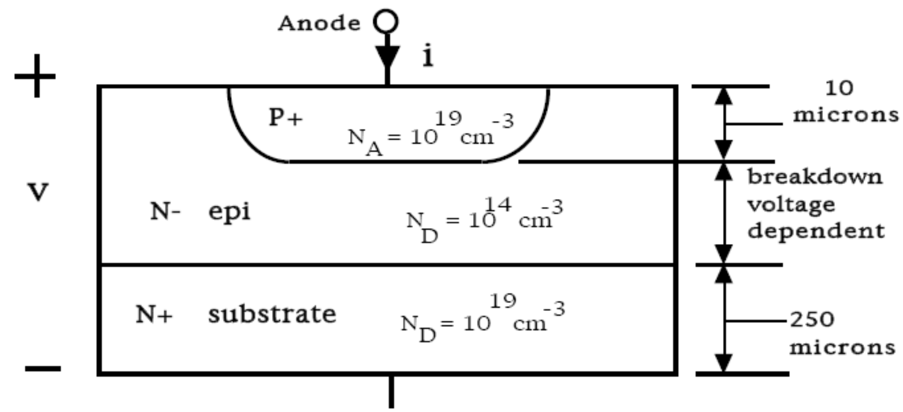
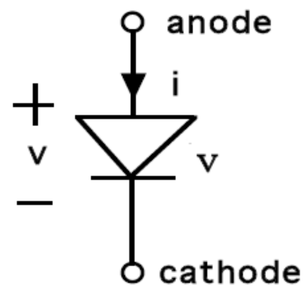
Power Electronics

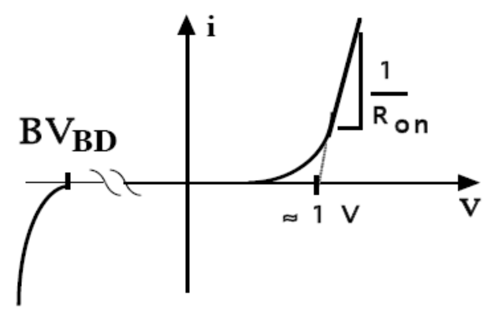
- Power electronics
  - Devices
  - Losses and cooling
  - AC-DC converters: Rectifiers 1-phase and 3-phase
  - DC-DC converters (switched-mode power supplies)
  - DC-AC switched-mode inverters

Basic Structure

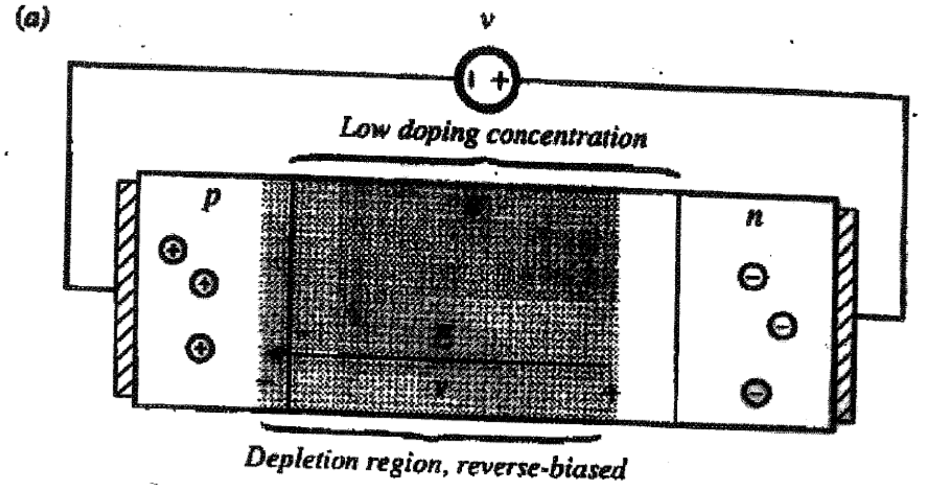
- A *pn* junction
- Conducts in one direction when ‘forward biased’.
- Blocks in the other direction (‘reverse baised’).
- Provides unidirectional current flow.





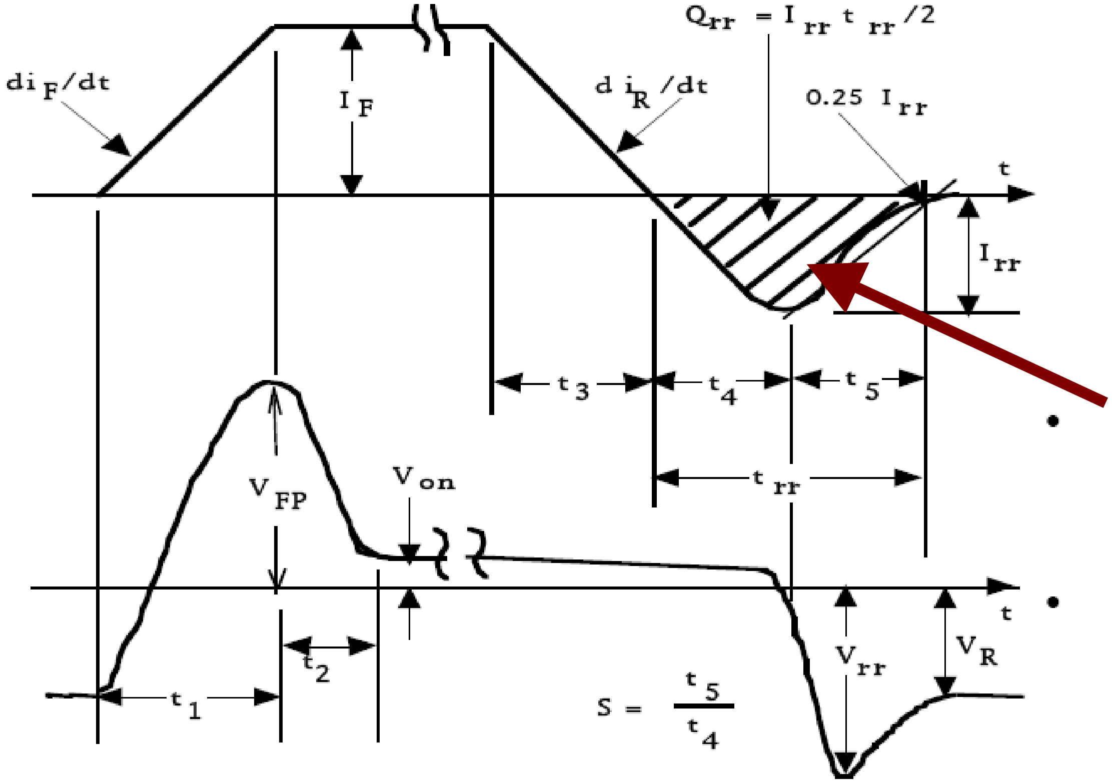


Depletion Layer



When reverse biased, all mobile carriers are swept away from the junction forming a depletion layer (a region that has no charge carriers therefore is non-conducting)

Turn-on and turn-off waveforms



Reverse recovery is the process by which the diode transits from being forward biased to reverse biased.

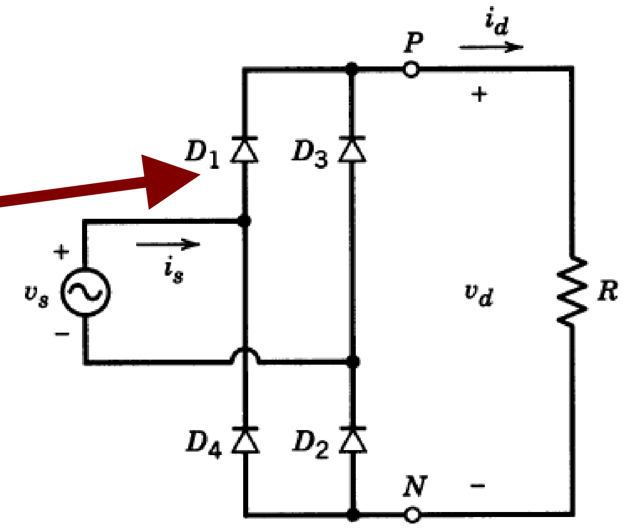
In essence, the diode will conduct current in the reverse direction.

The charge represented by the integral of reverse current with time is known as the recovery charge.

Big problem in power electronics

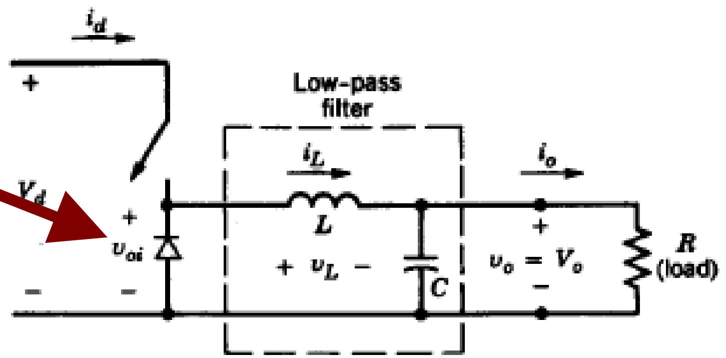
Diode flavours

- Rectifier diodes for mains and low frequency applications.



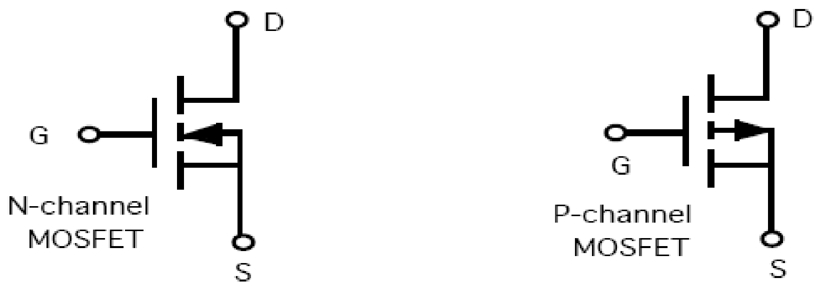
- Fast and ultrafast recovery diodes for high-frequency switching circuits (e.g. switched-mode power supplies)

- Schottky diodes – excellent reverse recovery and low forward voltage drops, but restricted voltage and current ratings and high reverse leakage current



MOSFET

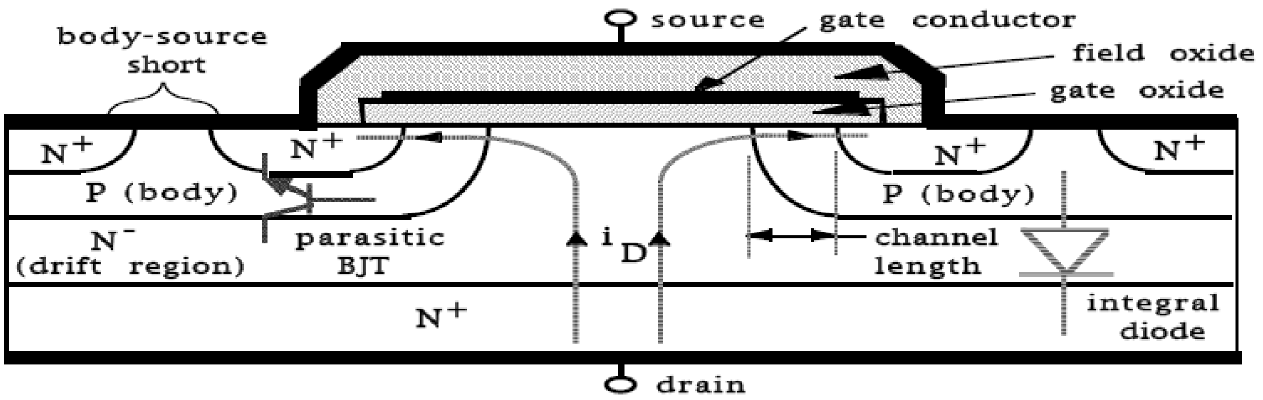
- Metal-Oxide-Semiconductor Field-Effect Transistor



- A voltage-controlled switch with three terminals – Gate, Drain and Source.

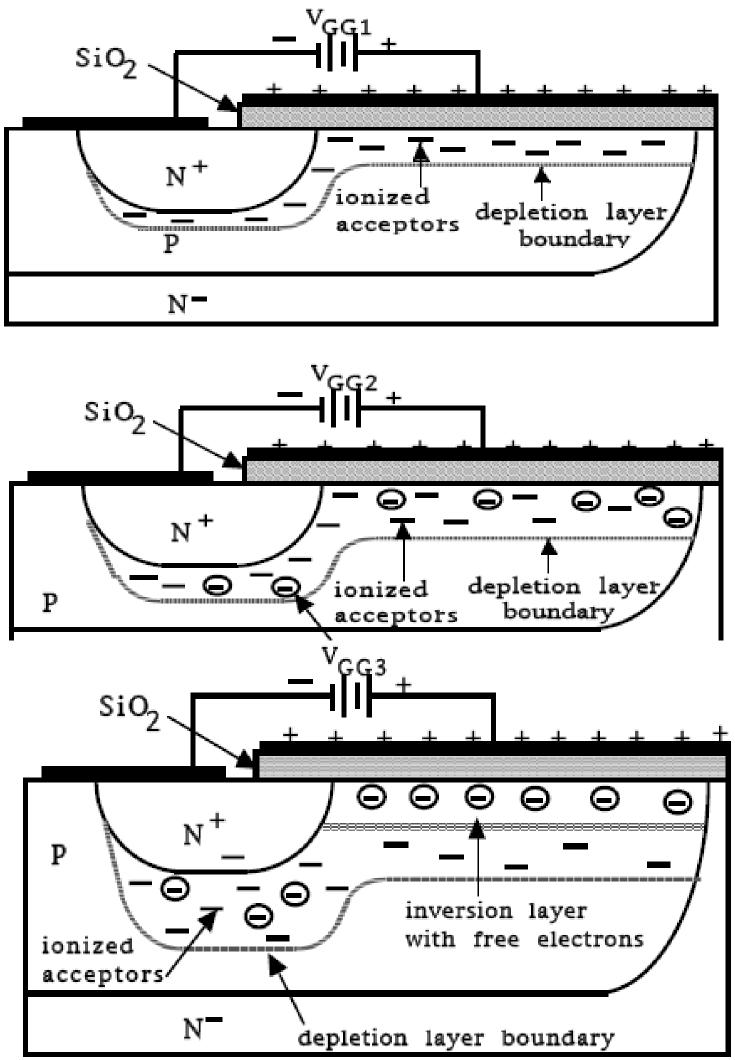
- Turn-on by applying a voltage (~15V) between Gate and Source. Turn-off by removing this voltage.

MOSFET Structure



- Gate-source characteristics– high-input impedance, low power requirement.
- Body diode – reverse bias voltage will force diode to conduct. Sometimes used as a freewheel diode.

The Field Effect



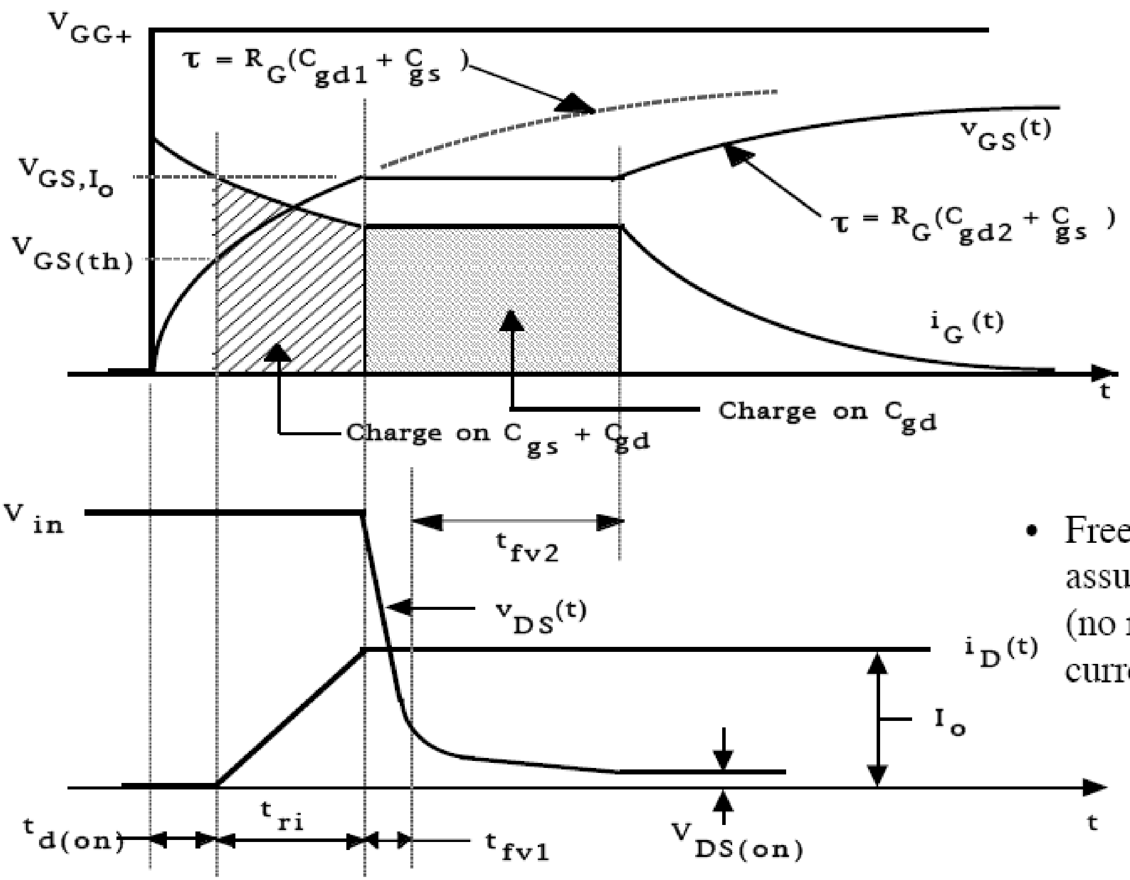
As Vgs is progressively increased the gate charge forms a depletion layer.

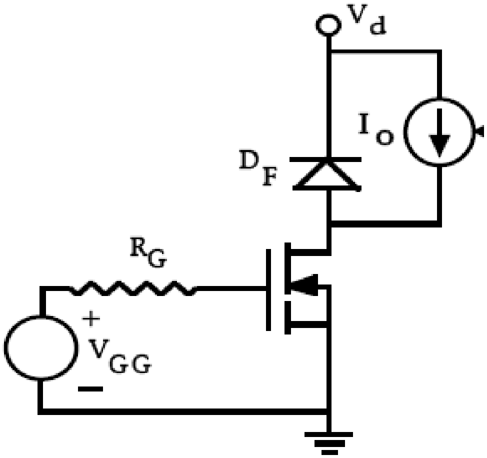
As Vgs is increased further it attracts free electrons to the underside of the oxide.

When enough free electrons have accumulated we have an inversion layer.

The inversion layer is a conducting channel and allows current to flow from drain to source.

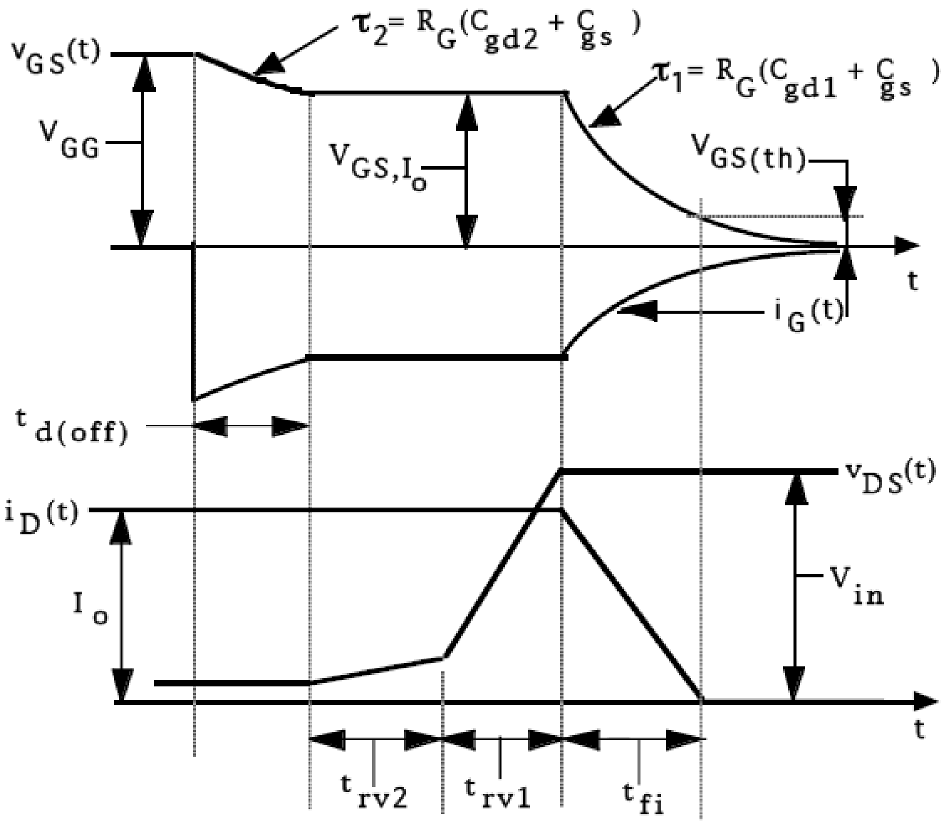
Turn-on waveforms

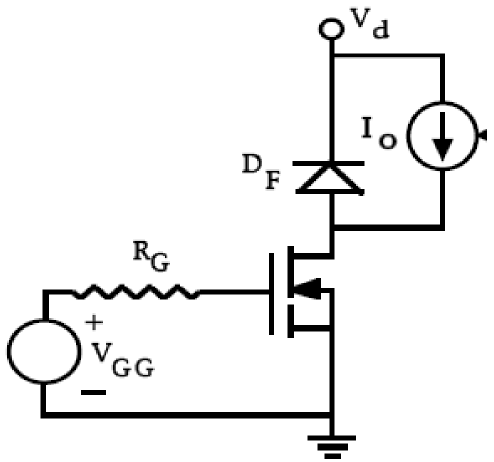




- Free-wheeling diode assumed to be ideal. (no reverse recovery current).

Turn-off waveforms





MOSFET

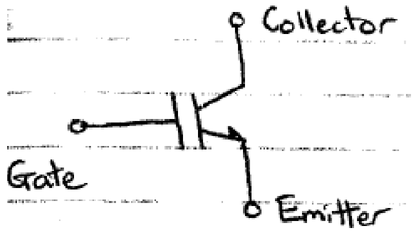
MOSFETs are easy to drive, have fast switching times and low losses.

Application Areas:

- Switched-mode power supplies
- Low voltage motor drives (AC and DC) typically below a few hundred volts.
- Synchronous rectification.

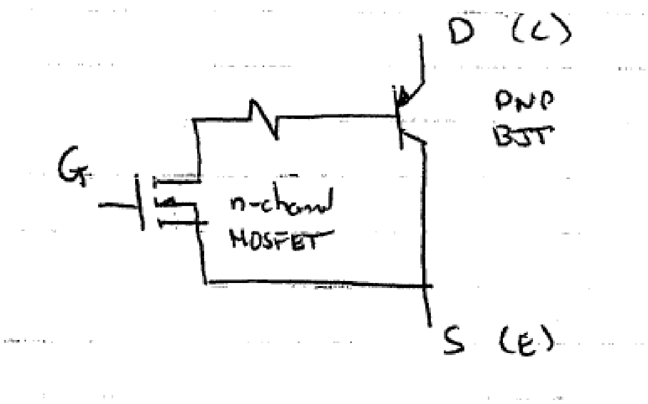
IGBT

- Insulated-Gate Bipolar Transistor

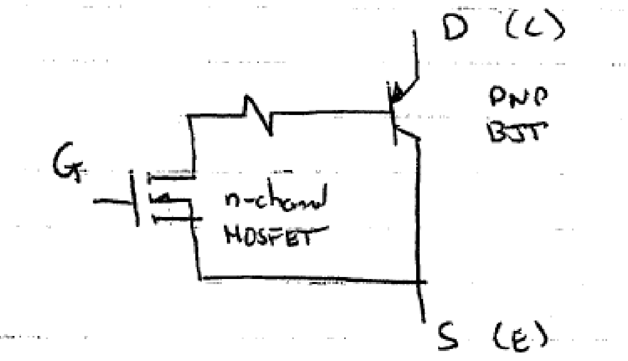


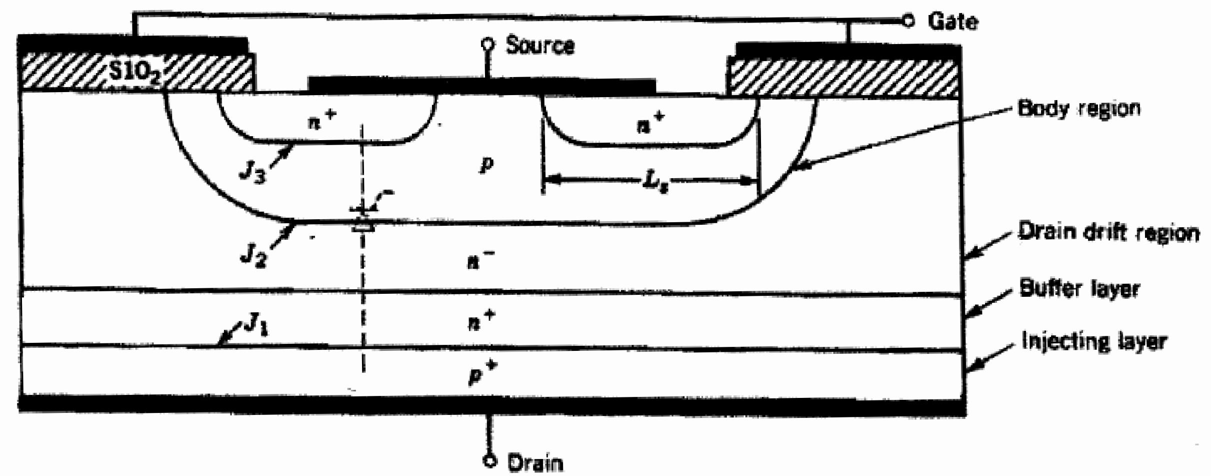
- Structure look similar to MOSFET but has some of the performance attributes of the BJT.

- Equivalent circuit sometimes drawn as



IGBT Structure





- Gate-source characteristics similar to MOSFET – high-input impedance, low power requirement.
- No body diode – must avoid excessive reverse bias voltage as this will destroy the device.

Turn-on waveforms

- At turn-on, MOSFET characteristics dominate. MOSFET current turns on internal PNP BJT section and the two sections share the current.
- During initial transient, MOSFET section carries all current.

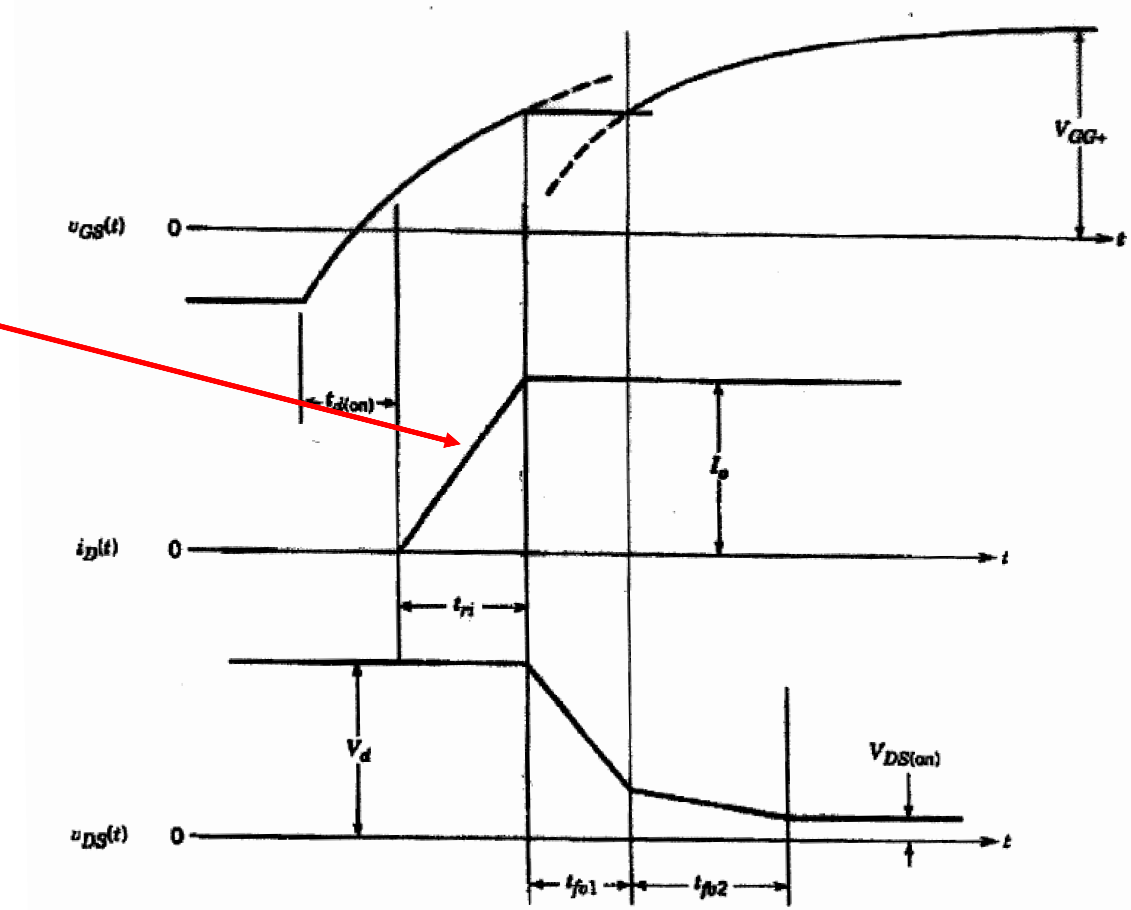


Figure 25-6 Turn-on voltage and current waveforms of an IGBT in a step-down converter circuit.

Turn-off waveforms

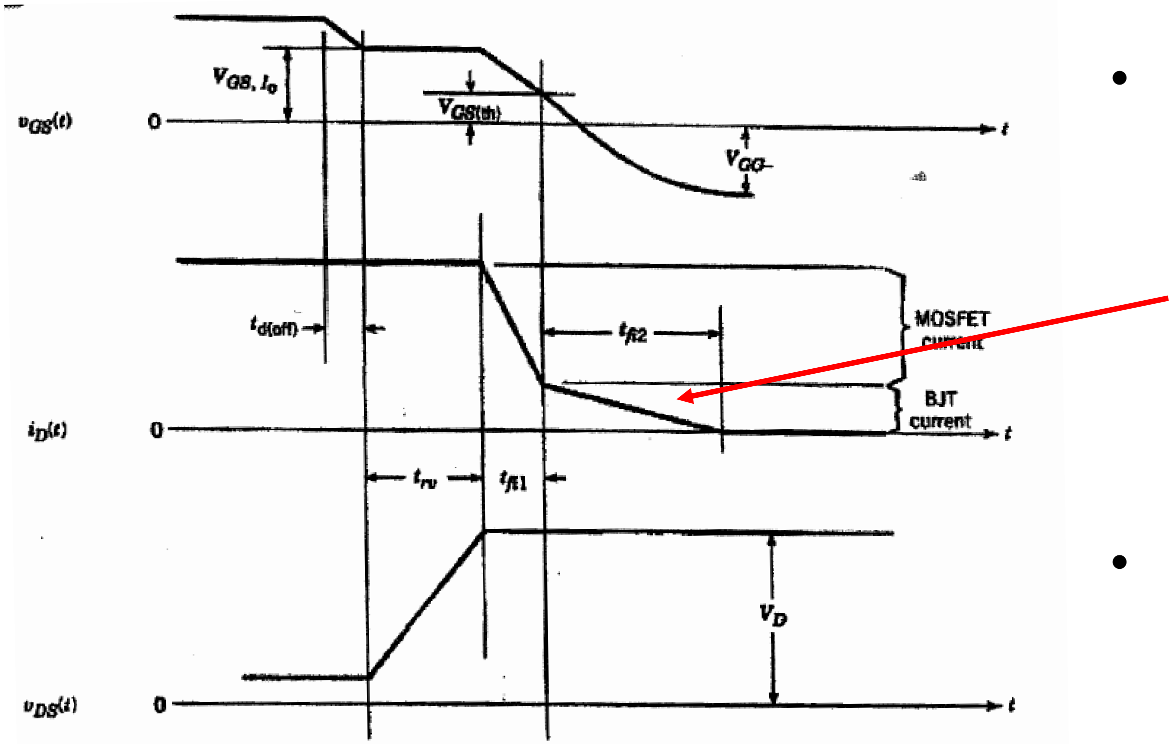


Figure 25-7 Turn-off voltage and current waveforms of an IGBT embedded in a step-down converter circuit.

- During turn-off, the MOSFET section turns-off quickly, but the BJT section turns off slower causing a current tail.
- The tail current contributes a significant lass as it conducts with off-state voltage across diode.

IGBT

Advantages over MOSFETS
- Higher voltage ratings
- Higher current ratings

Disadvantages
- Slow turn-off due to tail current
- Higher turn-off losses
- Lower switching frequencies

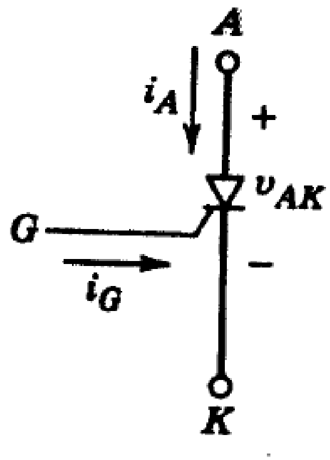
Application Areas
- Motor drive – traction drives (dc and ac), 400 – 3000V
- Utility interfaces – AC-DC, UPS, VAr compensation
- Unity power factor converters

Use
- Above 600 V use IGBT
- Below 200 V use MOSFET
- Between 200 and 600V consider both options.

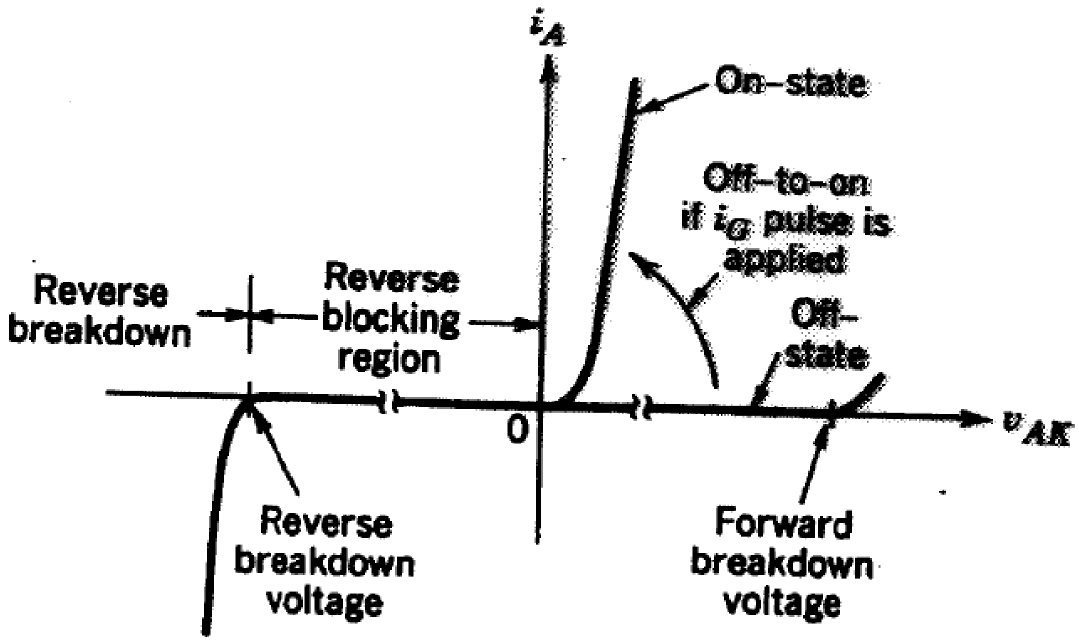
Thyristor Characteristics

- Can block voltages of both polarities
- Conducts a current from anode to cathode if a gate current is. injected when *Vak* is positive.
- Conduction will continue as long as anode current exceeds ‘latching current’.
- Conduction continues if positive-biased and anode current exceeds ‘holding current’.
- Once turned on, thyristor will continue to conduct until current falls below latching current or holding current. (You can’t turn it off).

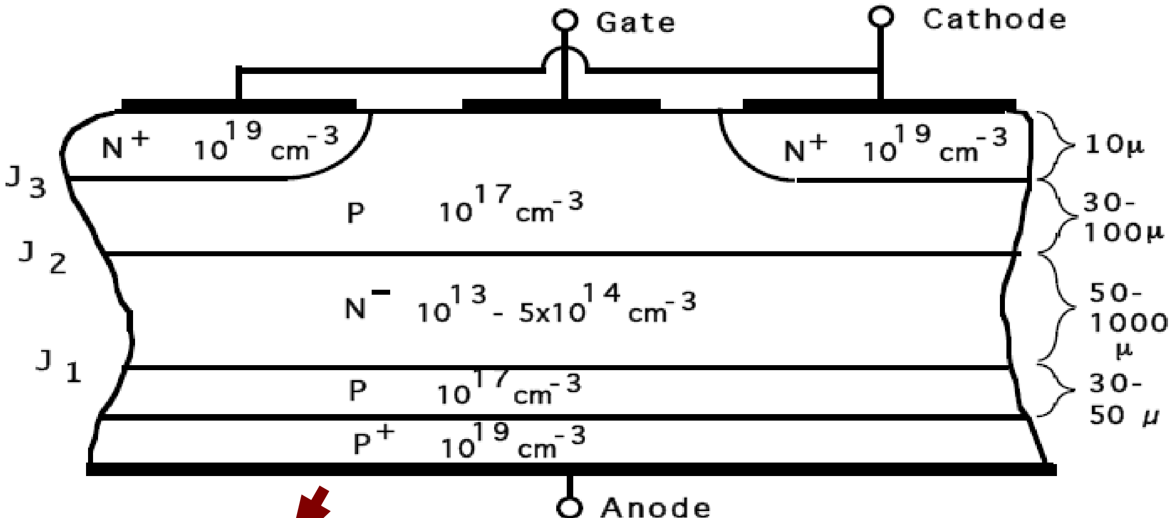
VI Characteristics



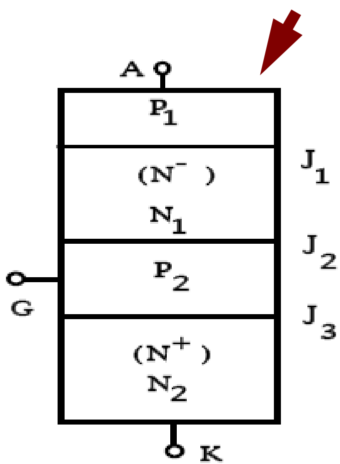
(a)



Basic Structure



- Cross-sectional view showing vertical orientation of SCR.
- SCRs with kiloamp ratings have diameters of 10 cm or greater.



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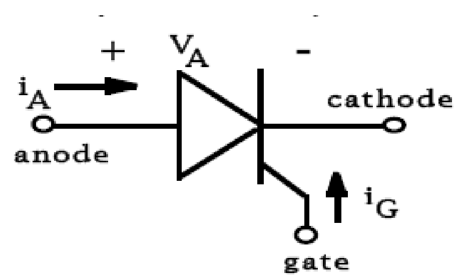
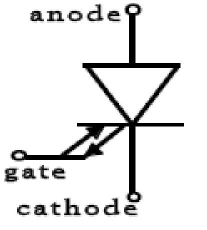


Gate-turn off thyristor (GTO)

- Like a thyristor but has the ability to turn-off if a sufficiently large gate current applied.

- Typically gate current for turn-off is 0.2 to 0.3 of the anode current. In a 1kA application this is a lot of current.



POWER ELECTRONICS I

CONTROLLED RECTIFIERS

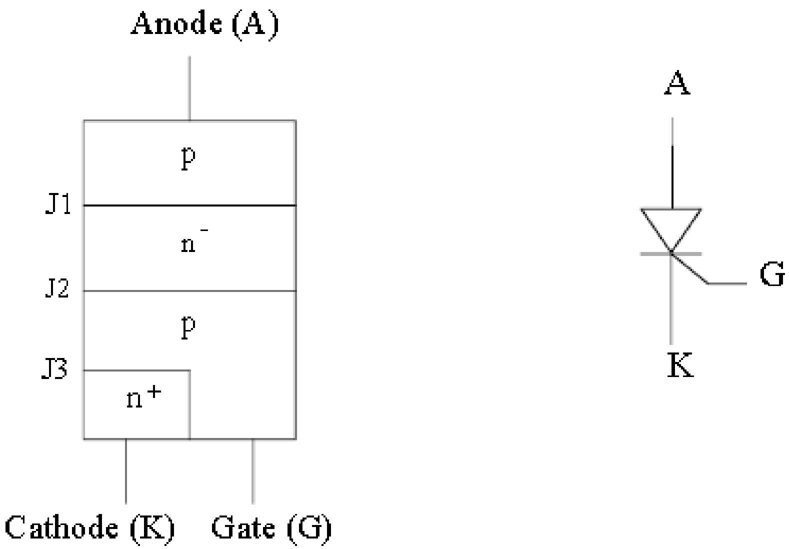
(AC-DC CONVERTERS)

Introduction

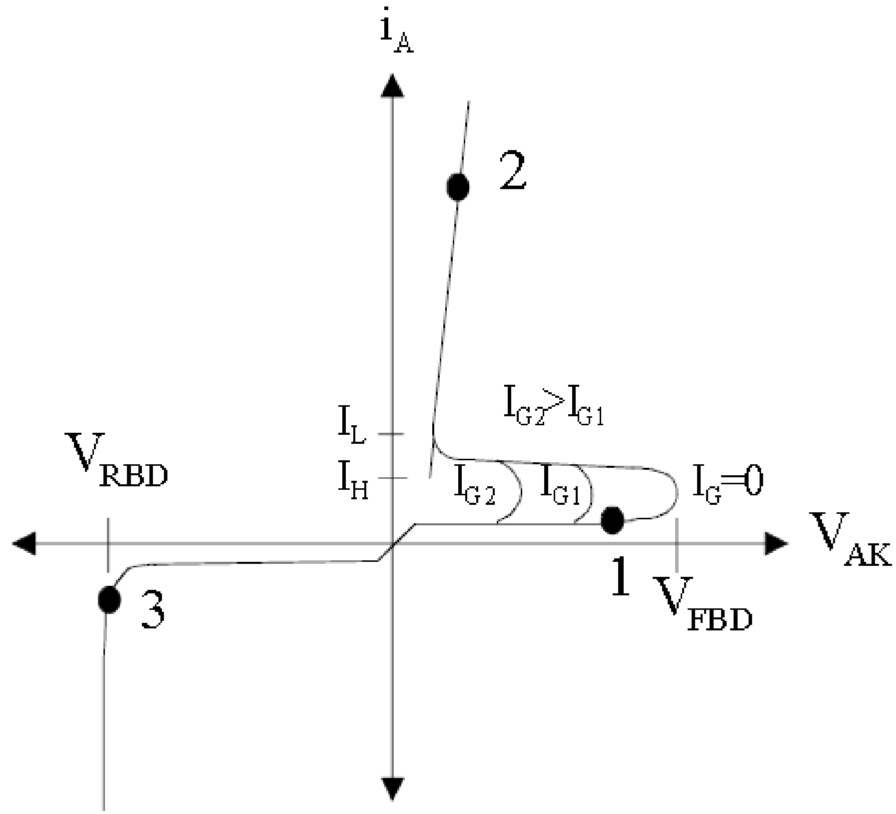
To control the output dc voltage of a rectifier, diodes are replaced with thyristors. **Thyristors** or *controlled silicon rectifier (CSR)* are commonly used in applications requiring variable dc supplies.

Thyristor [CSR]

- The thyristor (SCR) is a controllable switch which can be turned on by a gate current. A few milliamps of gate current can turn on a high current SCR, provided that the SCR anode to cathode voltage is positive.
- The thyristor (SCR) is a three-terminal switch *(Anode, Cathode, and gate)*.



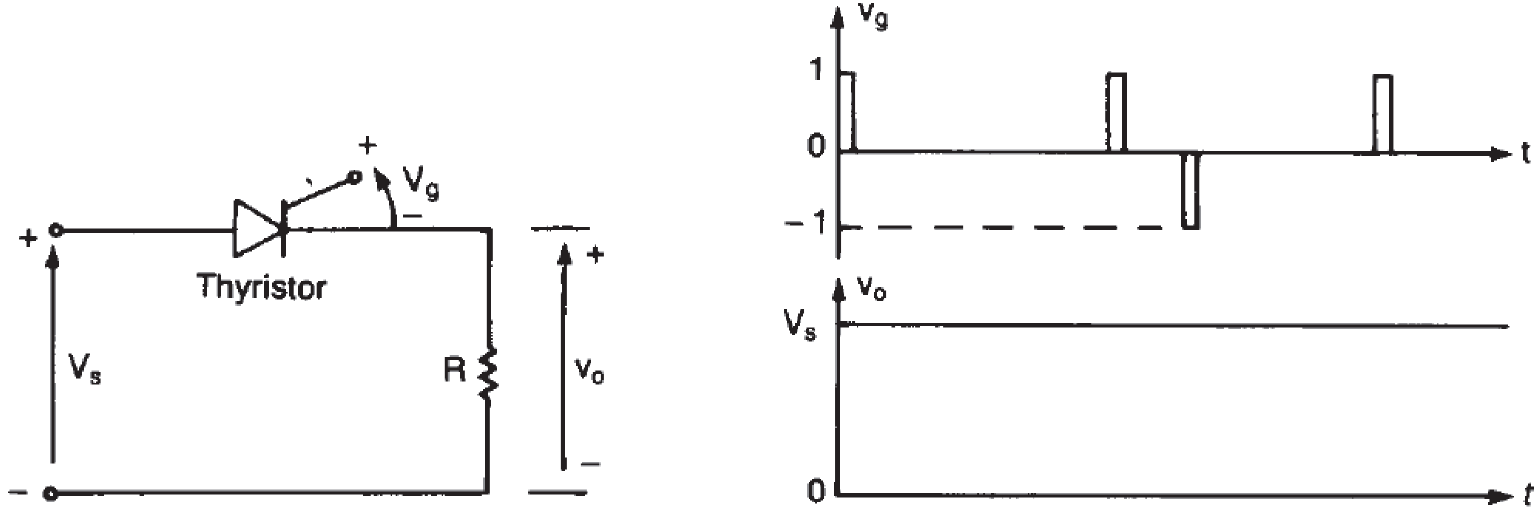
Structure and symbol of a thyristor



Characteristics of a thyristor

SCR consists of 3 p-n junctions.

When a positive voltage is applied to the anode (with respect to a cathode), the thyristor is in its forward-blocking state. A thyristor is turned on by applying a short pulse on its gate (typically 5V, 100µs).



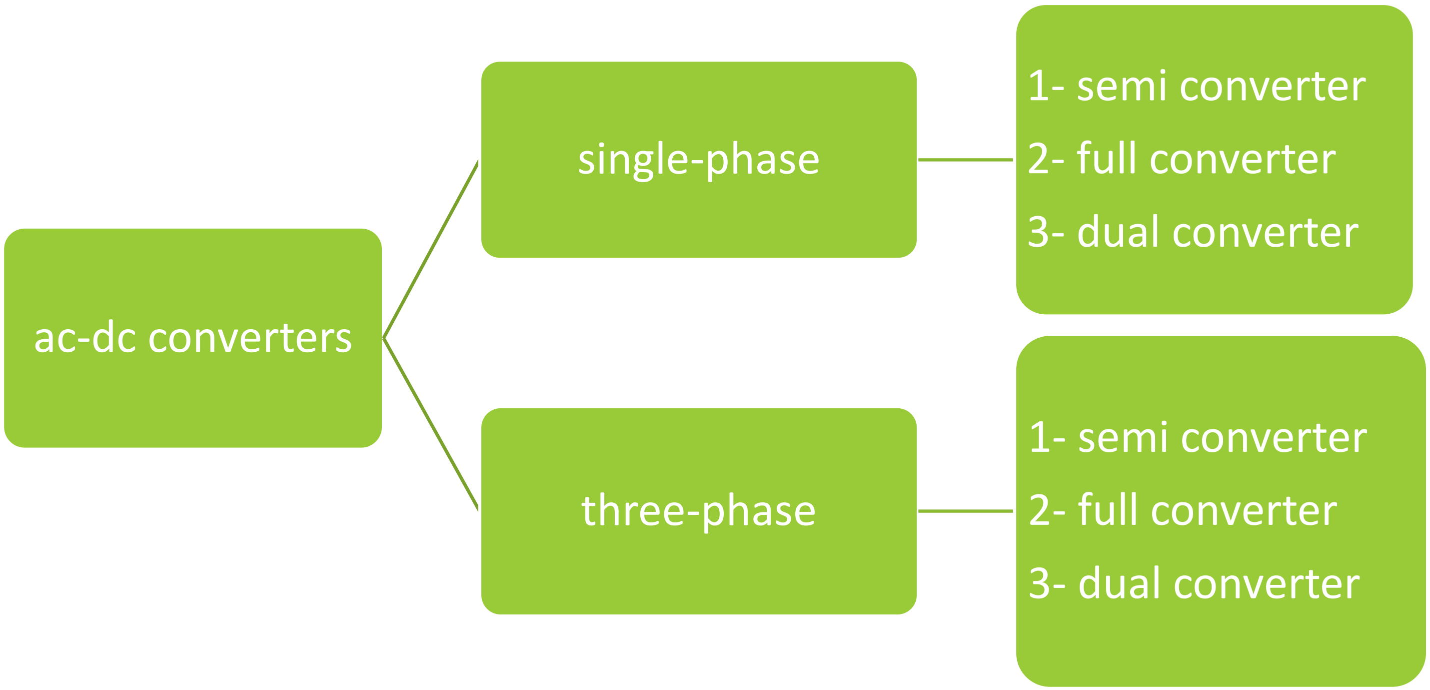
Thyristor switch

- Once a SCR is fired, the gate has no control on the device.

- A SCR turns off when the current falls below its holding current. This could be due to the load current decrease or a large reverse voltage across the SCR.

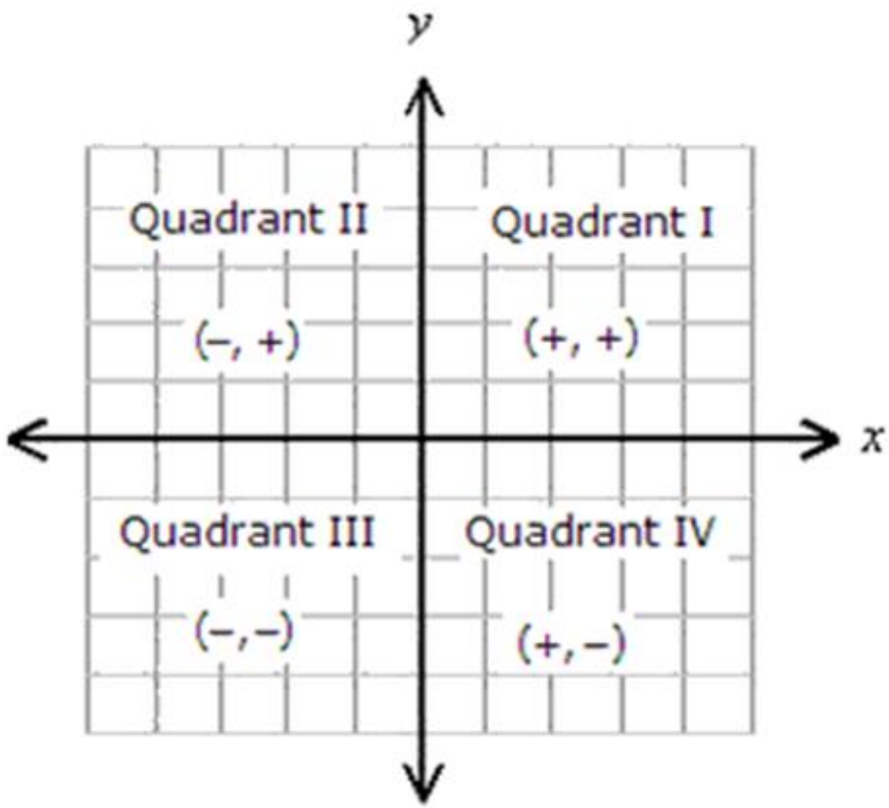
- In this lecture, a phase-control thyristor is turned on by applying short pulse to its gate and turned off due to **natural or line commutation**. And for high inductive load, it is turned off by firing another thyristor of the rectifier during the negative half-cycle of input voltage. [**forced commutation**]

- Since the rectifiers are used to convert ac to dc, these controlled rectifiers are also called ***ac-dc converters***. These converters are used extensively in industrial applications especially in variable speed drives.



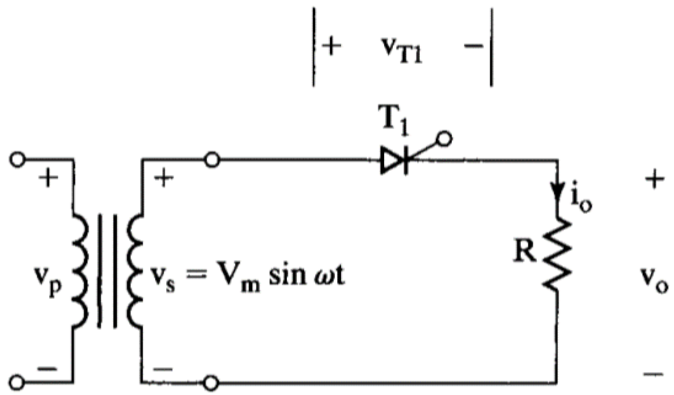
Classification of ac-dc converters

- A semi converter is a one quadrant converter. It has one polarity of output voltage and current (positive or negative). A full converter is a two quadrant converter. While a dual converter is a four quadrant converter.

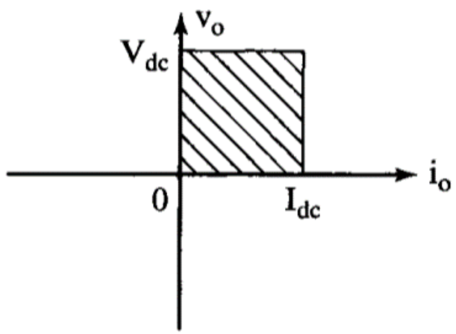


Quadrants

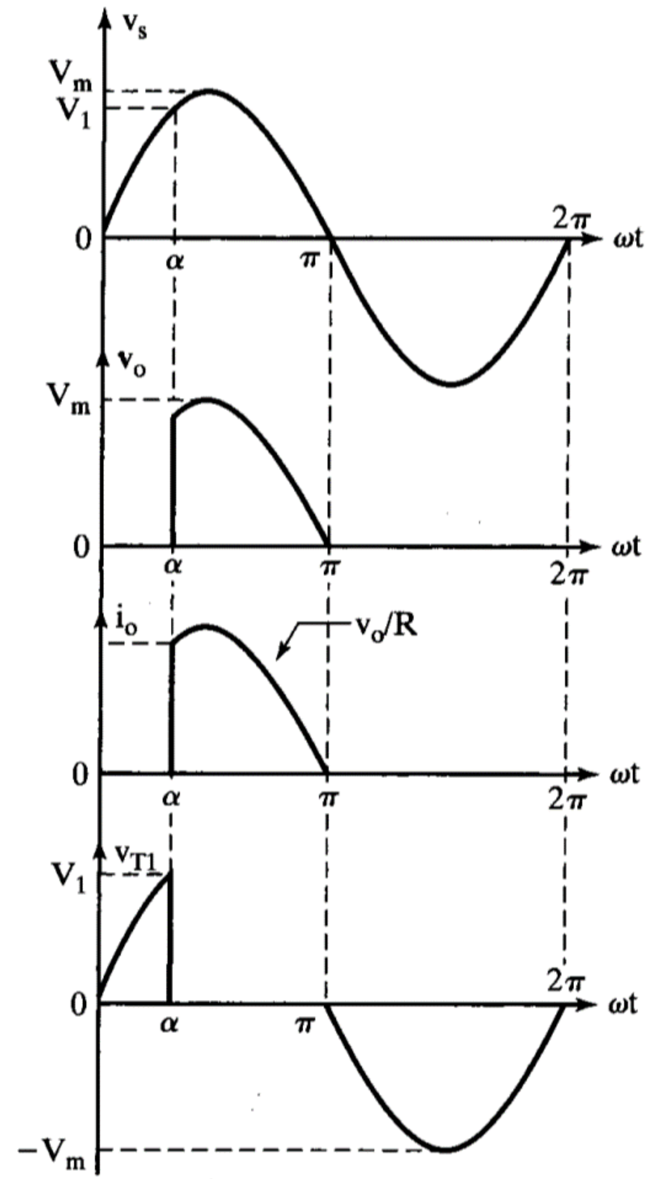
Single-phase half-wave controlled rectifier (resistive load)



(a) Circuit



(b) Quadrant



(c) Waveforms

Note that: α = Firing angle (delay angle)

The average value of output voltage

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t\, dt = \frac{V_m}{2\pi}(1+\cos\alpha)$$

Therefore, Changing the firing angle from 0 to π, the output voltage varies from Vm/π to 0.

The rms value of output voltage

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m^2\, sin^2\,\omega t\, dt} = \frac{V_m}{2}\sqrt{1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}}$$

- In this rectifier, the output voltage and current have only one polarity and thus the rectifier is called semi converter.
- This type of rectifier is not usually used in industrial applications due to the high ripple content and the low ripple frequency.
- The frequency of output ripple voltage equals the source frequency.
- The transformer carries a dc current which is not desirable.

E#1 If a single-phase half-wave controlled rectifier has a purely resistive load R and the delay angle α=π/2, determine a) the converter efficiency, b) ripple factor, and c) the PIV of the thyristor.

a) At α=π/2

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha) = 0.1592V_m$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.1592V_m}{R}$$

$$V_{rms} = \frac{V_m}{2}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}} = 0.3536V_m$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.3536V_m}{R}$$

$$\eta = \frac{P_{dc}}{P_{rms}} = \frac{V_{dc}\, I_{dc}}{V_{rms} I_{rms}} = 20.27\%$$

b) Ripple factor

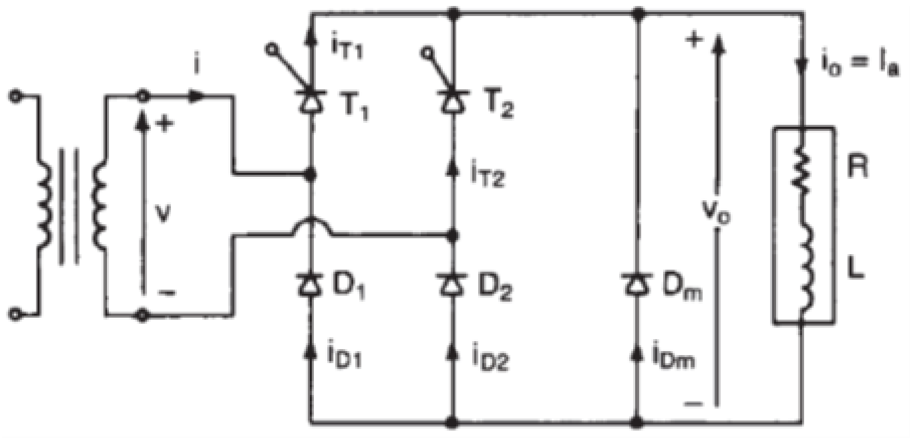
$$\mathrm{RF} = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = 1.983 \ or \ 198.3\%$$

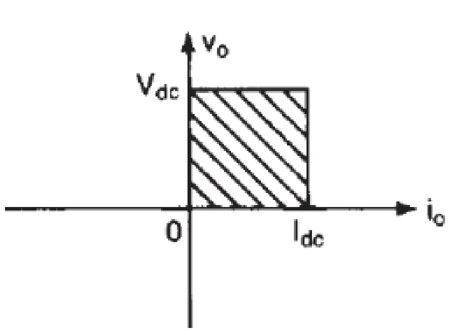
c) PIV of the thyristor

$$PIV = V_m$$

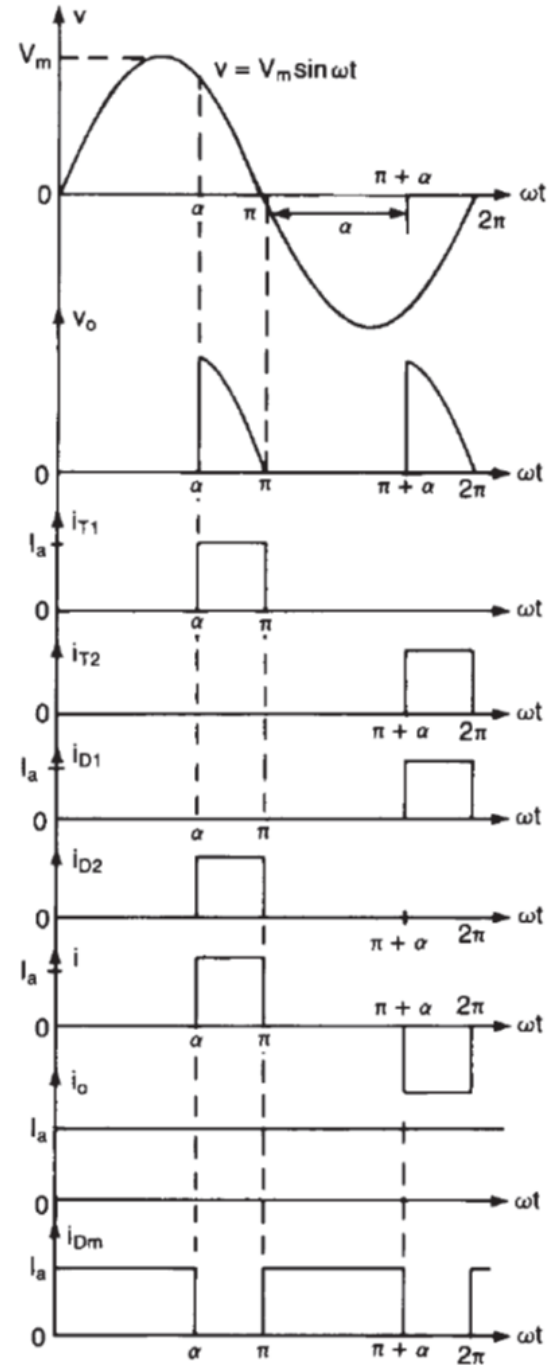
E#2 For the previous example, draw a) the output voltage, b) the load current, and c) the voltage a cross the thyristor.

Single-phase semi converter (highly inductive load)





Quadrant



This converter has a better power factor due to the freewheeling operation and is used for applications up to 15KW, when one quadrant operation is acceptable.

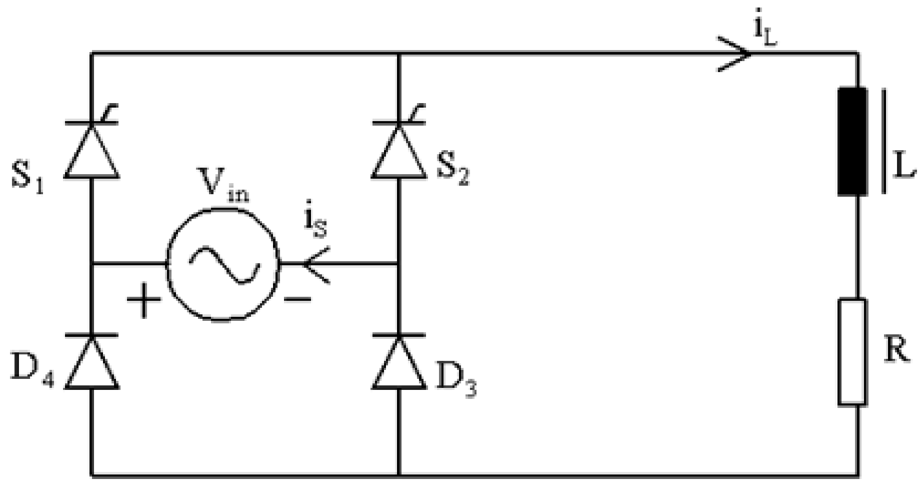
The average value of output voltage

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t\, dt = \frac{V_m}{\pi}(1 + \cos\alpha)$$

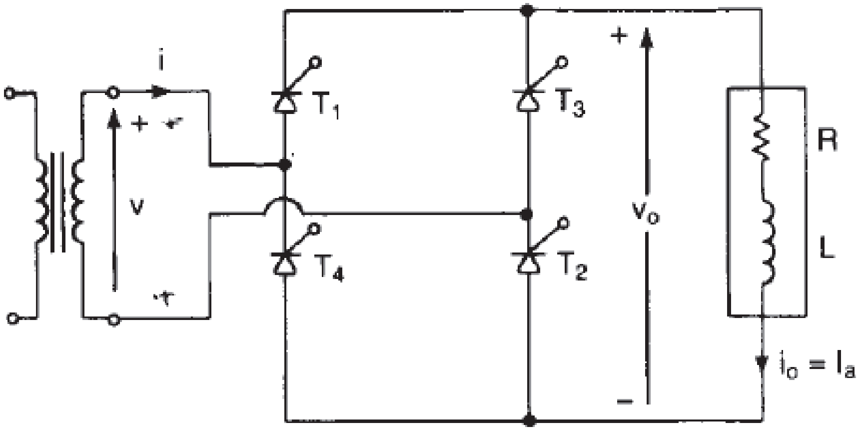
Therefore, Changing the firing angle from 0 to π, the output voltage varies from 2Vm/π to 0. **The rms value of output voltage**

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2\, sin^2\,\omega t\, dt} = \frac{V_m}{\sqrt{2}}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$

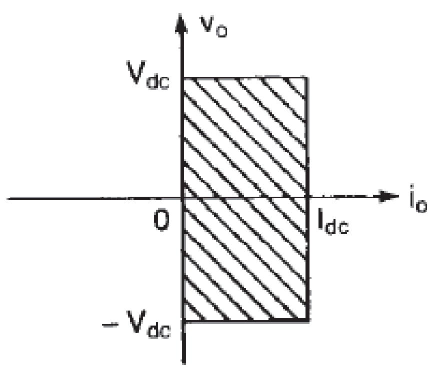
E#3 For the following is another configuration of a single-phase semi converter, if the delay angle 30 degree, draw a) the output voltage, b) the load current, and c) the voltage a cross the thyristors. Showing how the freewheeling action takes place.



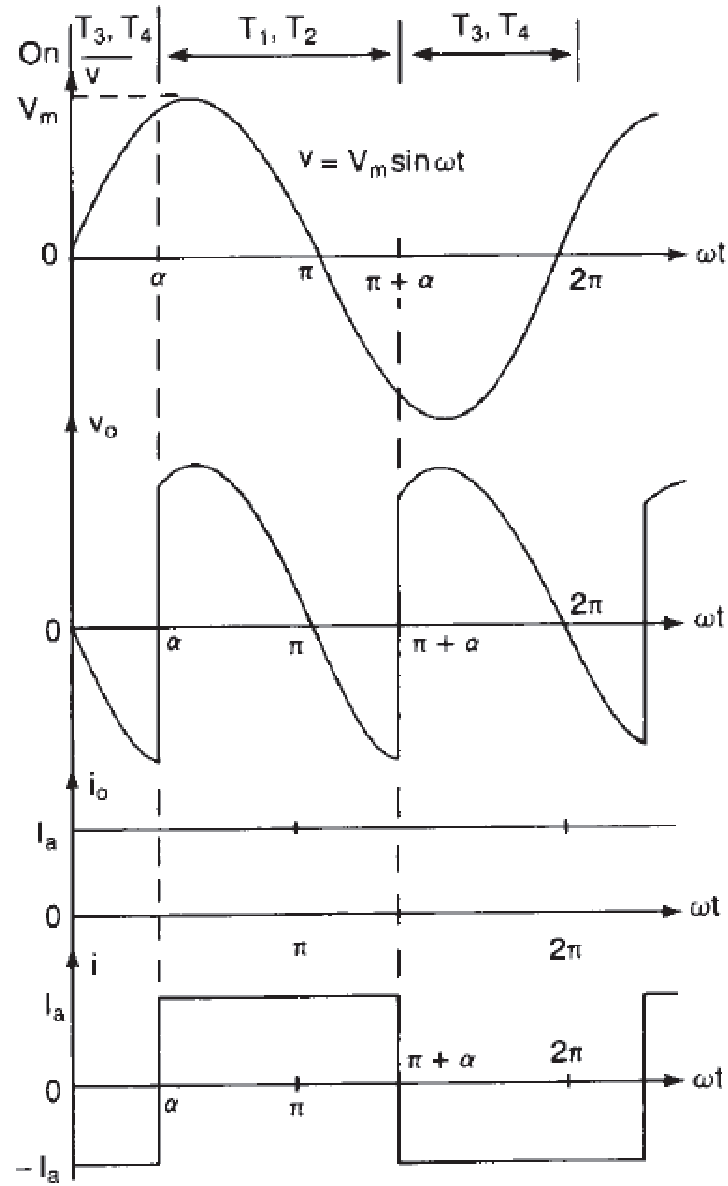
Single-phase full converter (highly inductive load)



(a) Circuit



(b) Quadrant



(c) Waveforms

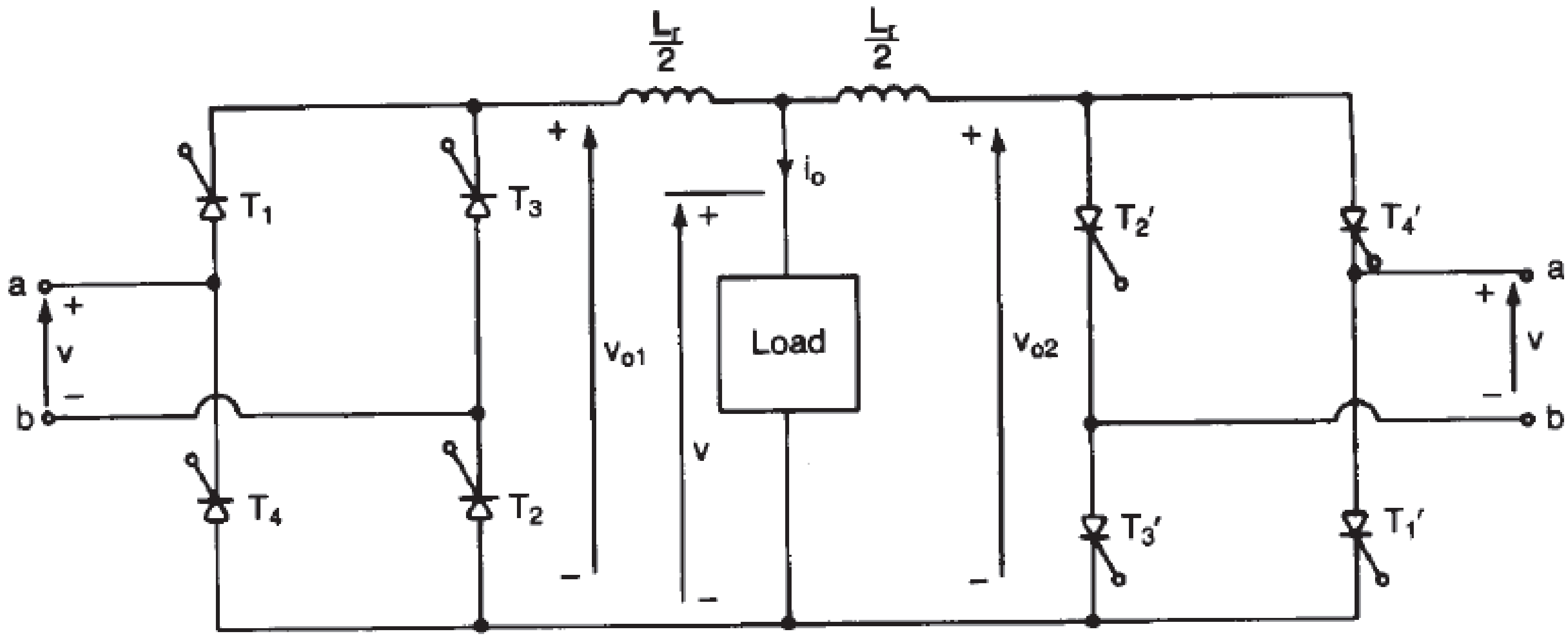
The average value of output voltage

$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, dt = \frac{2V_m}{\pi}\cos\alpha$$

Therefore, Changing the firing angle from 0 to π/2, the output voltage varies from 2Vm/π to 0. The rms value of output voltage

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m^2\, sin^2\,\omega t\, dt} = \frac{V_m}{\sqrt{2}}$$

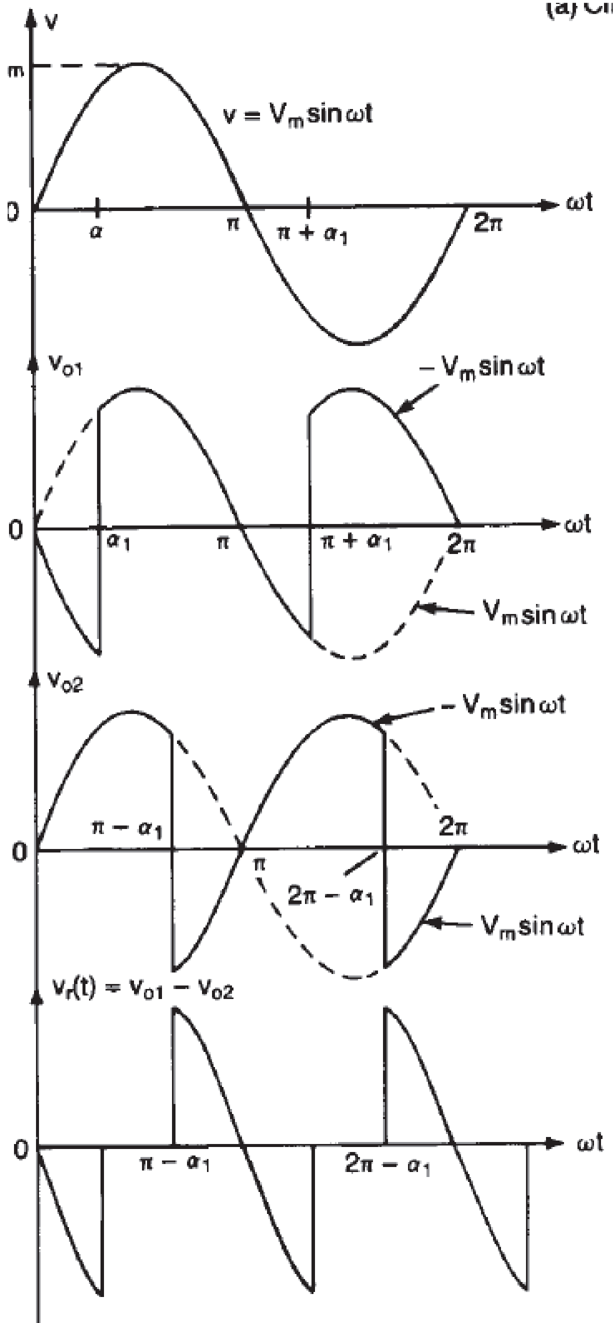
Single-phase dual converter (highly inductive load)



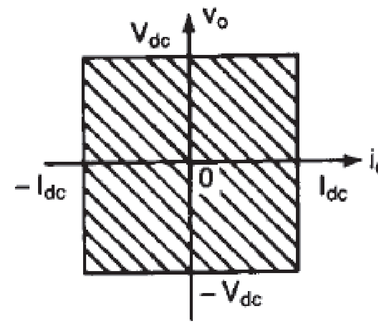
(a) Circuit

Single-phase dual converter consists of two single-phase full converter connected back to back. Thus, both output voltage and load current can be reversed. Therefore, the dual converter can be operated in the four quadrants.

(a) Circuit



(b) Waveforms



(c) Quadrant

$$V_{dc1} = \frac{2V_m}{\pi}\cos\alpha_1$$

$$V_{dc2} = \frac{2V_m}{\pi}\cos\alpha_2$$

$$V_{dc1} = -V_{dc2}$$

$$\cos\alpha_2 = -\cos\alpha_1 = \cos(\pi - \alpha_1)$$

Therefore

$$\alpha_2 = \pi - \alpha_1$$

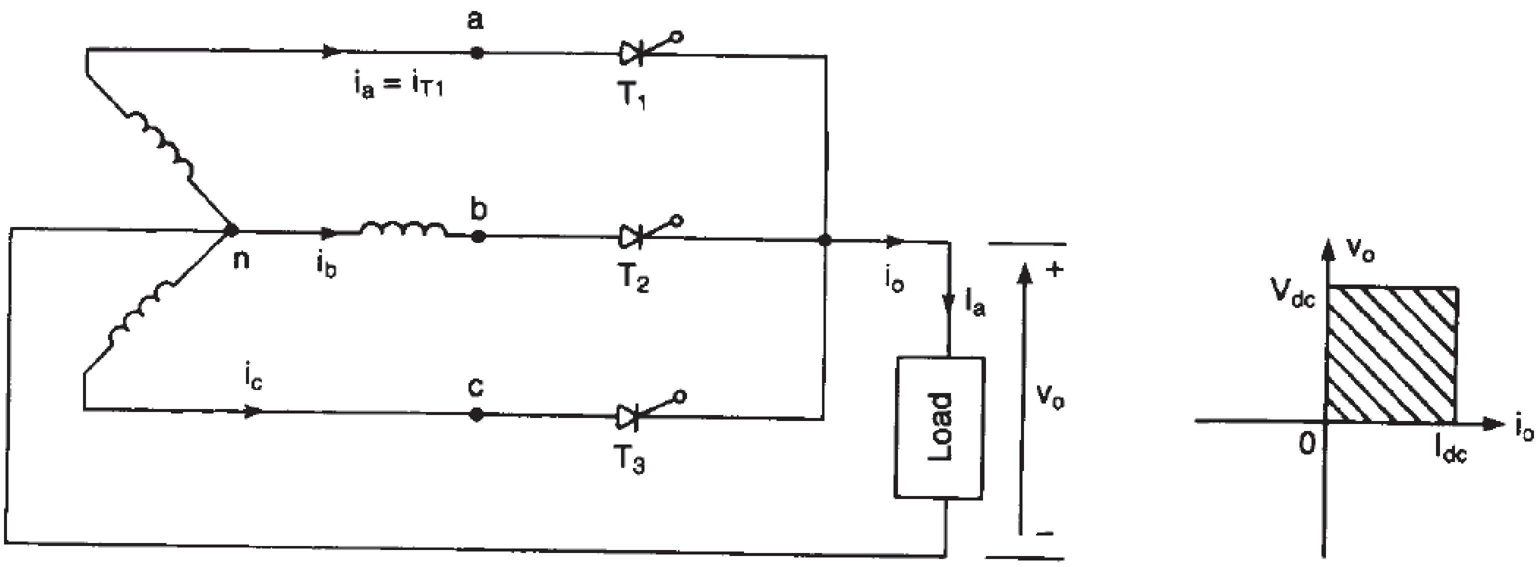
Three Phase Controlled Rectifiers

- Three-phase rectifiers provide higher average output voltage compared to the single-phase rectifier.

- The frequency of output voltage ripples in a three-phase rectifier is higher compared to the single-phase rectifier. Thus, the three-phase rectifier requires a smaller filter with a lower cost.

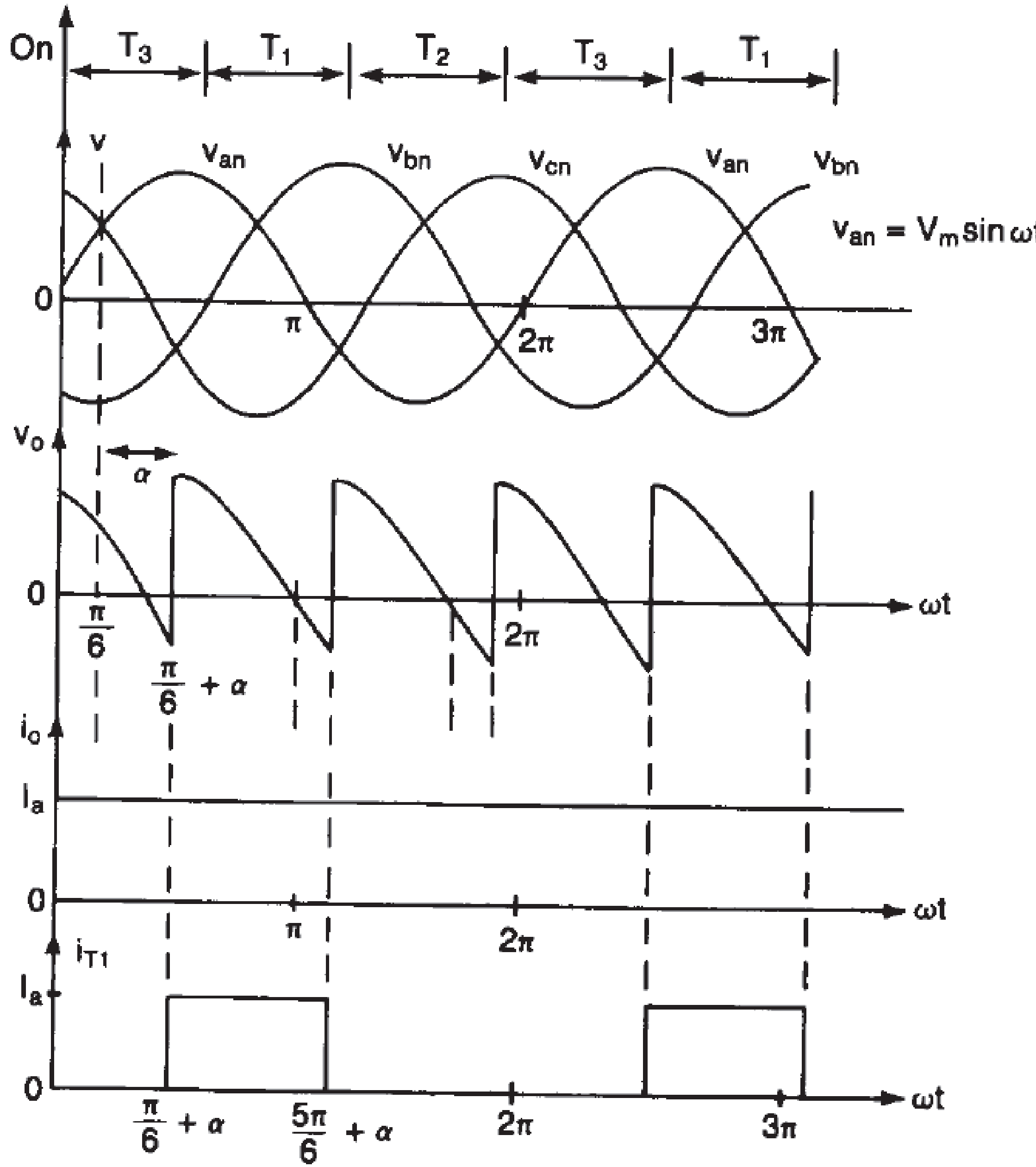
- Three-phase rectifiers are extensively used in high-power industrial applications including variable-speed motor drives.

Three Phase half-wave Controlled Rectifiers



(a) Circuit

(b) Quadrant



On
T3
T1
T2
T3
T1
v
van
vbn
vcn
van
vbn
van = Vm sin ωt
0
π
2π
3π
vo
α
0
π/6
π/6 + α
2π
ωt
io
Ia
0
π
2π
ωt
iT1
Ia
0
π/6 + α
5π/6 + α
2π
3π
ωt

$$V_{dc} = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{5\pi/6+\alpha} V_m \sin \omega t \, d(\omega t) = \frac{3\sqrt{3}\,V_m}{2\pi} \cos \alpha$$

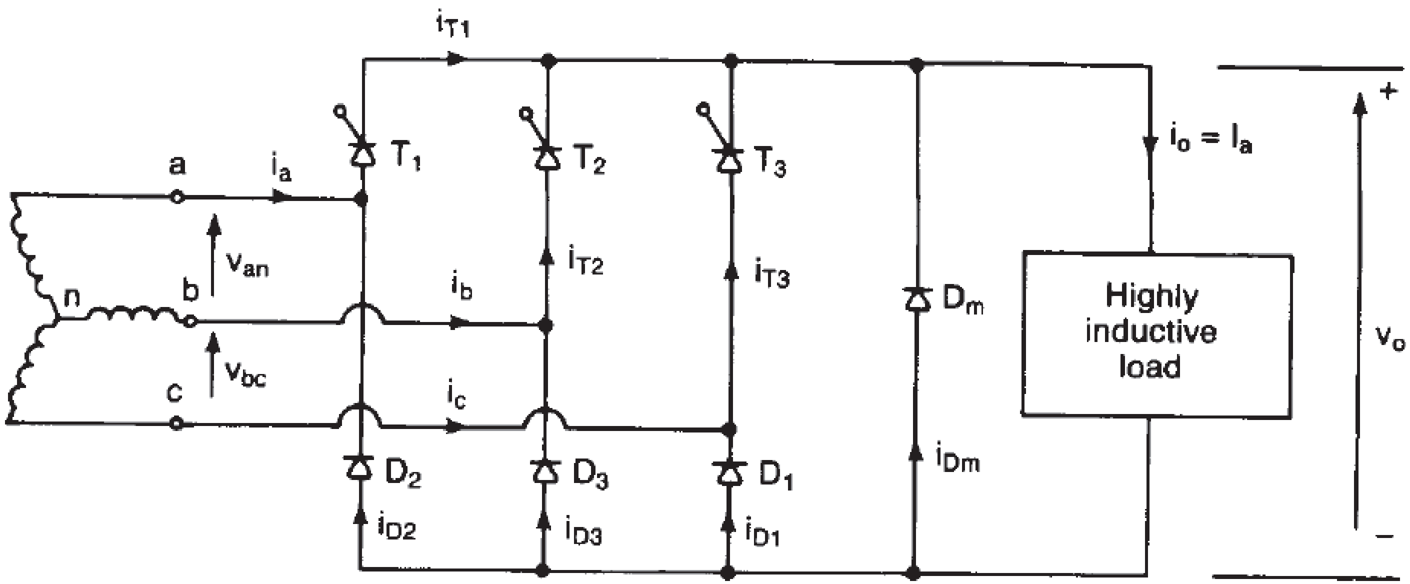
The rms output voltage is found from

$$V_{rms} = \left[\frac{3}{2\pi} \left[\int_{\pi/6+\alpha}^{5\pi/6+\alpha} V_m^2 \, sin^2 \, \omega t \, d(\omega t) \right] \right]^{1/2}$$

$$= \sqrt{3}\, V_m \left(\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right)^{1/2}$$

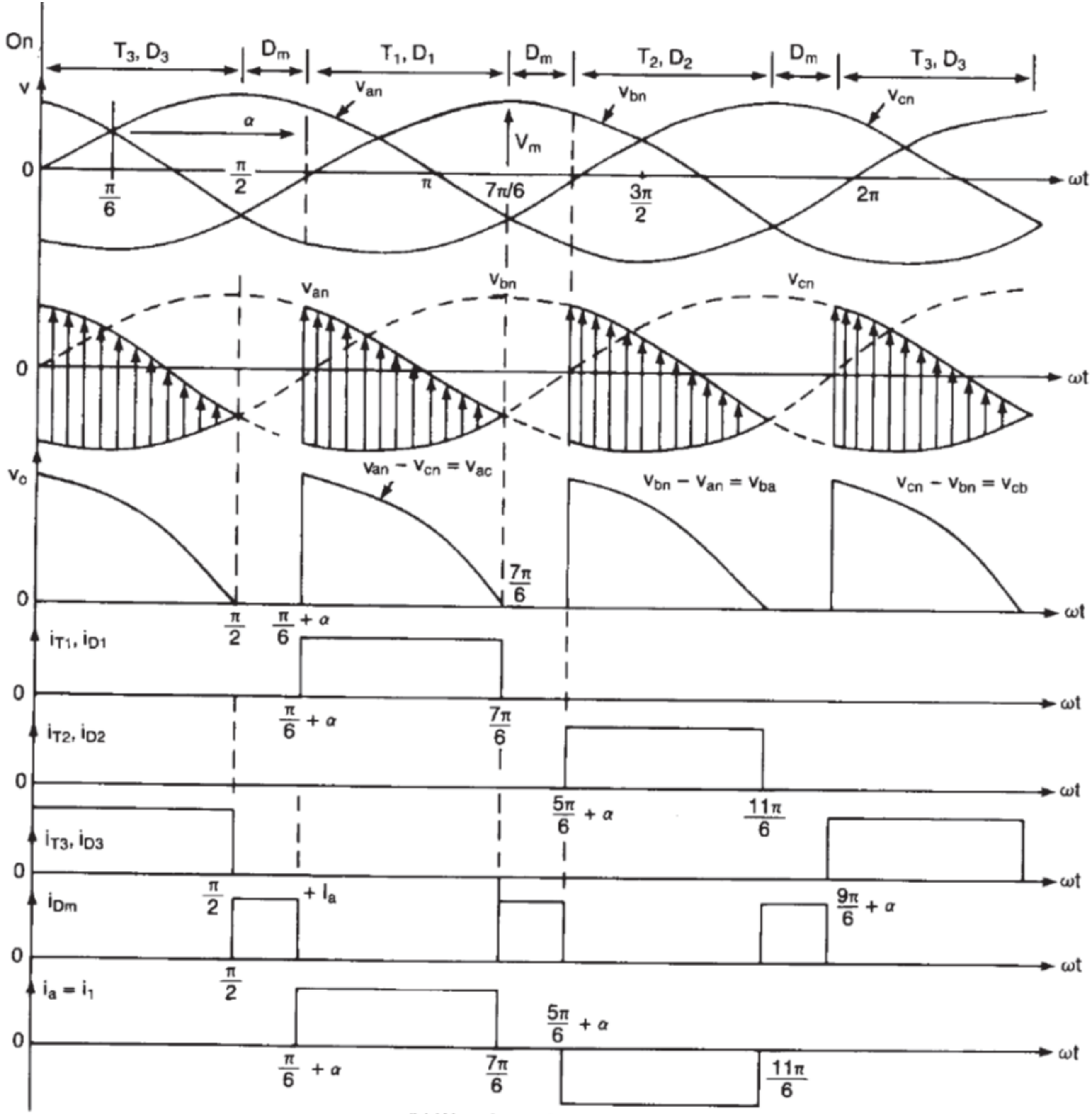
A three-phase half-wave converter in Fig. 4-7a is operated from a three-phase Y-connected 208-V 60-Hz supply and the load resistance is $R = 10\ \Omega$. If it is required to obtain an average output voltage of 50% of the maximum possible output voltage, calculate the (a) delay angle α; (b) rms and average output currents; (c) average and rms thyristor currents; (d) rectification efficiency; (e) transformer utilization factor, TUF; and (f) input power factor, PF.

Three Phase semi-converter



(a) Circuit

I



(b) Waveforms for α = 90°

$$V_{dc} = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} v_{ac}\, d(\omega t) = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} \sqrt{3}\, V_m \sin\left(\omega t - \frac{\pi}{6}\right) d(\omega t)$$

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

The rms output voltage is found from

$$V_{rms} = \left[\frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} 3V_m^2 \sin^2\left(\omega t - \frac{\pi}{6}\right) d(\omega t)\right]^{1/2}$$

$$= \sqrt{3}\, V_m \left[\frac{3}{4\pi}\left(\pi - \alpha + \frac{1}{2}\sin 2\alpha\right)\right]^{1/2}$$

For $\alpha \leq \pi/3$, and continuous output voltage:

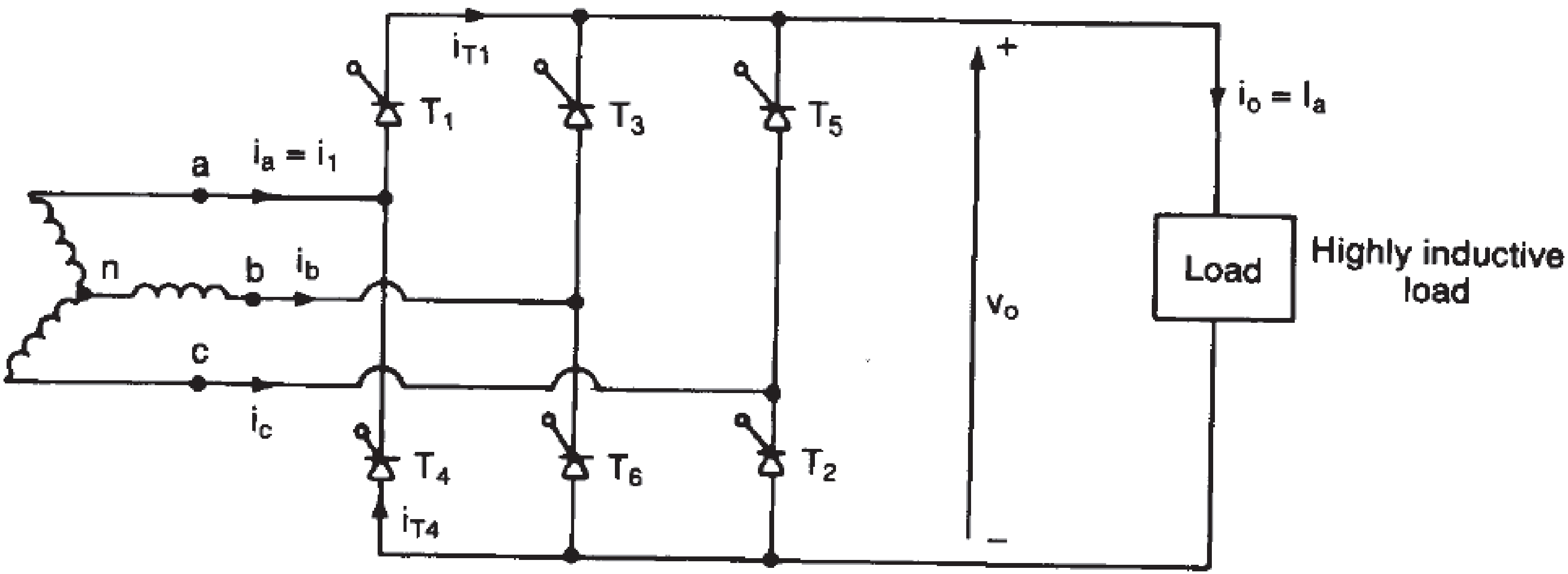
$$V_{dc} = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{5\pi/6+\alpha} v_{ac}\, d(\omega t) = \frac{3\sqrt{3}\, V_m}{2\pi} (1 + \cos \alpha)$$

$$V_n = \frac{V_{dc}}{V_{dm}} = 0.5(1 + \cos \alpha)$$

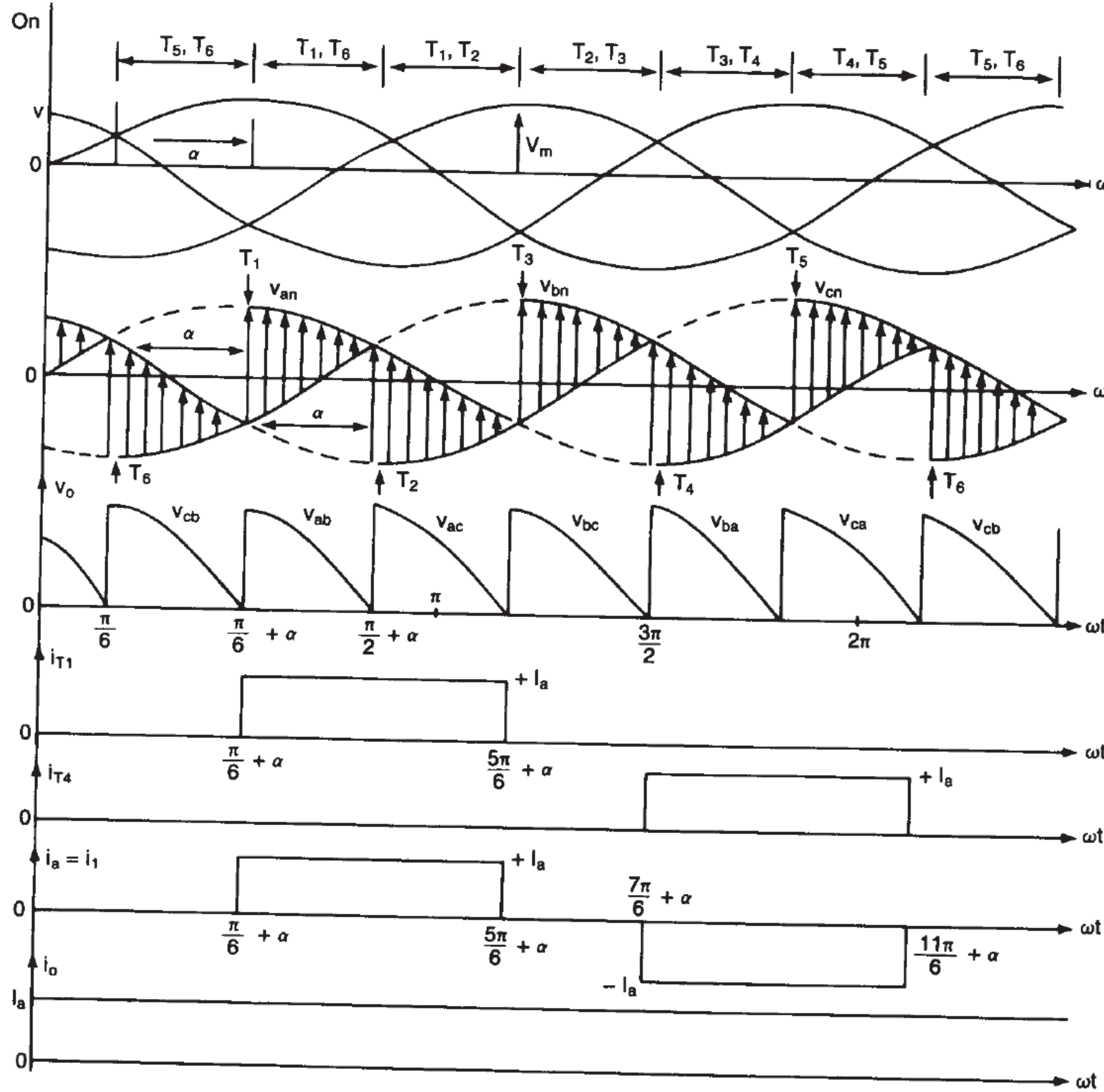
$$V_{rms} = \left[\frac{3}{2\pi} \int_{\pi/6+\alpha}^{5\pi/6+\alpha} 3V_m^2 \sin^2 \left(\omega t - \frac{\pi}{6} \right) d(\omega t) \right]^{1/2}$$

$$= \sqrt{3}\, V_m \left[\frac{3}{4\pi} \left(\pi - \alpha + \frac{1}{2} \sin 2\alpha \right) \right]^{1/2}$$

Three Phase Full Converter



(a) Circuit


On
T5, T6
T1, T6
T1, T2
T2, T3
T3, T4
T4, T5
T5, T6
v
0
α
Vm
ωt
T1
T3
T5
van
vbn
vcn
T6
T2
T4
T6
vo
vcb
vab
vac
vbc
vba
vca
vcb
π/6
π/6 + α
π/2 + α
π
3π/2
2π
iT1
+ Ia
5π/6 + α
iT4
ia = i1
7π/6 + α
11π/6 + α
− Ia
io
Ia

(b) Waveforms

The average output voltage is found from

$$V_{dc} = \frac{3}{\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} v_{ab}\, d(\omega t) = \frac{3}{\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} \sqrt{3}\, V_m \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t)$$

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

The rms value of the output voltage is found from

$$V_{rms} = \left[\frac{3}{\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} 3V_m^2 \sin^2\left(\omega t + \frac{\pi}{6}\right) d(\omega t)\right]^{1/2}$$

$$= \sqrt{6}\, V_m \left(\frac{1}{4} + \frac{3\sqrt{3}}{8\pi} \cos 2\alpha\right)^{1/2}$$

The three-phase full, Y-connected 208 V, 60 Hz controlled rectifier has a resistive load R=10 ohms. The average output voltage needs to be 50% of the maximum average voltage.

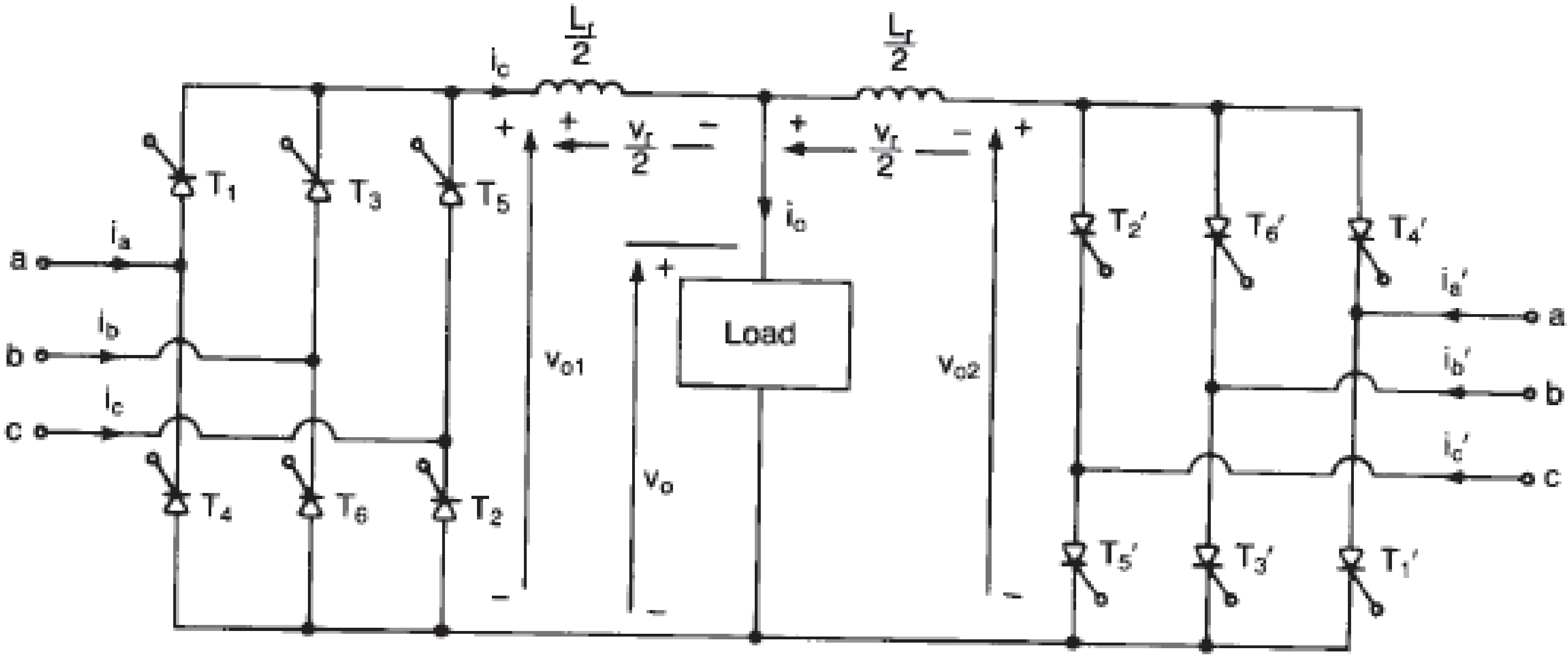
Calculate

a) the delay angle a

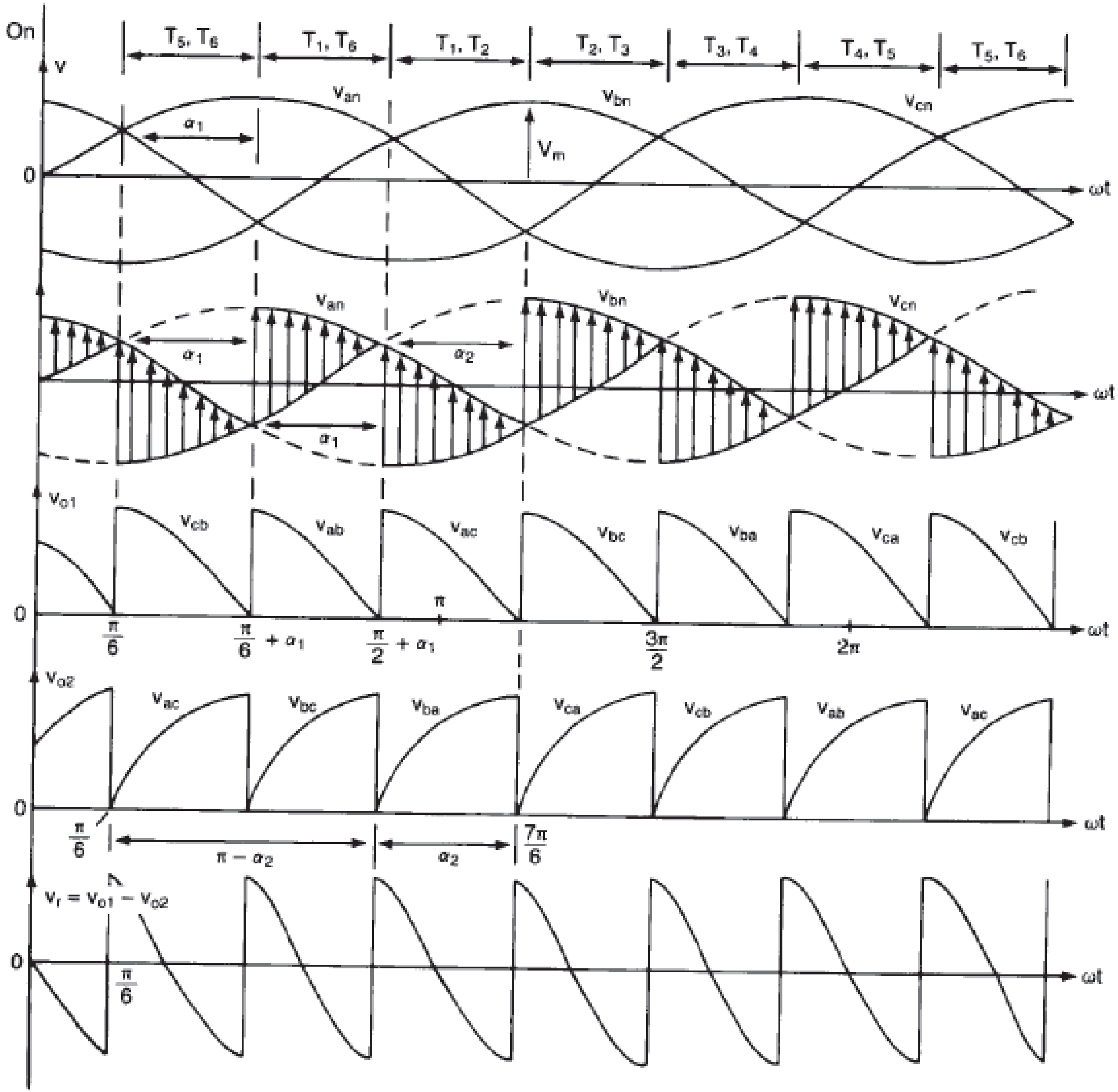
b) the average and rms output currents

c) the average and rms thyristor currents

Three Phase dualConverter



(a) Circuit


On
T_5, T_6
T_1, T_6
T_1, T_2
T_2, T_3
T_3, T_4
T_4, T_5
T_5, T_6
v
v_{an}
v_{bn}
v_{cn}
α_1
V_m
0
ωt
α_2
v_{o1}
v_{cb}
v_{ab}
v_{ac}
v_{bc}
v_{ba}
v_{ca}
v_{cb}
π
$\frac{\pi}{6}$
$\frac{\pi}{6} + \alpha_1$
$\frac{\pi}{2} + \alpha_1$
$\frac{3\pi}{2}$
2π
v_{o2}
v_{ac}
v_{bc}
v_{ba}
v_{ca}
v_{cb}
v_{ab}
v_{ac}
$\pi - \alpha_2$
$\frac{7\pi}{6}$
$v_r = v_{o1} - v_{o2}$

(b) Waveforms

If v_{o1} and v_{o2} are the output voltages of converters 1 and 2, the instantaneous voltage across the inductor during interval $(\pi/6 + \alpha_1) \le \omega t \le (\pi/2 + \alpha_1)$ is

$$v_r = v_{o1} - v_{o2} = v_{ab} - v_{bc}$$

$$= \sqrt{3}V_m \left[\sin\left(\omega t + \frac{\pi}{6}\right) - \sin\left(\omega t - \frac{\pi}{2}\right)\right] \tag{4-63}$$

$$= 3V_m \cos\left(\omega t - \frac{\pi}{6}\right)$$

The circulating current can be found from

$$i_r(t) = \frac{1}{\omega L_r}\int_{\pi/6+\alpha_1}^{\omega t} v_r\, d(\omega t) = \frac{1}{\omega L_r}\int_{\pi/6+\alpha_1}^{\omega t} 3V_m \cos\left(\omega t - \frac{\pi}{6}\right) d(\omega t)$$

$$= \frac{3V_m}{\omega L_r}\left[\sin\left(\omega t - \frac{\pi}{6}\right) - \sin\alpha_1\right] \tag{4-64}$$

The circulating current depends on delay angle and on inductance, L_r. This current becomes maximum when $\omega t = 2\pi/3$ and $\alpha_1 = 0$. Even without any external load, the converters would be continuously running due to the circulating current as a result of ripple voltage across the inductor. This allows smooth reversal of load current during the change over from one quadrant operation to another and provides fast dynamic responses, especially for electrical motor drives.

UPS-UNINTERRUPTABLE POWER SUPPLIES

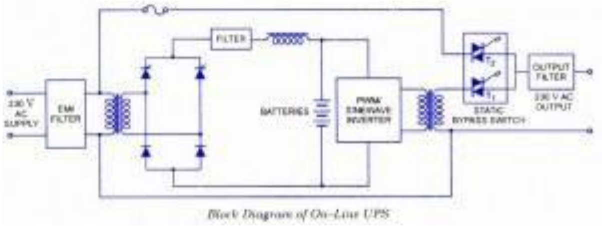
Most of us take the mains ac supply for granted and use it almost casually without giving the slightest thought to its inherent shortcomings and the danger posed to sophisticated and sensitive electronic instruments/equipments. For ordinary household appliances such as incandencent lamps, tubes, fans, TV and fridge, the mains ac supply does not make much difference, but when used for computers, medical equipments and telecommunica¬tion systems, a clean, stable interruption free power supply is of the utmost importance. Of the myriad of devices, processes and systems which rely on ac power, computers are probably the most sensitive to power disturbances and failures. Interruptions in power supply may cause the contents of a memory to be lost or corrupted, the entire system to malfunction or fail, or even variety of components failures to occur, all of which not only result in inconvenience but also loss of money.

As more and more PCs, word processors and data terminals find their way into small business, UPS systems that meet the power requirements and price range needs of even the small business organizations and offices are being manufactured.

Uninterruptible Power Supply Systems.

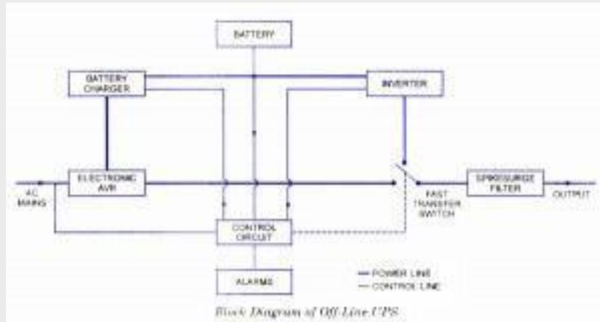
There are three distinct types of uninterrupted power supplies, namely, (£) on-line UPS (ii) off-line UPS, and (Hi) electronic generators. In the on-line UPS, whether the mains power is on or off, the battery operated inverter is on all the time and supplies the ac output voltage. When the mains power supply goes off, the UPS will be on only until the battery gets discharged. When the main power resumes, the battery will get charged again. In off-line UPS and electronic generators, ther inverter is off when the mains power is present and the output voltage derived directly from the mains is the same as the mains supply voltage. The inverter turns on only when the mains supply goes off.

Online UPS:



Online UPS Block Diagram

In case of On-line UPS, the battery operated inverter works continuously whether the mains supply is present or not. Triac T_1 is on for all the times while Triac T_2 has been provided to bypass the UPS inverter, only when a fault develops in the UPS inverter. When the mains supply fails, the UPS supplies power only until the batteries get discharged. However, once the mains power resumes, the batteries will get charged again. The switching times of these supplies is considered to be zero. Usually sealed maintenance free batteries are used and the running time of the inverter is low (approximately 10 to 30 minutes).



Offline UPS Block Diagram

In the case of Off-Line UPS, the inverter is off when the mains power is on and the output voltage is derived directly from the mains. The inverter turns on only when the mains supply fails. Its switching time is less than 5 ms. These UPS are generally used with PCs or computers or other appliances where a small duration (5 ms or less) interruption in power supply can be tolerated. Usually, sealed batteries or lead-acid batteries are used. The running time of these supplies is also low (about 10 to 30 minutes).

The demand is the highest for the electronic generators meant for house hold applications, followed by the off-line UPS, and then the on-line UPS systems. The off-line or online UPS systems are mainly used in places where PCs or computers are used. The demand for on-line UPS systems is less than for off-line UPS systems because the price of the on-line UPS systems is higher.