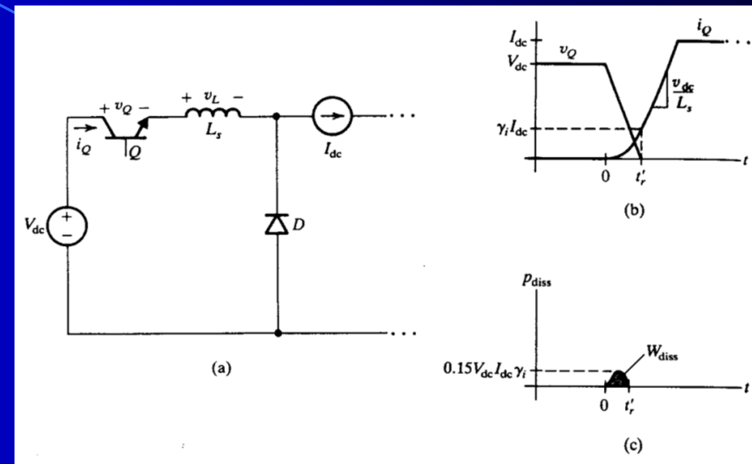


R_S -- to limit the discharge current when the BJT is turned on.

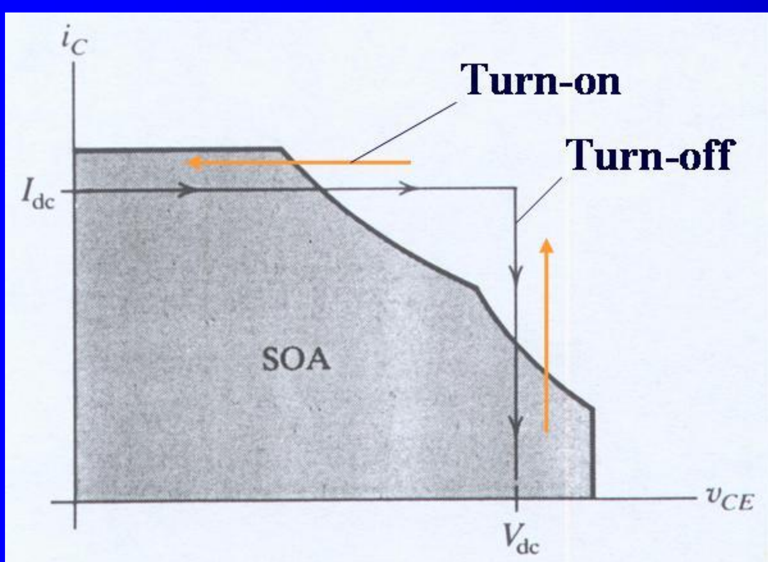
D_S -- to allow the charging current to bypass R_S during turn-off.

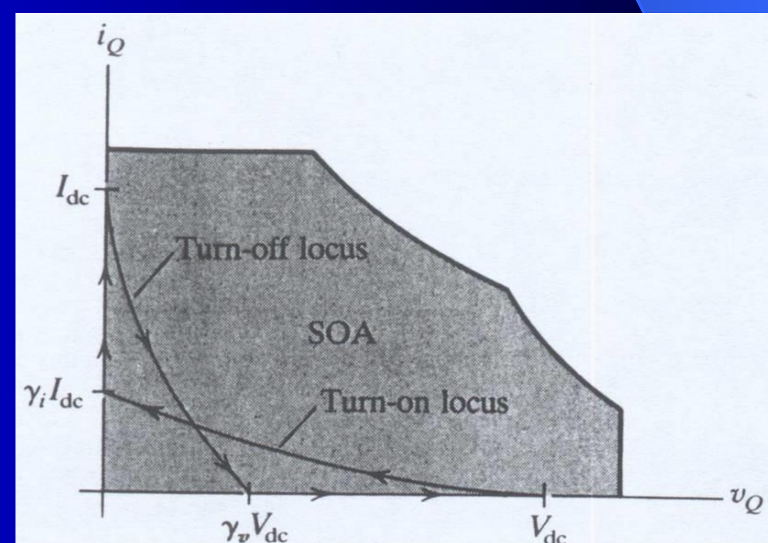
7-2 The Turn-on Snubber



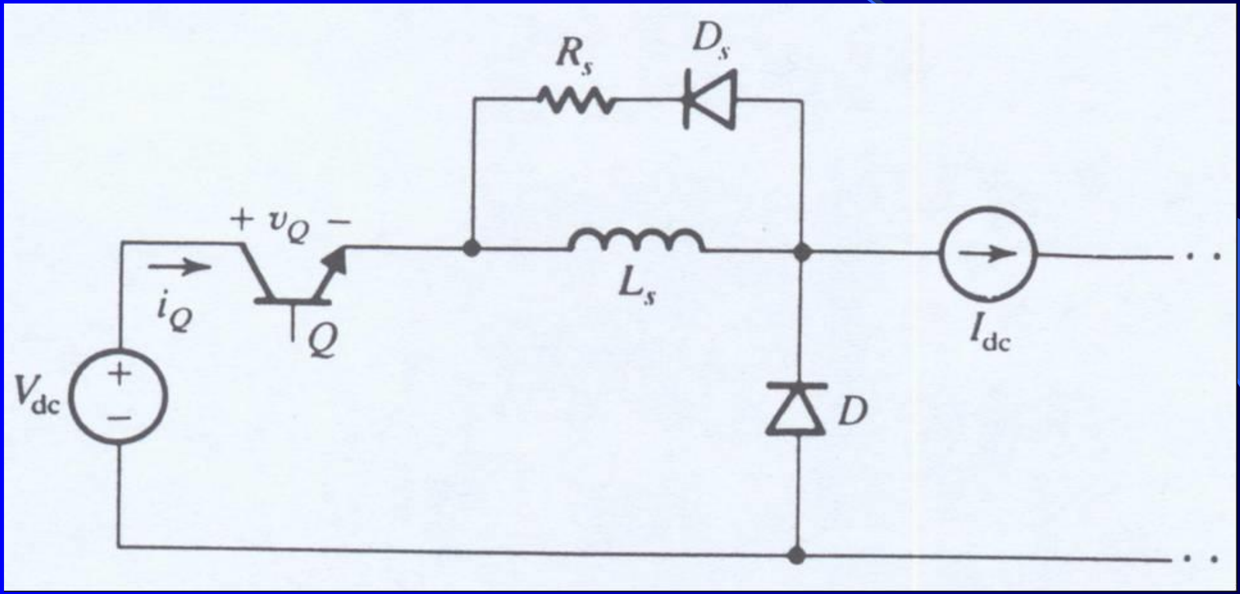


L_S -- to limit the rise rate of the current during the turn-on transition.





A More Practical Snubber



R_S – to provide an alternative path for L_S current when turn-off.

D_S -- to keep R_S from conducting during turn-on.

The End

Good Luck !