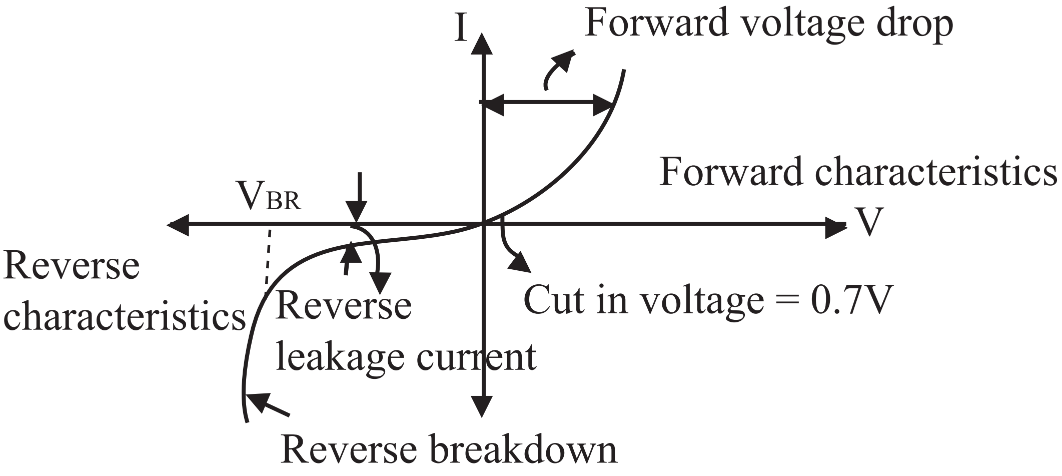
Power Semiconductor Devices

Power semiconductor devices that find application in power electronics are those which can act as power switches. The common power semiconductor switches are diodes, bipolar junction transistors (BJTs), thyristors, gate turn - OFF thyristors (GTO), Triac, metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs). The simplest of the power devices is the power semiconductor diode. These are devices that are used for rectification purpose to generate DC voltage from AC source.

Characteristics of Powe Diodes

(a) Diode V-I characteristics



Types of Power Diode

Parameter Diode	t_{rr}	Voltage rating	Current rating	Application
General Purpose diode	25µsec	50V - 5 kv	1A - 1000A	• Battery charging • Ups
Fast recovery diode	5µsec	50v - 3 kv	1A - 1000A	• Choppers • SMPS
Fast recovery diode	Nano second	100 V in reverse direction	1A - 300 A	• High frequency instruments • Switching power supplies

Bipolar Junction Transistor

Power bipolar transistors, also called bipolar junction transistors (BJT), are used to handle bulk power. These were the first semiconductor devices that approximated an ideal fully controlled power switch which allows power flow when the device is ON and blocks power when OFF, completely controlled by a separate control input. The BJTs were used to control power at signal levels for a long time. However, many devices designed in the transistor category after these, with superior performance parameters, have now replaced BJTs. The construction and operating characteristics of a power BJT differs significantly from the signal level BJTs due to the requirement for a large blocking voltage in the OFF state and a much higher current carrying capacity in the ON state.

Static Characteristics of BJTs

The BJT is a current-controlled device. The base-emitter junction is equivalent to a simple p-n junction. The I_B vs. V_{BE} characteristics with increasing V_{CE} are shown in Fig. (a). the output characteristics, that is , I_C versus V_{CE} depends on the base current I_B . Figure (b) shows the output characteristics (I_C vs. V_{CE}) of a NPN transistor.

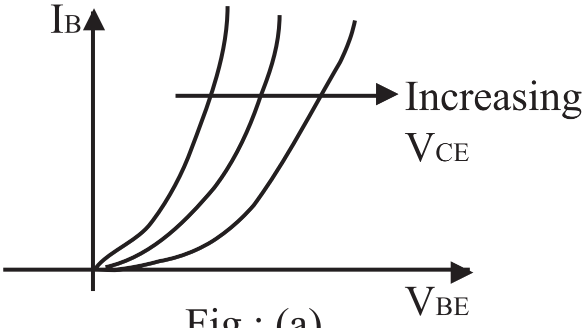


Fig : (a)

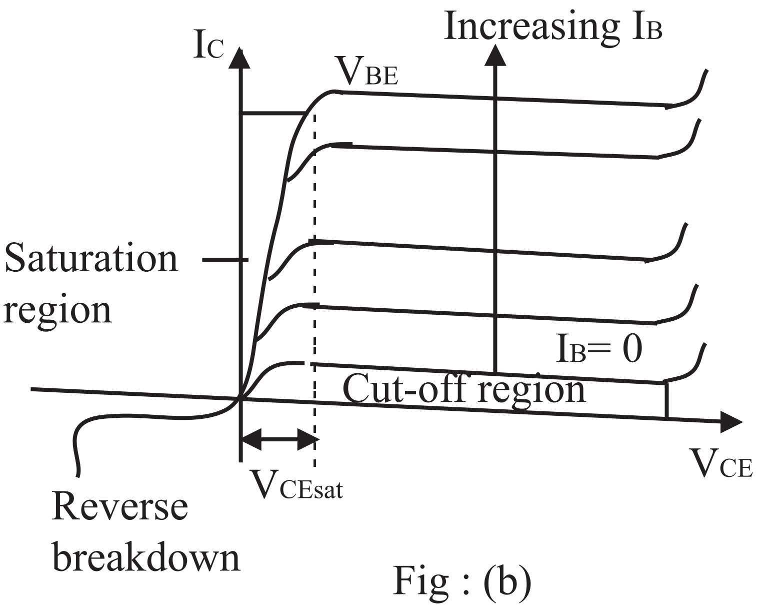


Fig : (b)

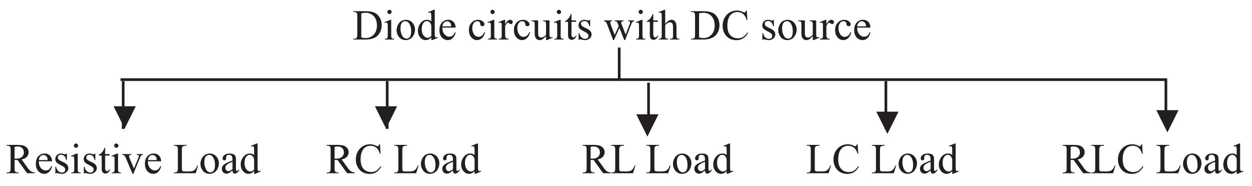
For zero or negative base voltage, that is, for $V_{BB} = 0$ or negative, amount of injected minority carrier into the base from the emitter side is small. Therefore in this condition $I_B = 0$ and the collector current I_C is negligibly small. Thus the transistor is said to be in the cut-off or OFF region under this condition. Here the transistor is capable for supporting applied external voltage.

As the base voltage V_{BB} is increased from zero, the base current starts increasing. From eq. it is evident that the collector current will also increase proportionately independent of V_{CE} . However, Fig (b) depicts that for given I_B , the collector current (I_C) shows a slight increase with V_{CE} . This is because as V_{CE} increases, a higher value of V_{BE} is required to maintain the given I_B . Therefore, the current component of αI_E of collector current will also increase But $I_{CS}$is generally independent of V_{CE} for all practical purposes. This is known as the active or amplifier mode of operation of the transistor.

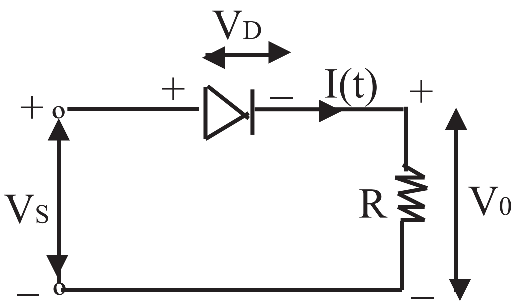
In the active opearting region, where I_B increases with I_C and for a given value of V_{CC} , V_{CE} reduces with increasing I_C . At one point the base collector junction (J_{CB}) becomes forward biased and V_{CE} is then equal to the difference between the voltages across two forward biased junctions, that is base-emitter (J_{BE}) and collector-base (J_{CB}). In this situation, the transistor is considered to be in the satuaration or ON mode of operation. The ratio I_C / I_B at in the saturation mode is called β_{min} and is an important parameter for its use as power transistor. In saturation region the collector current I_C mostly determined by the external load and further increase in I_B has very little influence on I_C or V_{CE} .

For a transistor to be operated as a switch, it is primary switched between saturated region (ON-region) and the cut-off (OFF-region). However, during the transition from the saturation region to the OFF-region and back, the operating mode transits through active region, resulting in loss called the switching loss.

Diode Circuits With DC Source



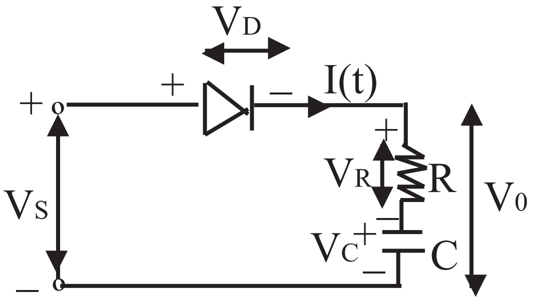
(a) R Load



- Load Curremt $I(t) = \dfrac{V_S}{R}$

  V_S = D.C Source Voltage
  R = Load resistance

(b) RC Load



- $I(t) = \frac{V_S}{R} e^{-t/RC}$
- Voltage across capacitor

  $V_C(t) - V_S - (1 - e^{-t/RC})$
- $V_C(t)$ = Voltage across capacitor at time t.
- Rate of rise of V_C (initial)

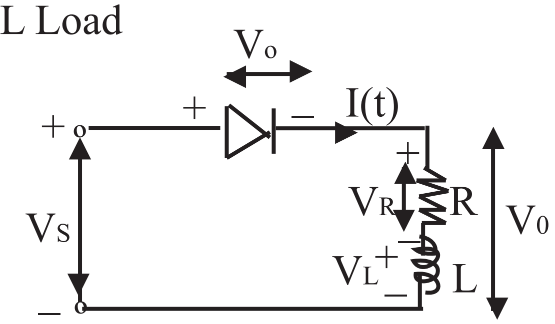
  $$\left(\frac{dV_C}{dt}\right)_{t=0} = \frac{V_S}{RC}$$
- Time constant

  Note : At t = 0; C acts as conductor

  $$\tau = RC = \frac{V_S}{\left(\frac{dV_C}{dt}\right)_{t=0}}$$

  $\tau = \infty$; C acts as insulator

(c) RL Load



- $I(t) = \frac{V_S}{R}\left[1 - e^{\frac{-R}{L}t}\right]$
- Voltage across inductor

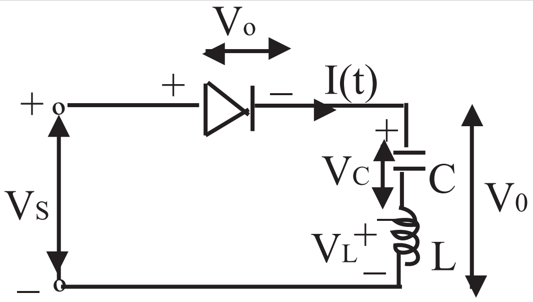
  $V_L(t) = V_S \times c^{\frac{-R}{L}t}$
- Initial rate of rise of current

  $$\left(\frac{di}{dt}\right)_{t=0} = \frac{V_S}{L}$$

Note : At t = 0; L becomes insulator

t = ∞ ; L becomes conductor

(d) LC Load

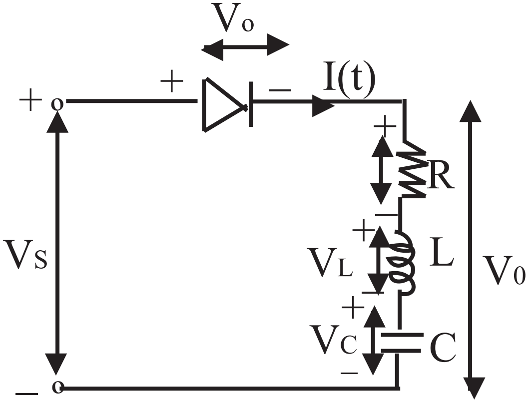


- $I(t) = V_S\sqrt{\frac{c}{L}}\ \sin \omega_0 t$

  $\omega_0 = \frac{1}{\sqrt{LC}}$; resonant frequency
- $V_C(t) = V_S\,(1 - \cos \omega_0\, t)$
- $V_L(t) = V_S \cos \omega_o\, t$
- Condition Time $t_o = \frac{\pi}{100} = \pi\sqrt{LC}$

Note : In LC circuit I and V waveforms are 180° out of phase. If I is sine then V is cosine and vice versa.

(e) RLC Load

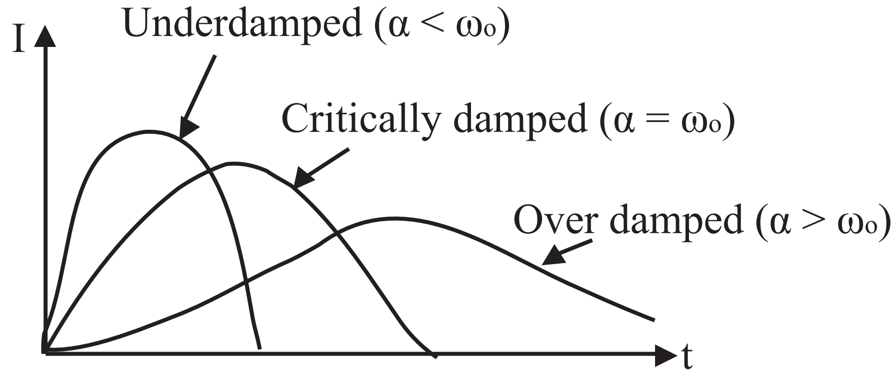


- Characteristic equation

  $$S^2 + \frac{R}{L}s + \frac{1}{LC} = 0$$
- Damping factor

  $$\alpha = \frac{R}{2L} = \varepsilon\omega_o$$
- Ringing frequency

  $$\omega_r = \sqrt{\omega_r^2 - \alpha^2}$$



(i) $\alpha < \omega_o$

$$I(t) = \frac{V_S}{\omega_r L} \times e^{-\alpha t} \sin \omega_r t$$

Roots are complex; ckt is underdamped.

(ii) $\alpha > \omega_o$

$$I(t) = \frac{V_S}{L\sqrt{\alpha^2 - \omega_o^2}} \sin h(\sqrt{\alpha^2 - \omega_o^2 \tau})$$

Roots are real ; ckt is overdamped.

(iii) $\alpha = \omega_o$

$$I(t) = \frac{V_S}{L} \times te^{-\alpha t}$$

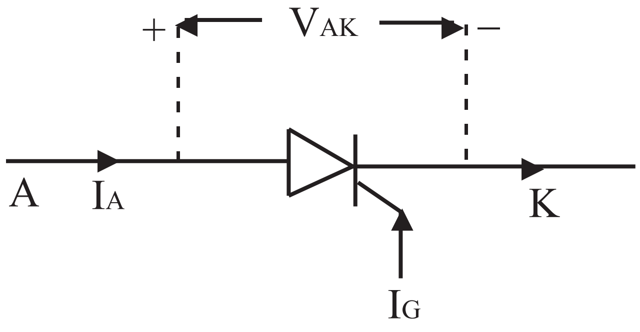
Thyristors

Thyristors were developed after the semiconductor diodes and then spearheaded the advancement of modern power electronics. Thyristors are a family of semiconductor switches having four or more layers, that is, p-n-p-n type of structure. The concept was introduced in 1956 by Dell laboratories and the first commercial silicon controlled rectifier (SRC) was released by General Electrical in 1957. It had a continuous current carrying capacity 25 A and a blocking voltage of 300 V. Now a days, thyrsitors with blocking voltage in excess of 6 kV and continuous current rating in excess of 4 kA are available.

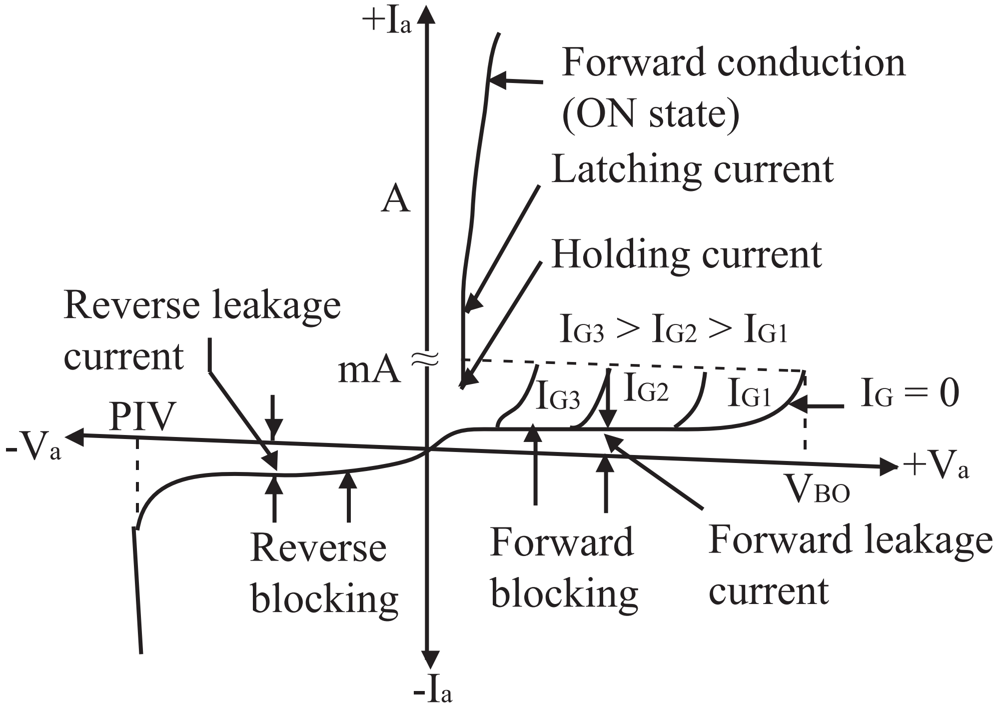
In a thyristor, if the ohmic connection is made to the first p-region and the last n-region and no other connection is made in the intermediate region, then the device is called triode thyristor and if the connection is made to both the intermediate regions, the device is called terode thyristor. The simplest in structure and most common thyristor is reverse blocking triode thyristor, also called as the silicon-controlled rectifier (SCR) and the more complex thyristor structure is the bi-directional triode thyristor or TRIAC.

Static Characteristics of a Thyristor

Figure (a) shows the circuit symbol and the conventions for the different variables used in the V-I characteristics of the thyristor, shown in fig (b).



(a)



- Turn ON characteristics

  Delay time (t_g) = 0.9 I_g to 0.1 I_a

  Rise time (t_r) = 0.1 I_a to 0.9 I_a

  Spread time (t_p) = 0.9 I_a to I_a

- Turn OFF characteristics

  $t_q = t_{off} = t_{rr} + t_{gr}$

  t_q → turn off time

  t_{rr} → reverse recovery time

  t_{gr} → gate recovery time

  Note : $t_c > t_q$

  t_c ↓ Circuit turn off time

String Efficiency (S)

It is measure of utilisation of SCR rating to its full capacity.

$$S = \frac{\text{Total string voltage/ current rating}}{\text{n (Individual volateg/ current rating of one SCR)}}$$

n = no. of SCR's connected

Derating factor = 1 - S

Connections of SCR

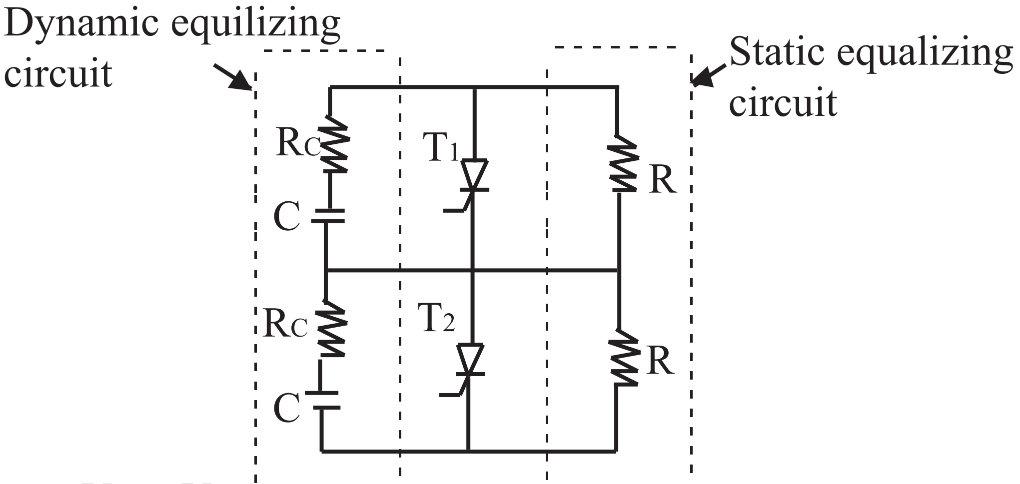
Series Connections   Parallel Connections

1. Series Connection of SCR : It is used to increase the voltage rating.

- Main problem with series connection of SCR is unequal sharing of voltage.
- To overcome this we use "State Equalizing Circuit" if unequal sharing of voltage is due to difference in forward blocking characteristics of series

connected SCR.

- If it is due to difference in reverse recovery characteristics then we use "dynamic equilising circuit.".



$$R = \frac{nV_{bm} - V_S}{(n - 1)\Delta I_b}$$

$$C = \frac{(n - 1)\, Q_R}{nV_{bm} - V_S}$$

V_{bm} = Maximum permissible blocking voltage

$\Delta I_b = I_{b(max)} - I_{b(min)}$

= Difference between maximum and minimum leakage current

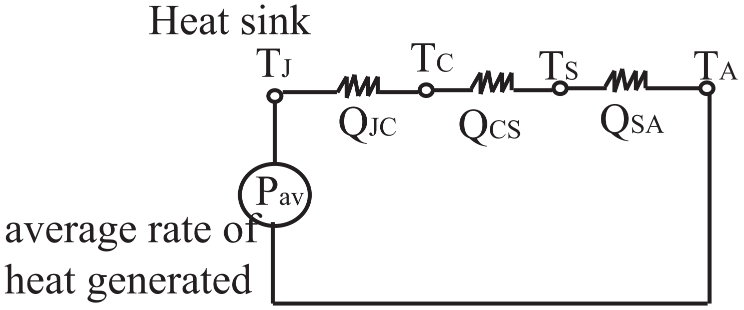
Number of SCR connected in series

Total string voltage

Difference in recovery charge

2. Parallel Connection of SCR : Used to increase the available current rating.

- Main problem with parallel connection of SCR is unequal sharing of current.
- If unequal sharing of current is due to difference in conduction characteristic of both SCR connected in parallel than we use " Current equalising circuit."
- If unequal sharing of current is due to temperature difference then we put all SCR in common symmetric heat sink.



T_C = Case temperature

T_J = Junction temperature

T_S = Sink Temperature

T_A = Ambient temperature

θ_{JC} = Thermal resistance b/w junction & case

θ_{CS} = Thermal resistance b/w case & sink

θ_{SA} = Thermal resistance b/w sink & ambient

$$P_{ar} = \frac{T_J - T_C}{\theta_{JC}} = \frac{T_C - T_S}{\theta_{CS}} = \frac{T_S - T_A}{\theta_{SA}} = \frac{T_J - T_A}{\theta_{JA}}$$

$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$$

Triggering methods of SCR

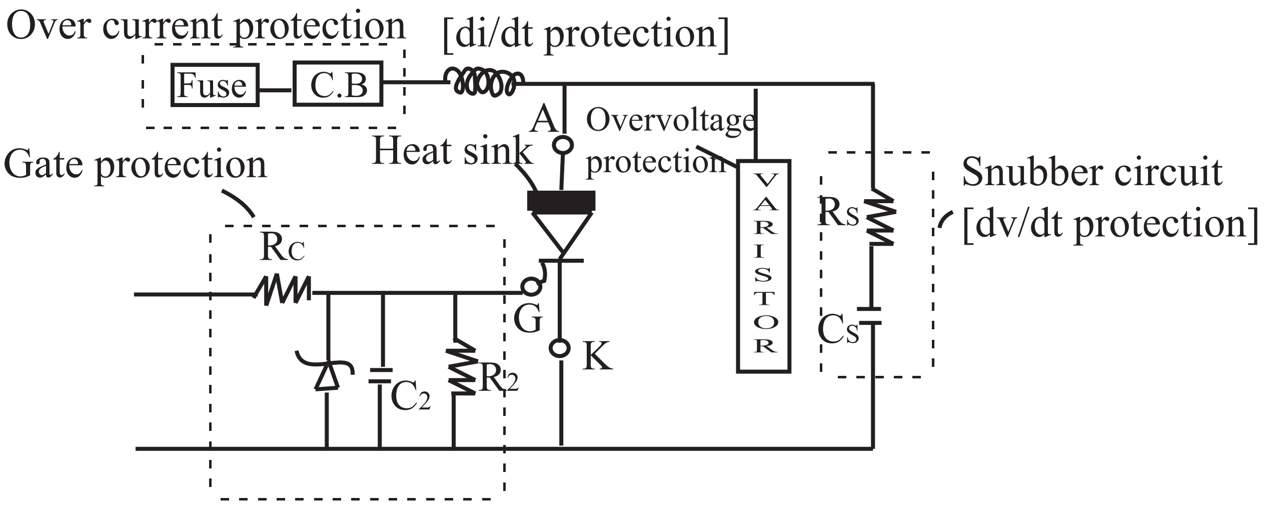
(a) Forward voltage triggering
(b) Gate voltage triggering
(c) dv/dt voltage triggering
(d) Temperature voltage triggering
(e) Light voltage triggering (used in HVDC transmission system)

Protection of Thyristor

(a) Over current protection
connect a fuse or circuit breaker in series with SCR
(b) Over voltage protection
connect varistor across SCR
(c) High dv/dt protection
connect snubber circuit across SCR
(d) High di/dt protection
connect inductor in series with SCR
(e) Thermal protection
provides heat sink in SCR

Gate Protection

(a) Over current protection
connect a resistance in series with Gate
(b) Over voltage protection
Zener diode is connected across gate & cathode Junction
(c) Protection against noise
connect a capacitor & resistor across gate & cathode



Circuit for protection of SCR

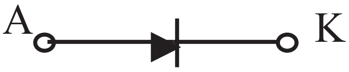
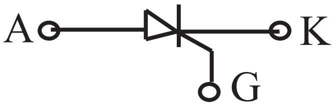
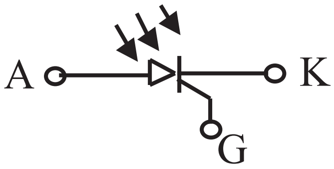
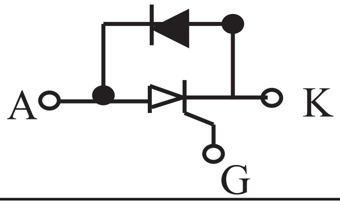
Note :

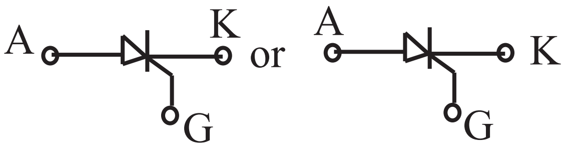
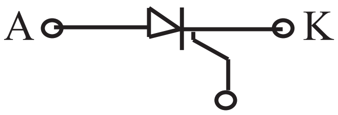
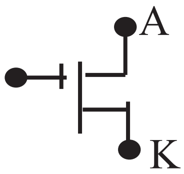
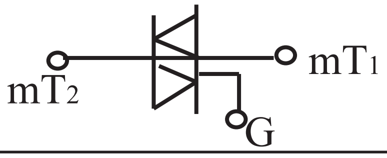
- Gate current magnitudes are of the order of 20 to 200mA.
- Triac is combination of antiparallel connection of two SCR.
- Diac is antiparallel connection of two SCR when $I_g = 0$

Thyristor Protection

The various methods of thyristor protection are listed as follows :

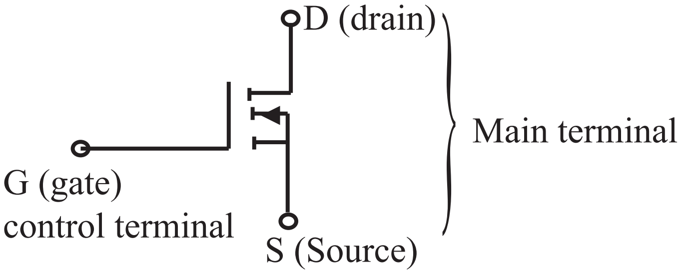
1. **di/dt Protection :** When the thyristor is switched on, its current rises and reaches the final value decoded by the load connected to it. But the rate of rise of current, which is also decided by the inductive nature of the load, can cause damage of the thyristor junction J_2 if exceeded above a certain value. The high di/dt can cause hot spots in the junction J_2 which injects more current through that area due to negative temperature co-efficient nature of the junction. Thus the current further increases and causes the damage spot to spread and the entire junction breaks down. Thus proper projection to limit the impressed di/dt under the allowable value has to be provided. This is achieved connecting an inductor (L) is series with the device to form a snubber circuit.
2. **dv/dt Protection :** As discussed earlier, when the forward voltage is impressed on the thyristor and if the dv/dt is more than the allowable dv rating, the thyristor can undergo spurious turn-ON. The dv/dt in reverse direction is alse developed during turn-ON situation. The high dv/dt can even damage the thyristor junctions. Thus, a circuit, usually consisting of R and C in series combination is connected in parallel with the thyristor, is used to protect it from high dv/dt being impressed upon it when subjected to any voltage stress during turn-OFF or turn-ON process.

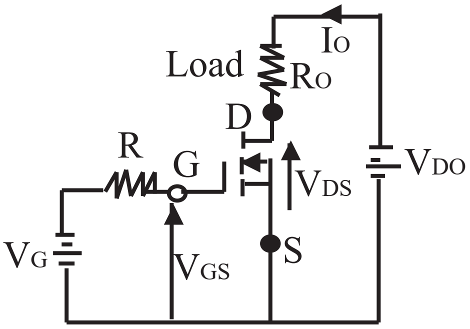
Device	Circuit symbol	Voltage/ current rating
Diode		5000 V 5000 A
Thyristors		
(a) SCR		7000 V 5000 A
(b) LASCR		6000 V 3000 A
(c) ASCR/ RCT		2500 V 400 A

(d) GTO		5000 V 3000 A
(e) SITH		2500 V 500 A
(f) MCT		1200 V 40 A
(g) Triac		1200 V 1000 A

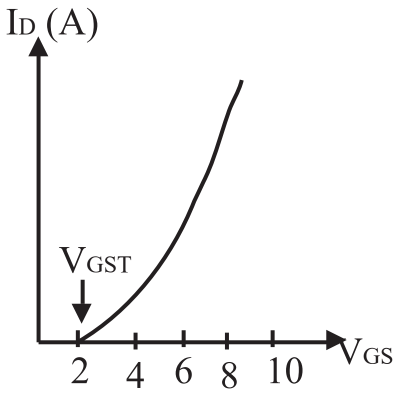
b) Power MOSFET

It is designed to handle significant power levels.

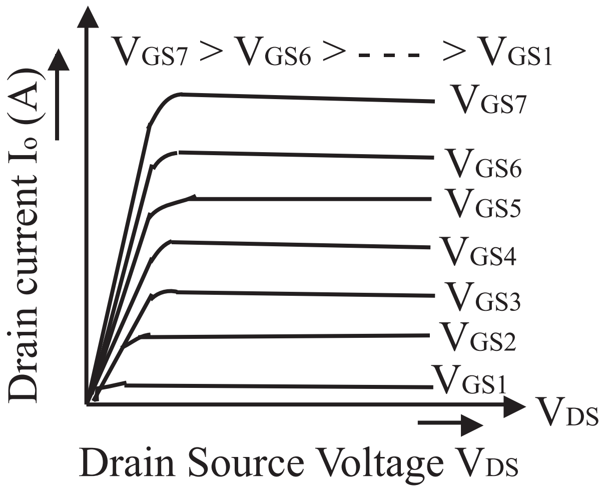




n-channel power MOSFET circuit diagram



Transfer characteristic



Output characteristics of a power MOSFET

Note :

- n-channel enhancement MOSFET is used because of higher mobility of electrons.
- Control signed in BJT > control signal in MOSFET.
- BJT is current controlled device & MOSFET is voltage controlled device.

(c) Power IGBI

It combine the advantages of both MOSFET and BJT

Insulated Gate Bipolar Transistor (IGBT)

The insulated gate bipolar transistor (IGBT) combines the advantages features of MOSFET (such as voltage control, fast switching) and BJT (such as low ON-state losses and high OFF-state voltage capability. These were developed in initial form as IGT device by the GE Research Laboratory and evolved to the current IGBT form through a number of improvement cycles. These devices have near ideal characteristics for high voltage (> 100V) and medium frequency (< 20 kHz) applications.

The IGBT can be viewed as equivalent to a MOSFET with a diode connected to its drain or as combination of a MOSFET and a PNP transistor. It behaves essentially as a MOSFET when considered from the input perspective with three terminals, collector, emitter and gate. When the gate-emitter voltage is less than the minimum threshold voltage, no inversion layer is formed in the p-type body region and the device is in the OFF state due to negligible current through the collector. Only very small leakage current flows through the device between the collector and emitter under this condition. The forward voltage applied between the collector and the emitter drops almost entirely across the junction J_2 as shown in the figure. When the gate to emitter voltage is increased to exceed the threshold value, an inversion layer is formed in the p-type body region under the gate. This inversion layer or channel shorts the emitter and the drain layer, resulting in an electron current flowing from the emitter through this channel to the drain drift region. This causes substantial hole injection from the p^+ type collector to the drain drfit region and a portion of these holes recombine with the electrons coming to the drain drift region t hrough the channel. The rest of the holes cross the drift region and reach the p-type body, to be collected by the source metallisation.

Performance Parameters

1. Input power factor : It is defined as the radio of the input mean power to rms apparent power. Thus input power factor (PF or pf) is given by

$$PF = \frac{\text{Mean power}}{V_{rms} I_{rms}} = \frac{\text{Mean power}}{V_s I_s}$$

The input voltage is sinusoidal thus the input mean power is defined as $V_S I_1 \cos\phi_1$ where as defined V_S is the rms value of input and I_{1rms} is the rms value of fundamental current and ϕ_1 is the angle between the input voltage and fundamental current. Then

$$PF = \frac{V_S I_1 \cos\phi_1}{V_S I_{rms}}$$

$$PF = \left(\frac{I_{1rms}}{I_{rms}}\right) \cos\phi_1$$

Here $\phi_1 \approx \alpha$

2. Displacement factor : It is defined as the cosine of the angle between source voltage and fundamental input current. Thus,

$$\text{Displacement factor} = \cos\phi_1$$

3. Distortion factor : It is defined as the ratio of fundamental component of rms value input current to rms value of total input current. Thus,

$$\text{Distortion factor} = \frac{I_{1rms}}{I_{rms}}$$

4. Total harmonic distortion (THD) : This is defined as the ratio of rms value harmonic component of input current to the rms value of fundamental component input current. Thus,

$$THD = \frac{\sqrt{\sum_{I=2}^{n} I_i^2}}{I_{1rms}} = \frac{\sqrt{I_{rms}^2 - I_{1rms}^2}}{I_{1rms}}$$

$$= \frac{\sqrt{I_{2rms}^2 + I_{3rms}^2 + \ldots\ I_{n\,rms}^2}}{I_{1rms}}$$

5. Crest Factor : It is the ratio of peak value of input emf to its rms value. Thus,

$$CF\ (\text{or } c) = \left(\frac{I_{max}}{I_{rms}}\right)$$

6. Ripple factor : It is the ratio of rms value ac component of input current to the average value of input emf. Thus,

$$RF\ (\text{or } r) = \frac{\sqrt{I_{rms}^2 - I_{avg}^2}}{I_{avg}}$$

7. Form Factor : It is the ratio of rms value to average of input current. Thus,

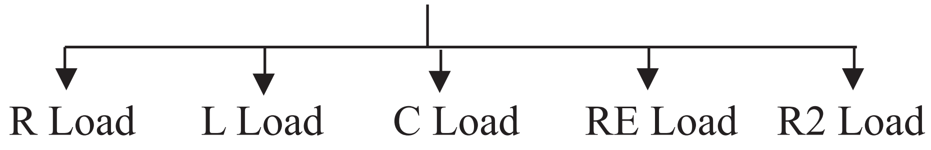
$$FF\ (\text{or } F) = \left(\frac{I_{rms}}{I_{avg}}\right)$$

Based on the above relation, the RF can be again defined as

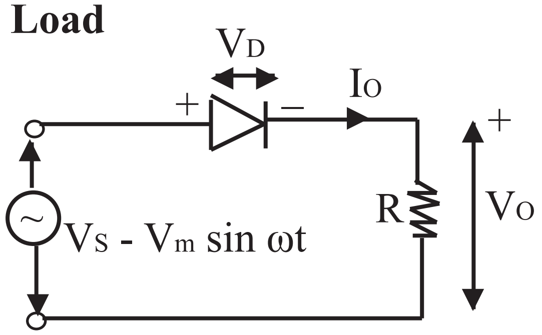
$$RF = \sqrt{\left(\frac{I_{rms}}{I_{avg}}\right)^2 - 1} = \sqrt{(FF)^2 - 1}$$

DIODE RECTIFIERS

1. Single Phase Half Wave Diode Rectifier



(a) R Load



- Voltage rms value of output

$$V_{or} = \frac{V_m}{2}$$

V_m = maximum value of V_s (source voltage)

- Average value of O/P voltage

$$V_O = \frac{V_m}{\pi}$$

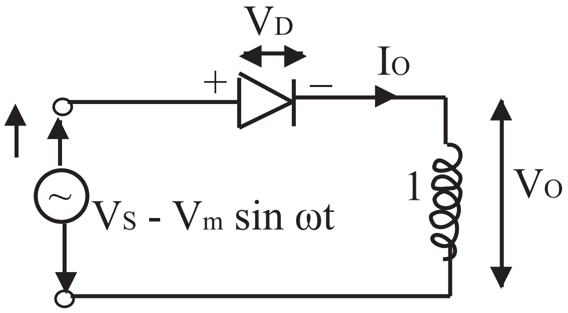
- Power delivered

$$P = I^2_{or}R$$

I_{or} = rmsvalue of load current

- P/V = V_m
- I/P Power Factor = $\frac{V_{or}\,.\,I_{or}}{V_s\,.\,I_{or}} = 0.707$

(b) Inductive Load



- O/P current

$$I_o = \frac{V_m}{\omega L}\,(1 - \cos\omega t)$$

- Peak value of current

$$I_{max} = \frac{2V_m}{\omega L}$$

- Average value of current

$$I_o = \frac{1}{2}\,I_{max}$$

- Rms value of current

$$I_r = \frac{I_o}{\sqrt{2}}$$

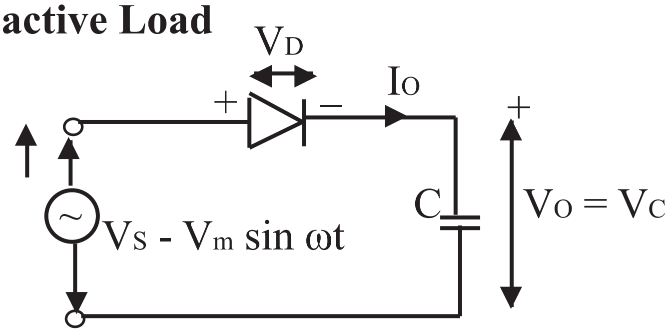
- Output voltage

$$V_o = V_m \sin\omega t = V_S$$

- Average value of o/p voltage

$$V_o = 0$$

(c) Capactive Load



- o/p Current

$$I_0 = \omega c V_m \cos\omega t$$

- o/p Voltage

$$V_0 = V_m \sin\omega t = V_S = V$$

- Diode Voltage

$$V_D = V_m (\sin\omega t - 1)$$

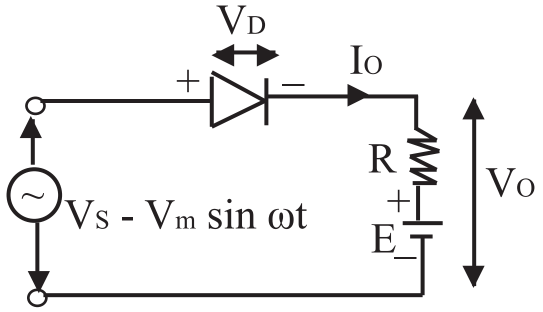
- Average Value of V_D

$$V_D = V_m$$

- Rms Value of V_D

$$V_{rD} = 1.225\ V_m$$

(d) RE Load



- Turn an angle

$$\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$$

- Avg value of o/p Current

$$I_0 = \frac{1}{2\prod R}\left[2V_m \cos\theta_1 - E(\prod - 2\theta_1)\right]$$

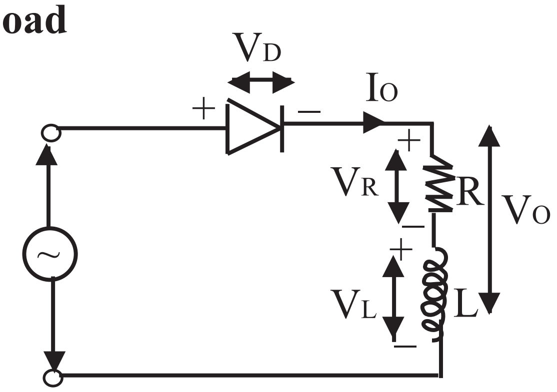
- Conductive angle

$$CA = \pi - 2\theta_1$$

- PIV

$$PIV = V_m + E$$

(e) RL Load



- Avg value of o/p Voltage

$$V_0 = \frac{V_m}{2\pi}(1 - \cos\beta)$$

β is ectinction angle of diode

- Avg value of o/p Current

$$I_0 = \frac{V_m}{2\pi R}(1 - \cos\beta)$$

2. Single Phase full Wave Diode Rectifier

- Avg o/p Voltage

$$V_0 = \frac{2V_m}{\pi}$$

- Rms Value of o/p Voltage

$$V_{or} = \frac{V_m}{\sqrt{2}}$$

3. Three Phase Half Wave Diode Rectifier R Load

- Avg Value of o/p Voltage

$$V_0 = \frac{3\sqrt{6}}{2\pi} V_{ph} = \frac{3}{2\pi} V_{ml}$$

V_{ph} = max value of phase Voltage

V_{ml} = max value of line Voltage

$$V_l = \sqrt{3} V_{ph}$$

Comparison of Various 1-φ diode rectifier

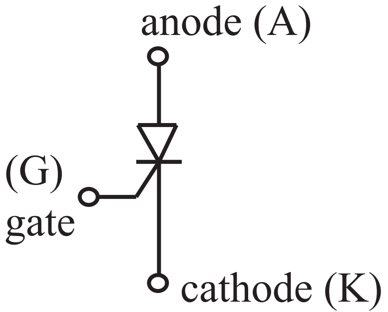
Parameters	Half-Wave	Full-Wave	
		Centre-tam(M-2)	Bridge (B-2)
DC output voltage, V_o	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
RMS output voltage, V_{or}	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$
Ripple Voltage, V_r	0.3856 V_m	0.3077 V_m	0.3077 V_m
Voltage ripple factor, VRF	1.211	0.482	0.482

Rectifier efficiency, η	40.53%	81.06%	81.06%
TUF	0.2865	0.672	0.8106
PIV	V_m	$2V_m$	V_m
Crest factor, CF	2	$\sqrt{2}$	$\sqrt{2}$
Number of diodes	1	2	4
Ripple frequency	f	2f	2f

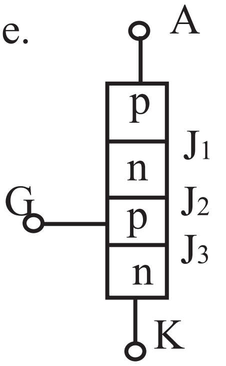
Thyristor

It is a 4-layered semiconductor rectifier in which flow of current between two electrodes is triggered by a signal at the third electrode.

It is 3 terminal, 3 junction pnpn device.

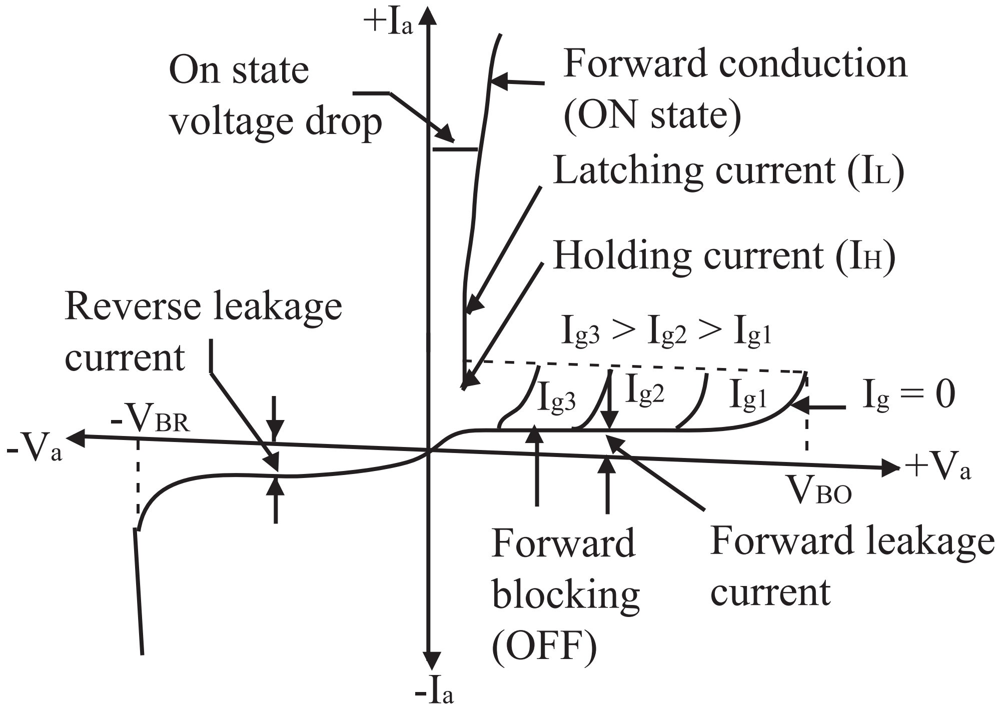


Circuit



Schematic

Static V-I Characteristics :



Where, V_{BO} = Forward breakover voltage

V_{BR} = Reverse breakover voltage

I_g = Gate Current

Operating Region of Thyristor :

(a) Forward Blocking Mode

- $V_a < V_{BO}$

- Device is OFF
- Anode +ve, Cathode -ve
- $I_g = 0$
- J_1 Forward bias
- J_2 Reverse bias
- J_3
- Only forward leakage current

(b) Forward Conduction Mode

- $V_a > V_{BO}$
- Device is ON
- Anode +ve, Cathode -ve
- $I_g = 0$
- J_1 Forward bias
- J_2 Reverse bias
- J_3 Forward bias

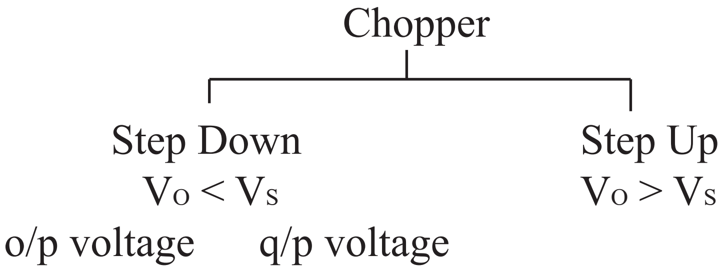
(c) Reverse Blocking Mode

- Device is OFF
- Anode -ve, Cathode +ve
- $I_g = 0$
- J_1 Reverse bias
- J_2 Forward bias
- J_3 Reverse bias

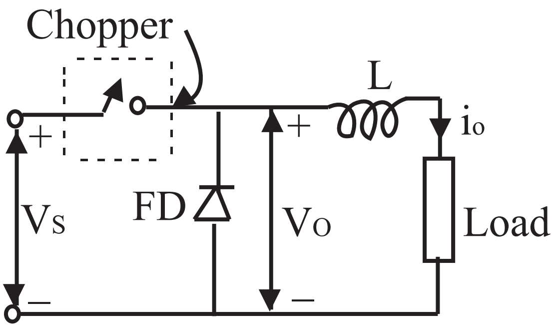
- **Latching Current (I_L) :** Turn ON process
  The minimum anode current required to maintain thyristor in ON-state immediately after thyristor has been triggered ON.
- **Holding Current (I_H) :** Turn OFF Process
  The minimum value of current that must be there to provide a path b/w anode & cathode to flow anode current & thus maintain thyristor in ON state.
- **Procedure to turn :** OFF SCR
  Anode current should be less than I_4 to turn OFF SCR, then apply reverse voltage till excess carrier are removed & regains its blocking capability.

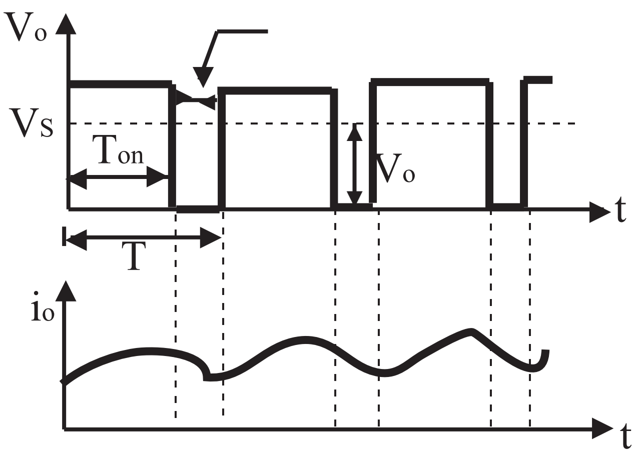
CHOPPERS

It is a device that converts fixed DC input to a variable DC o/p voltage directly. It is a high speed ON/OFF semiconductor switch.



(a) Step Down Chopper





Here L is used to reduce the ripple content in o/p.

- Duty cycle

$$\alpha < 1 \text{ and } \alpha = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

- Average load voltage

$$V_0 = \alpha V_s$$

- Rms load voltage

$$V_{rms} = \sqrt{\alpha}\, V_s$$

- Average load current

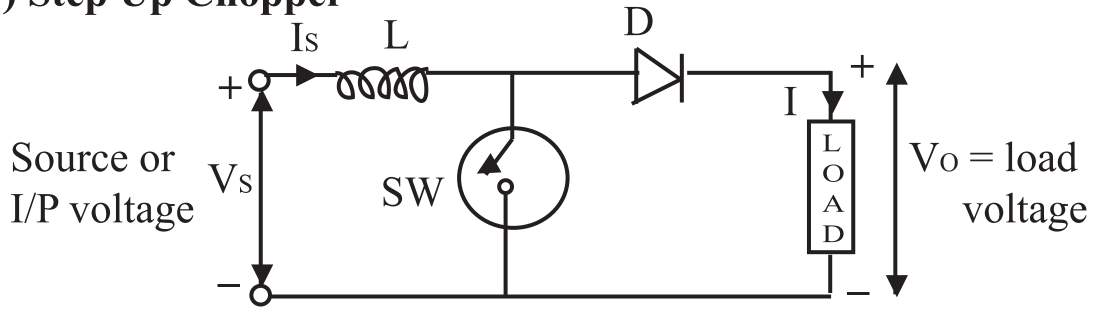
$$I_0 = \frac{V_0}{R} = \frac{\alpha V_s}{R}$$

- Rms load current

$$I_{rms} = \frac{\sqrt{\alpha}\, V_s}{R}$$

Note : Formulas are valid only for continuous conduction.

(b) Step Up Chopper



- Average load voltage

$$V_O = \frac{1}{1 - \alpha} V_S$$

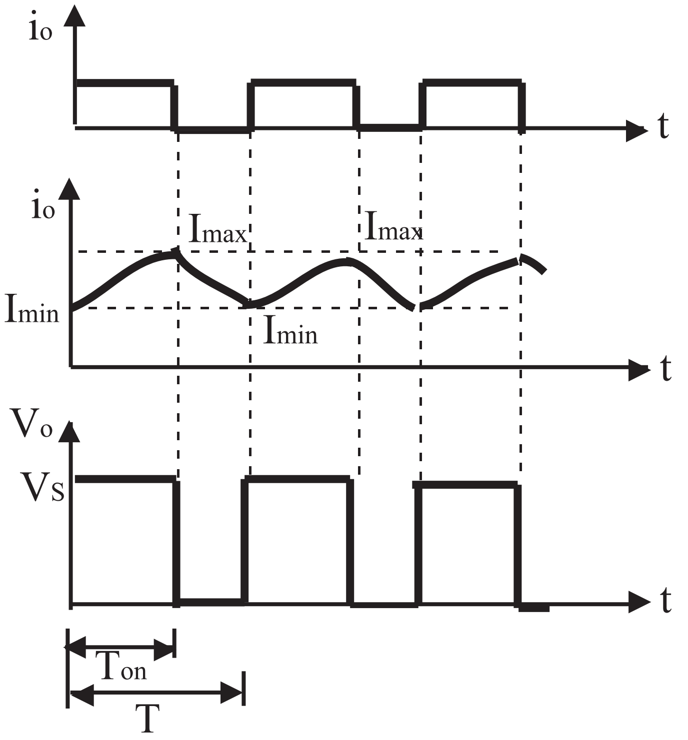
- For basic DC to DC converter, critical inductance of filter circuit is given by,

$$L = \frac{V_0^2\,(V_s - V_0)}{2fV_s\, p_0}$$

P_0 = Load power

f = Chopping frequency

Steady State Time Domain Analysis of Type-A Chopper



- Maximum value of current

$$I_{max} = \frac{V_S}{R}\left[\frac{1 - e^{-T_{ON}/T_a}}{1 - e^{-T/T_a}}\right]\frac{E}{R}$$

- Minimum value of current

$$T_a = \frac{L}{R}$$

$$I_{min} = \frac{V_S}{R}\left[\frac{e^{-T_{ON}/T_a} - 1}{e^{-T/T_a} - 1}\right]\frac{E}{R}$$

- Per unit ripple current- (p)

$$P = \frac{I_{max} - I_{min}}{V_S/R} = \frac{(1 - e^{\propto T/T_a})(1 - e^{-(1-\propto)T/T_a})}{1 - e^{T/T_a}}$$

Note : When $\alpha = 0.5$, then peak to peak ripple current has maximum value

$$\Delta I_{max} = \frac{V_S}{R}\tanh\left.\frac{R}{4fL}\right|_{\alpha = 0.5}$$

- If 4fL >> R then

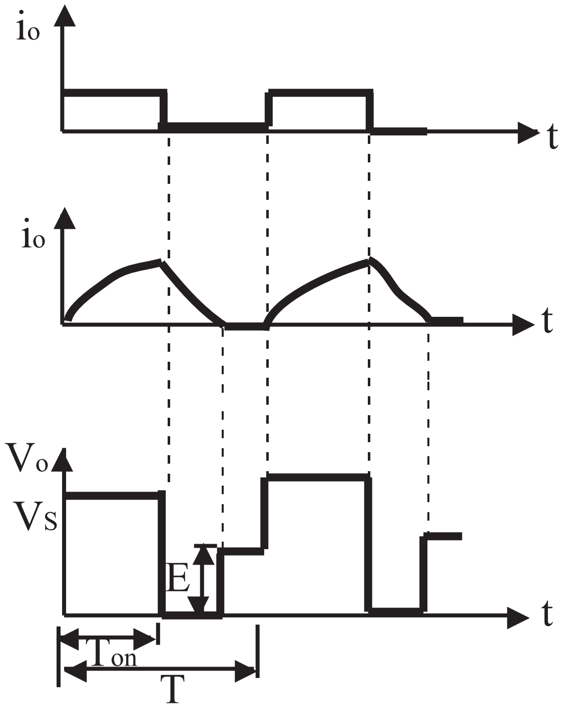
$$\tanh\frac{R}{4fL} = \frac{R}{4fL} \quad \Delta I_{max} = \frac{V_S}{4fL}$$

Note : If L is high, ripple is minimum.

- Value of duty cycle at limit of continuous conduction

$$\alpha \geq \frac{T_a}{T}\ln\left[1 + \frac{E}{V_S}\left(e^{T/T_a} - 1\right)\right]$$

Load Current Discontinuous



- Minimum value of current

$$I_m = 0$$

- Maximum value of current

$$I_{max} = \frac{V_S - E}{R}\left(1 - e^{-T_{ON}/T_a}\right)$$

- Extinction time tx

$$t_x = T_{ON} + t_a \ln\left[1 + \frac{V_S - E}{E}\left(1 - e^{-T_{ON}/T_a}\right)\right]$$

- Average o/p voltage

$$V_0 = \alpha V_S + \left(1 - \frac{t_x}{T}\right)E$$

Inverters

An inverter is meant for conversion of a DC voltage source to an AC voltage source of specified magnitude and frequency. The main component of the inverter is the power semiconductor switch. Both the frequency and amplitude of the output voltage can be varied by inverters with the help of suitable switching techniques of the devices. The AC output waveform may be a square wave, a quasi-square wave or a sine wave.

Inverters can be broadly classified into the following two types :

1. **Voltage source inverter (VSI) :** These have DC voltage source at their input terminals. The output voltage waveform is not impacted by the load.
2. **Current source inverter (CSI) :** These are fed with DC current source. The output current waveform is not impacted by the load.

The inverters can be classified into the single phase and three phase inverters depending on whether they are feeding single phase or three phase load. Further classification is possible based on the type of connections of the semicoinductor devices, as bridge, series and parallel inverters.

MOSFET : These devices are switched alternately in a cyclic manner to obtain an AC output voltage of amplitude $V_{DC}/2$. Since only two switching devices are used, it is known as half bridge inverter. The switching pulses and the output voltage waveform are shown in Fig.

Single-Phase Full-Bridge VSI

The circuit configuration and the output voltage waveform of a single phase full-bridge inverter.

In thic circuit, four switching devices, with two per arm are connected along with four anti-parallel diodes D_1 to D_4 . Thus it is named as full bridge inverter. The switching devices Q_1 , Q_2 and Q_3 , Q_4 are switched simultaneously in an alternate manner, in a repeatable symmetrical cycle of time period T. Thus the frequency of the output voltage is given by f = 1/T. The diodes are connected to protect the devices from switching surge reverse current flow when the load is inductive. They actually carry the current due to stored energy in the load induced during the transition of current from one device set say Q_1 , Q_2 to the other Q_3 , Q_4 or vice versa. The same is depicted in the circuit diagram describes the voltage and current waveform of the inverter. The output voltage waveform in this case is a square wave of amplitude V_{DC} . The harmonic components of the output voltage V_o is given by

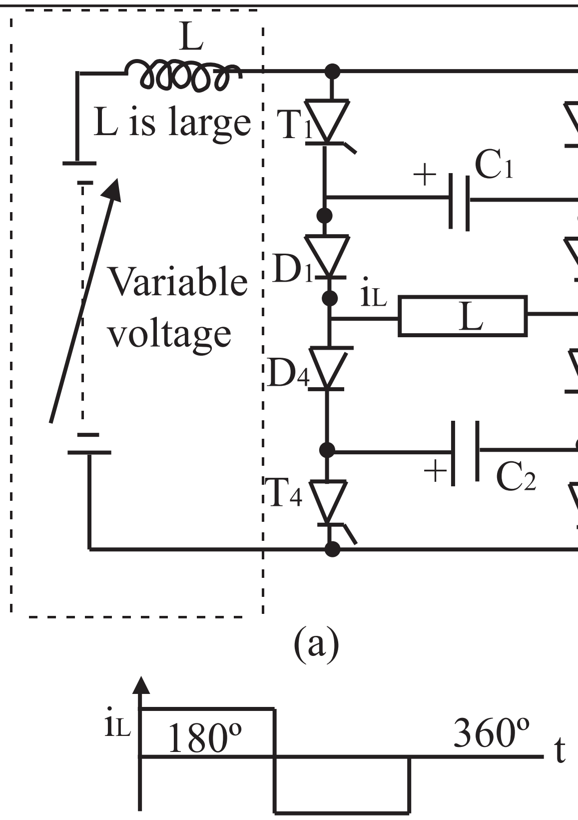
$$V_o = \sum_{n=1,3,5}^{\infty} \frac{2V_{DC}}{n\pi} \sin n\omega t$$

Current Source Invertes

Current source inverters assume that the DC-bus voltage to be constant. This is achieved generally by connecting a large capacitor in parallel to the DC-bus, so as to absorb the switching ripples and the load changes keeping the DC-bus voltage constant. These inverters can be categorized in a manner similar to voltage source inverters, where the bus voltage is almost constant. there can be another category of the inverter where the DC bus is usually connected with a large inductor. So that the inverter voltage changes can occur but current changes can be counter balanced by L di/dt and since L is large, change in current, that is, di/dt will be small. Thus the inverter will maintain a constant current.

Single-Phase CSI

The configuration circuit and the load current waveform of single phase CSI is shown in Fig (a) and (b) respectively.



(a)

(b)

Figure : Single-phase current source inverter.
(a) Circuit (b) Output load waveform

When both T_1 and2Tare ON, both the capacitors are charged (left side positive) through D_3 and D_4 , the load current flows through T_1 D_1 D_2 T_2 path. Then when T_3 and T_4 are triggered, these capacitors are connected across T_1 and T_2 , respectively and thus effectively turning them OFF. Then the capacitor voltages will be reversed and the load current gets transferred to D_3 and D_4 from D_1 and D_2 . After the capacitor charge is fully reversed, D_1 and D_2 turn OFF. The load current is exact square wave as the current remains same during its operation.

Speed Control Of DC Motor Drives

The DC motor drive system consists of a DC motor and a power electronic converter to generate a variable DC voltage. A separately excited motor, as shown in Fig is considered here for the purpose.

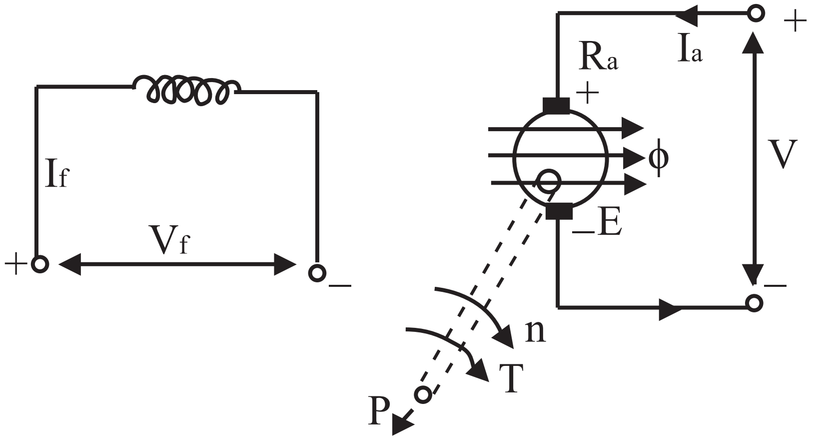


Fig : Separately excited DC motor

Equations (i) and (ii) represent the voltage (emf) and torque for separately excited DC motors.

$T = K_a \phi I_a$ (i)

$E = K_a \phi\omega$ (ii)

where T is electromagnetic torque (Nm); ϕ is flux per pole Wb), I_a is armature current (amperes), E is induced emf (in volts), ω is angular velocity, rad/s and P is mechanical power (watts). The parameter K_a is referred to as the universal torque or emf constant that can be expressed either in Nm/rad/s/Wb or in V/rad/s/Wb.

When an input voltage V is supplied to teh armature with resistance r_a , the emf from the equivalent circuit of the machine can be expressed as,

$E = V - I_a R_a = K_a \phi\omega$ (iii)

and the power for the machine can be expressed as

$P = \omega T = VI_a - I_a^2R_a$ (iv)

where $P = EI_a$ is the mechanical output power, VI_a is the electrical input power, $I_a^2R_a$ is the electrical ohmic losses in the armature.

Speed Control of AC Motor Drives

The speed of induction machines can also be controlled like the DC motors, through the drive systems to control these are more complex. However, their control assumes importance in view of the advantages of induction motors over DC motors and their increasing use in modern industry. For most of the appplications, the induction motor drive systems are becoming more and more popular to replace the DC drive systems in modern industries.

Induction Motor Speed Control

From the torque vs. speed characteristics of a three-phase induction motor, it can be observed that at any rotor speed, the magnitude and/ or frequency of the supply voltage can be controlled for obtaining a desired torque. It can be known from the rotor speed equation of $N_r = N_s (1 - s)$ that the rotor speed N_r broadly depends on the synchronous speed N_s (neglecting the slip term s). Thus change in synchronous speed can vary the rotor speed in a broader sense.