Chapter 1

Power Semiconductor Devices

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Power scale
- Drive applications
- Power devices
- Power diode
- Power transistor
- Bipolar junction transistor
- BJT darlington pair
- Voltage and current rating
- Safe operating region
- Thyristor

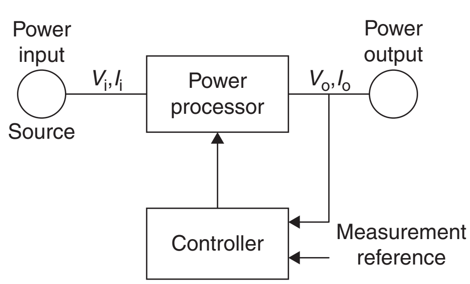
Introduction

To convert and control the flow of electric power by power semiconductor devices where these devices operate as switches by supplying voltages and currents in a form that is optimally suited for user loads.

Power Scale

Milli watts (mW) → Megawatts (MW) → Giga watts (GW)

Block Diagram



Power electronic devices are used to convert electric energy from source to load with the following properties.

- Highest efficiency
- Highest availability
- Highest reliability
- Lowest cost
- Smallest size
- Least weight.

Static Applications

Static applications of power electronics involve non-rotating or moving mechanical components.

Examples:

- DC Power supply
- Un interruptible power supply
- Power generation and transmission (HVDC)
- Electroplating
- Welding
- Heating
- Cooling
- Electronic Ballast

Drive Applications

Drive applications of power electronics intimately contains moving rotating components such as motors.

Examples:

- Electric trains
- Electric vehicles
- Air conditioning system
- Pumps
- Compressor
- Conveyer Belt (Factory Automation)

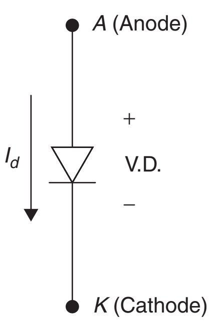
Power Devices

- Power Diodes (or Rectifiers).
- Bipolar Transistors—1948 and Power BJT—Bipolar Junction Transistor—1960.
- Thyristor or SCR (SILICON-CONTROLLED Rectifier)—1957.
- POWER MOSFETs (Metal oxide semiconductor field effect transistor)—1970.
- IGBT (Insulated gate bipolar transistor—1990 a hybrid between MOSFET and BJT).

Typical Power Devices

- Two-terminal devices—Pin Diodes (> 300 V)—Schottky Diodes (< 300 V), No reverse recovery loss.
- Three terminal Devices—BJT (not used much in power converters, high-voltage blocking capability).
- MOSFET (Commonly used for voltages < 300 V, very fast devices).
- IGBT (for voltages > 300 V) a hybrid of BJTs and MOSFETs.
- Thyristors—GTO, IGCT, ETO, MCT etc. used for high-voltage applications.

Power Diode



- It has two terminals, namely cathode and an anode.
- The power circuit controls the ON and OFF states.
- Power diodes are similar to p–n junction diodes but more complex in structure.
  They are of three types:
  - General purpose diodes
  - High-speed (fast recovery) diodes
  - Schottky diodes
- Diode blocks voltage in reverse direction and allows current in forward direction.
- They start conduction once the voltage in the forward direction goes beyond a certain value and a relatively small forward voltage drops across it.
- The diode is said to be reverse biased if the cathode potential is positive with respect to the anode, and a small amount of reverse current flows known as leakage current (mA or mA).
- A diode can be treated as an ideal switch.

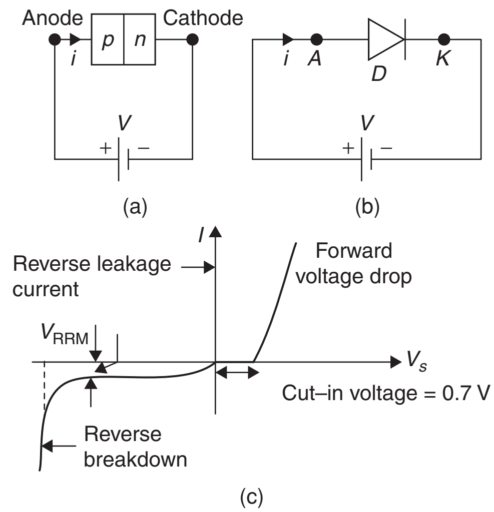


Figure 1 (a) p–n Junction; (b) Diode symbol; (c) *V.I.* Characteristics

- For silicon diode, the threshold voltage is around 0.7 V and the forward drop is around 0.8 V to 1 V.
- When the leakage current increases slowly with the reverse voltage until breakdown or avalanche voltage is reached, breakdown of diode takes place. At this point, diode is turn – on in the reverse direction.
- Peak reverse repetitive voltage (V_{RRM}): The reverse avalanche breakdown of a diode is avoided by operating the diode below specified peak repetitive reverse voltage beyond this voltage power diode is burn – out.
- Manufactures indicate the value of peak inverse voltage (PIV) or VRRM.
- Diode continues to conduct in reverse direction, because of the presence of stored charges in the two layers.
- The time for which the reverse current flows is known as reverse recovery time

$$t_{rr} = t_a + t_b$$

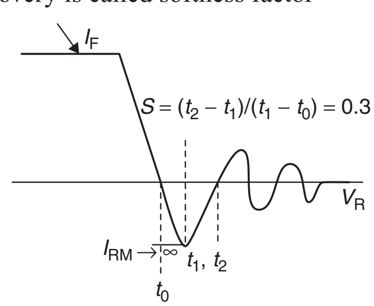
t_a – Time between zero crossing of forward current and I_{RM} (Peak reverse current).

t_b – Measure from the instant I_{RM} to the instant where 0.25 I_{RM} decays.

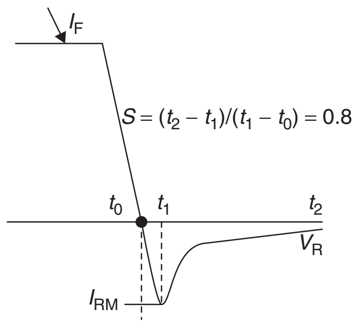
Softness Factor or S-factor

$$S = \frac{t_b}{t_a}$$

- The measure of voltage transients which occurs during diode recovery is called softness factor



Soft Recovery



Solved Examples

Example 1: The diode with a faster operation is
(A) Vacuum diode
(B) Zener diode
(C) Schottky diode
(D) Normal p–n diode

Solution: (C)

Example 2: Reverse recovery of a diode is delayed due to
(A) Metallic effects
(B) Different doping levels of two layers
(C) Higher voltage drop of the device
(D) During forward conduction, charge storage around the junction

Solution: (D)

Example 3: The rate of fall of diode current for a diode is 40 A/μs and reverse recovery time is 2.5 μs. The Peak reverse current (assuming the softness factor as 0.5) is given by
(A) 100 A (B) 75 A
(C) 50 A (D) 80 A

Solution: (A)

$$Q_{rr} = \frac{1}{2}\left(\frac{di}{dt}\right)t_{rr}^{2}$$
$$= \frac{1}{2}\times 40\times(2.5\times10^{-6})^{2}$$
$$= 125\ \mu c.$$
$$I_{rr} = \sqrt{2\times Q_{rr}\times\left(\frac{di}{dt}\right)}$$
$$= \sqrt{2\times125\times10^{-6}\times40\times10^{6}}$$
$$= 100\ A$$

Example 4: The correct pairs for the following listed in Table I to Table II are

TABLE I	TABLE II
(1) Schottky Diodes	(P) High-current–Low-voltage applications
(2) General purpose diodes	(Q) Low-speed applications
(3) Fast recovery diodes	(R) Less reverse recovery time (Less than 5 μs)

(A) 1 – Q 2 – P 3 – R
(B) 1 – P 2 – Q 3 – R
(C) 1 – R 2 – Q 3 – P
(D) 1 – P 2 – R 3 – Q

Solution: (B)

Power Transistor

- Can be turned 'ON' and 'OFF' by relatively very small control signals.
- Operated in saturation and cut-off modes only.
- Have controlled turn-on and turn-off characteristics.
- No 'linear region' operation is allowed due to excessive power loss.
- Generally, do not operate in latched mode.

They are classified into:

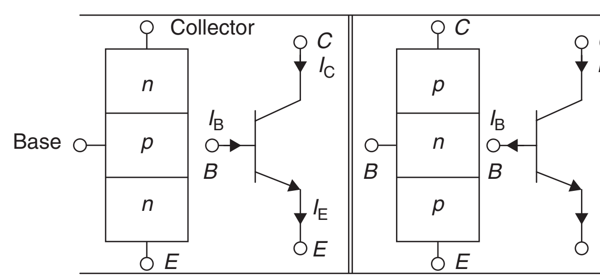
- Bipolar junction transistors (BJT).
- Metal oxide silicon field effect transistor (MOSFET).
- Insulated gate bipolar transistors (IGBT).
- Static induction transistor (SIT).

Emerging New Devices

Gate-controlled thyristors (GCTs).

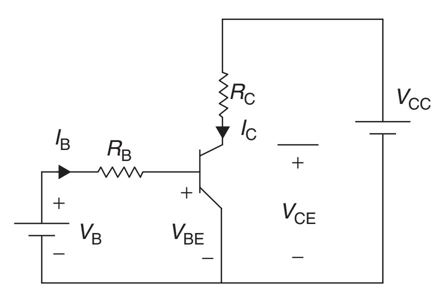
Bipolar Junction Transistor (BJT)

- It is a three layer, two junction, NPN or PNP device.
- It has three terminals, namely emitter, base and collector.
- Current flows in the device is due to movement of both holes and electrons.
- It is a current controlled device.



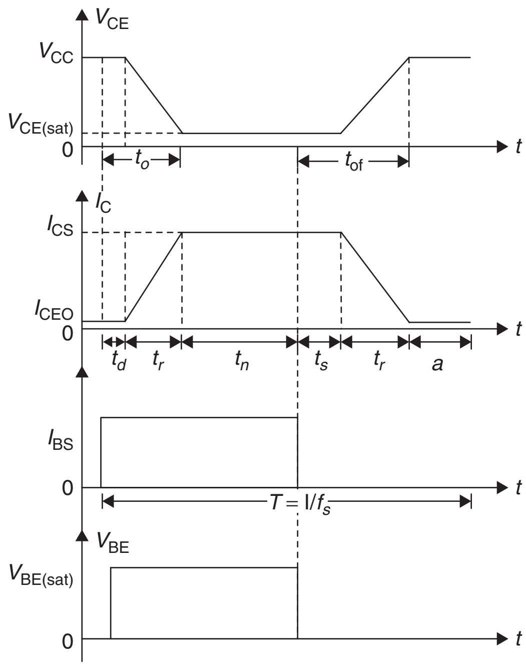
NPN transistor PNP transistor

Symbol



Transistor switch

NPN Transistor Circuit



Switching Waveform for NPN Transistor

$t_r \rightarrow$ rise time
$t_d \rightarrow$ delay time
$t_n \rightarrow$ conduction time
$t_s \rightarrow$ storage time
$t_f \rightarrow$ fall time

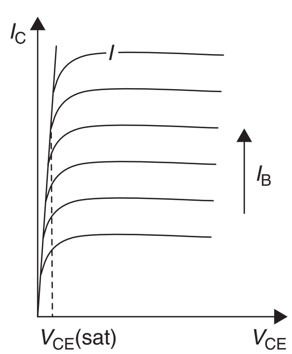


Figure 2 *V–I* characteristics

Ratings: voltage: $V_{CE} < 100$ current: $I_C < 400$ A
Switching frequency up to 5 kHz
Low on-state voltage, V_{CE} (sat): 2–3 V
Low current gain ($\beta < 10$)
Need high base current to obtain reasonable I_C

- Common emitter arrangement is more common in switching applications (N–P–N) transistors.
- For $I_B = 0$, V_{CE} is increased a small leakage (collector) current exists.

$$\text{DC current gain} = \frac{I_C}{I_B} \text{ and } \frac{I_C}{I_E} = \alpha$$

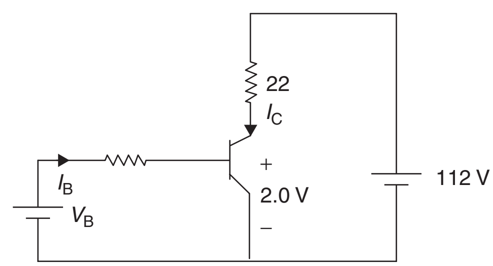
$$I_E = I_B + I_C$$
$$I_B = I_E - I_C$$
$$I_B = I_E - \alpha I_E$$
$$I_B = I_E(1-\alpha)$$

$$\therefore \beta = \frac{I_C}{I_\beta} = \frac{\alpha}{(1-\alpha)}$$

$$\alpha = \frac{\beta}{\beta+1} \text{ or } \alpha = \beta(1-\alpha)$$

$$\beta = \frac{\alpha}{(1-\alpha)} \text{ or } \beta = \alpha\,(1+\beta)$$

Example 5:



The BJT in the figure above is specified to have forward current gain in the range of 4 to 20. The value of base current at saturation for minimum value of current gain is

(A) 1.A (B) 1.25 A
(C) 1.5 A (D) 2 A

Solution: (B)

$$I_{C(\text{sat})} = \frac{112-2}{22} = 5 \text{ A}$$
$$\beta_{\min} = 4$$
$$\frac{I_C}{I_B} = \beta \Rightarrow I_B = \frac{I_C}{\beta} = 1.25 \text{ A}$$

- The collector voltage (V_C) must be greater and positive with respect to the emitter voltage, to allow current to flow through the transistor between the collector emitter junctions.
- There is a voltage drop about 0.7 V between the base and the emitter terminal for silicon devices.
- The base voltage of NPN must be greater than this 0.7 V. otherwise the transistor will not conduct with the base current given as

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

- A forward biased p–n junction exhibits two parallel capacitances
  - Depletion capacitance
  - Diffusion capacitance
- Reverse junction has only depletion capacitance.

- These capacitances influence the turn – ON and OFF behaviour of the transistor during transients.
- Due to internal capacitance the transistor does not turn on instantly.
- Delay Time (T_d): The time required for the base current to rise to I_{B_1}, as the input voltage V_B rises from 0 to V_1 before which any collector current flows.

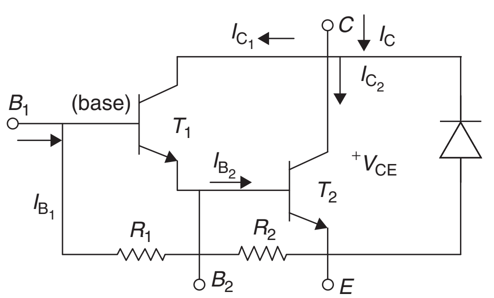
Rise Time (T_r)

The time in which the collector current rises to steady-state value is called Rise Time

- Storage Time (T_s): When input voltage is reversed from V_1 to V_2 and the base current is also changed to $I_1 - I_2$, the collector current does not change for a time t_s, called storage time.
  - Turn-ON Time
    $$T_{ON} = t_d + t_r$$
  - Turn-OFF Time
    $$T_{OFF} = t_s + t_f$$

BJT Darlington Pair

- Normally used when higher current gain is required.
- Whereas power transistor is used for low to medium power applications, with low current gain.
- Power transistor requires a continuous base drive during on–state conditions but does not require forced commutation circuitry.



- A Darlington pair consists of a cascade connection of two transistor stages and can have a large DC common emitter current gain.
  In the above diagram bypass diode has been fabricated on the same chip.
- The shunt resistors R_1 and R_2 reduce the collector leakage current and help establish bias voltage across base emitter junctions. The intermediate base B_2 can be used for fast turning off T_2.
- Base power requirement is low but it is at a cost of reduced switching frequency and higher conduction drop

$$\beta = I_C/I_{B_1} = (I_{C_1} + I_{C_2})/I_{B_1}$$

$$= \frac{I_{C_1}}{I_{B_1}} + \frac{I_{C_2}}{I_{B_1}}$$

$$= \beta_1 + \left[\frac{I_{C_2}}{I_{B_2}}\right]\left[\frac{I_{B_2}}{I_{B_1}}\right]$$

$$= \beta_1 + \beta_2\left[\frac{I_{B_1} + I_{C_1}}{I_{B_1}}\right] = \beta_1 + \beta_2(1 + \beta_1)$$

$$\beta = \beta_1 + \beta_2 + \beta_1\beta_2$$

Voltage and Current Rating

- Voltage rating is defined as collector to emitter breakdown voltage at a relatively higher value of collector current with base open.
- Collector current of a device are specified as I_{DC} continuous DC current $I_{Cmax} \rightarrow$ peak current which are limited on the basis of maximum junction temperature.
- Current Gain: The DC current gain of a transistor is a strong function of collector current it is influenced by the junction temperature and collector voltage.
- The gain is low at low collector current, it then increases with collector current, reaches peak value and then decreases again.

Safe Operating Region

- The collector current I_C and voltage must always lie within this area for reliable operation of the transistor. For DC as well as single pulse operation I_C and V_{CE} are taken as logarithmic scale.

Forward-biased Safe Operating Area (FBSOA)

When base–emitter junction is forward biased to turn on the transistor

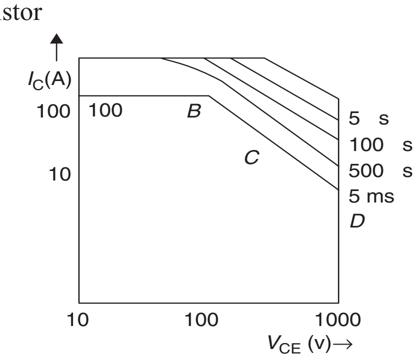


Figure 3 Forward-biased safe operating area

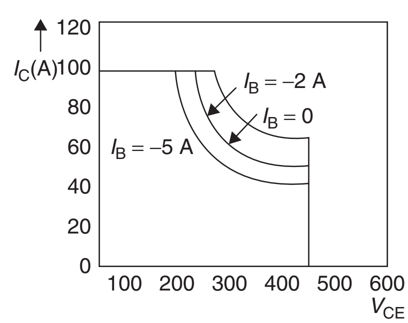


Figure 4 Reverse-block safe operating area

Thyristor (SCR)

- A thyristor is a four-layered semiconductor that is often used or handling large amounts of power.
- It can be turned ON or OFF; it can regulate power using something called phase angle control.
- It has the same characteristics as thyratron tube, it is a solid state device.
- It is a three-junction PNPN semiconductor switching device and has three terminals anode, cathode and gate.

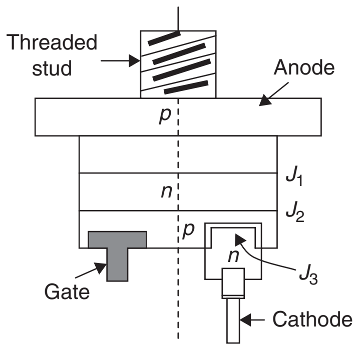


Figure 5 Schematic of thyristor

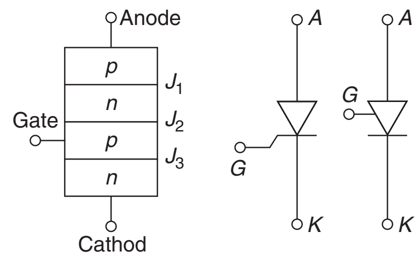


Figure 6 Circuit symbols of thyristor

- The threaded portion is meant for tightening the thyristor to the frame with the help of a nut.

Operation

- If the forward breakover voltage (V_{BO}) is exceeded the SCR 'Self-triggers' into conducting state.
- The presence of gate current will reduce V_{BO}.
- Normal conditions for thyristor to turn on: The device is in forward-blocking state (V_{AK} is positive).
- Once conducting the anode current is latched. V_{AK} collapses to normal forward voltage drop, typically 1.5–3 V.
- In reverse-biased mode the SCR behaves like a diode.

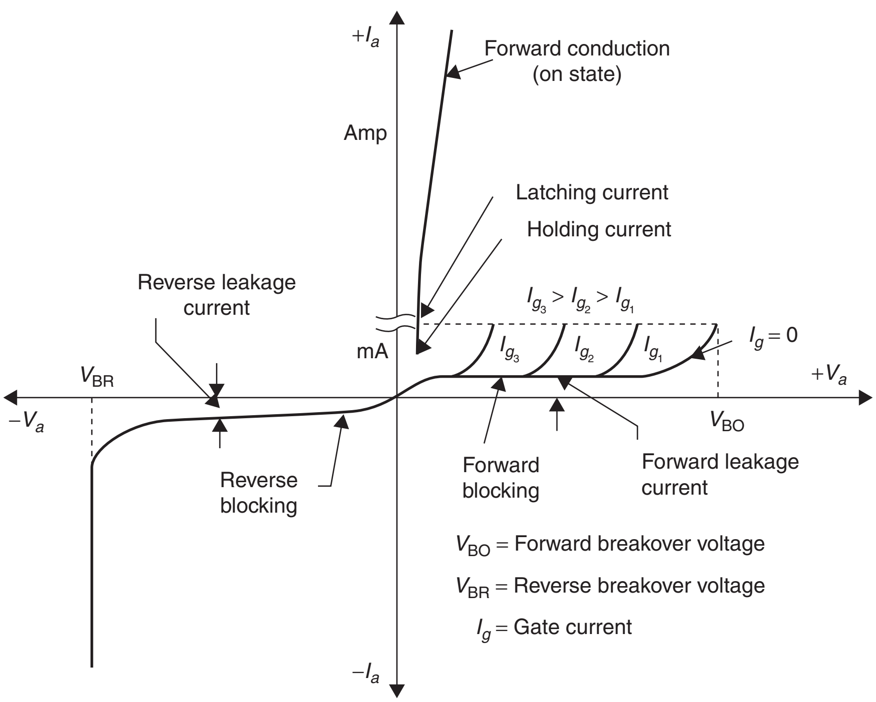


Figure 7 $V - I$ Characteristics

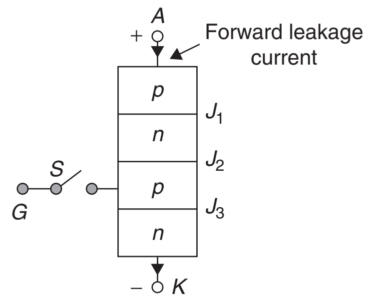
Forward Conduction Mode

- A thyristor is brought to the forward conduction mode by exceeding forward breakover voltage or by applying a gate pulse between gate and cathode.
- In this mode thyristor behaves as a closed switch and the voltage across the thyristor is 1 to 2 V depending on the rating of SCR.
- This small voltage drop depends upon the ohmic drop in the four layers.

Forward-blocking Mode

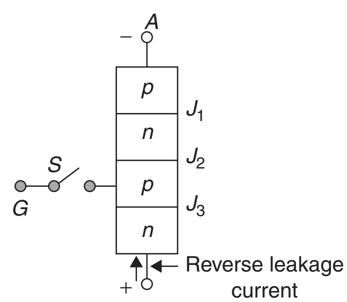
- In this mode anode is made positive with respect to cathode as shown with gate circuit open. J_1, J_3 are forward biased and J_2 is reverse biased.

- In this mode a small leakage current results and increasing the voltage in forward direction, J_2 will have an avalanche breakdown at a 'forward peak over voltage' V_{BO}. For a voltage less than V_{BO}, thyristor acts as open switch as it offers a high impedance.



Reverse-blocking Mode

When cathode is made positive with respect to anode with the switch S open as shown in the figure, thyristor is reverse biased.



- Junctions J_1, J_3 are seen to be reverse biased and J_2 forward biased. A small leakage current of a few milli amperes flows.
- This is the reverse-blocking mode called OFF-state of the thyristor. In this mode, increasing the voltage in reverse direction, avalanche breakdown occurs at J_1 and J_3 at a certain breakdown voltage called reverse breakdown voltage.
- At this voltage, a large reverse current results which can lead to thyristor damage. Hence maximum working voltage should not exceed V_{BR}. In this mode thyristor offers a high impedance, thus acts as an open switch.

Example 6: An asymmetrical thyristor has
(A) Anti parallel connection of a diode and thyristor.
(B) No reverse-blocking capability and small forward-blocking capability.
(C) Small forward-blocking capability and large reverse-blocking capability.
(D) Small reverse-blocking capability and large forward-blocking capability.

Solution: (D)

Example 7: Reverse conducting thyristors would possess which among the following features
(A) High survival voltage
(B) Large current handling capacity
(C) Faster turn off
(D) All of the above

Solution: (D)

Thyristor Turn-ON Methods

Forward Voltage Triggering

- When anode to cathode voltage exceeds forward breakover voltage thyristor turns ON.
- Junction J_2 has an avalanche break down, allows free movement of carriers across three junctions and large forward anode current results.
- Forward V_{BO} and reverse V_{BO} are of the same magnitude and are temperature dependent but practically V_{BR} is slightly more than V_{BO}.
- V_{BR} is taken as final voltage rating of a device.
- After avalanche breakdown, if the anode voltage is reduced below V_{BO}, SCR will continue conduction of current. The SCR is then turned off only by reducing the anode current below a certain value called holding current (I_H).

Gate Triggering

- When there is a positive gate voltage between gate and cathode, charges are inducted into the inner p-layer and V_{BO} is reduced, since cathode n-layer is more heavily doped than gate p-layer.
- As the thyristor is forward-biased, some of these electrons reach J_2.
- As a result, width of depletion layer shrinks, which causes J_2 to breakdown at an applied voltage lower than forward V_{BO}.
- Increasing the magnitude of gate current will turn on the thyristor at a lower forward voltage.

Once SCR is in conduction, reverse biased J_2 no longer exists and the conduction of current from anode to cathode remains unaffected. However if gate current is reduced to zero before the anode current attains a value called latching current the thyristor will turn-off again.

Switching Characteristics

Switching Characteristics During Turn-ON

A forward-biased thyristor is turned ON when a positive gate voltage is applied across gate and cathode, and it takes some time from forward OFF state to forward ON-state known as transition time. This transition time is divided into three intervals:

1. **Delay time (t_d):** It is defined as the time during which anode voltage falls from V_a to 0.9 V_a, where V_a is the initial value of anode voltage.

(or)

It can be defined as the time during which anode current rises from forward leakage current to $0.1I_a$, where, I_a is the final value of anode current.

2. **Rise time (t_r):** It is the time required for the forward-blocking OFF-state voltage to fall from 0.9 to 0.1 of its initial value. This time is inversely proportional to the magnitude of gate current and its build-up rate. (t_r) can be minimized if high and steep current pulses are applied to the gate.

   For series RL circuit $\frac{di}{dt}$ is slow therefore, t_r is more and for RC circuit $\frac{di}{dt}$ is higher, causing t_r to be less.

   Due to high anode voltage V_a and large anode current, turn-on losses are the highest during rise time.

3. **Spread Time (t_p):** It is the time required for the forward-blocking voltage to fall from 0.1 of its initial value to the ON-state voltage drop (1 to 1.5 V).

   After the spread time anode current attains steady-state value and voltage drop across SCR is equal to the ON-state voltage drop of the order of 1 to 1.5 V.

   Total turn-on time is typically of the order 1 to 4 μS depending upon the anode circuit parameters and gate signal wave shapes.

Switching Characteristics During Turn-OFF

- The process involving change of state of an SCR from the conduction state to forward-blocking state is called commutation process or turn-off process.
- If forward voltage is applied to the SCR at the moment, its anode current falls to zero the device is still in conduction since the carriers and electrons in the four layers still favour conduction. Therefore, a thyristor is reverse biased for a finite period after the anode current has reached zero.

Turn-off time (t_q): It is defined as the time between the instant anode current becomes zero and the instant SCR regains the forward-blocking capability.

Example 8: Which among the following statements regarding a Thyristor is/are true?

1. Thyristor can be turned off by a negative gate pulse.
2. Thyristor would remain in its blocking state if the forward anode current is reduced below its holding current.
3. Due to the regenerative effect in a thyristor during turn on, it can turn on with a small gate current and latch into conduction.

(A) 1 and 2 only
(B) 2 and 3 only
(C) 1, 2 and 3
(D) 1 and 3 only

Solution: (B)

Thyristor Protection

1. $\frac{di}{dt}$ **protection:** If the rate of rise of anode current is higher as compared to the spread velocity of carriers, local hot spots will be formed near the gate terminal due to high current density which can destroy the thyristor.

   The rate of rise of anode current at the time of turn-ON should be kept low. This can be achieved using a small inductor in series with the anode circuit.

2. $\frac{dV}{dt}$ **protection:** When anode is made positive with respect to cathode, junction J_2 is reverse-biased and having the characteristics of a capacitor due to stored charges across the junction.

   Entire voltage across the thyristor develops across the J_2 junction and if the charge stored is Q then

$$\text{Charging current, } i = \frac{dQ}{dt} = \frac{d}{dt}(C_j V_a)$$

$$= C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt}$$

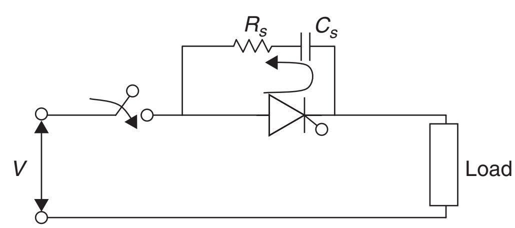
C_j, the capacitance of the junction J_2 is a constant

$$i = \frac{C_j\, dV_a}{dt}$$

If the rate of rise of forward voltage $\frac{dV_a}{dt}$ is high then resultant high charging can turn-ON the SCR even when gate signal is zero.

This can be avoided by using a snubber circuit in parallel with the device.

Snubber circuit consists of a series combination of resistance R_s and capacitance C_s.



Before SCR is being fired by gate pulse, C_s charges to full voltage V_s.

When SCR is turned ON, capacitor discharges through SCR and sends a current equal to V_s/(resistance of the local path formed by C_s and SCR).

As this resistance is quite low, the turn-ON $\frac{di}{dt}$ will be large enough to damage SCR. Therefore to limit the magnitude of discharge current, a resistance R_s is inserted in series with C_s.

Thyristor can be turned off by applying negative gate current. It can only be turned off if I_a goes negative (reverse).

- This happens when negative portion of the sine-wave occurs (natural commutation).
- Another method is forced commutation, where the anode current is 'diverted' to another circuitry.

Latching Current

Latching current is that minimum value of anode current which must be attained during turn on process to maintain conduction even after removal of gate signal.

- The gate pulse width should be chosen such that the anode current rises above the latching current.

Holding Current

The minimum value of anode current below which it must fall for turning off the thyristor

- Generally latching current is more than the holding current (2 or 3 times more than the holding current).

Types of Thyristors Phase-controlled

- Rectifying line frequency voltage and current for AC and DC motor drives.
- Large voltage (up to 7 kv) and current (up to 4 kA) capability.
- Low-on-state voltage drop (1.5 to 3 V).

Inverter Grade

- Used in inverter and chopper.
- Quite fast. Can be turned – on using 'forced-commutation' method.

Light Activated

- Similar to phase controlled, but triggered by pulse of light.
- Normally very high power ratings.

Example 9: In a $\frac{dV}{dt}$ protection employed for a thyristor protection it is observed that junction capacitance of the thyristor is 20 pF. The latching current of the thyristor is 10 mA. The value of additional capacitance required to limit $\frac{dV}{dt}$ to 200 V/μs is

(A) 50 pF (B) 20 pF
(C) 30 pF (D) 40 pF

Solution: (C)

Latching current $I_L = c\frac{dV}{dt}$

$$C = \frac{I_L}{\left(\frac{dV}{dt}\right)} = \frac{10\times10^{-3}}{(200\times10^{6})} = 50\times10^{-12} = 50 \text{ pF}$$

Additional capacitance = 30 pF

TRIAC

- Dual polarity thyristors.
- A TRIAC or bidirectional triode thyristor can conduct in both directions and is used in AC phase control.
- If two SCRs are joined in back-to-back parallel fashion two Schottky as if diodes were joined, we have a new device called TRIAC.

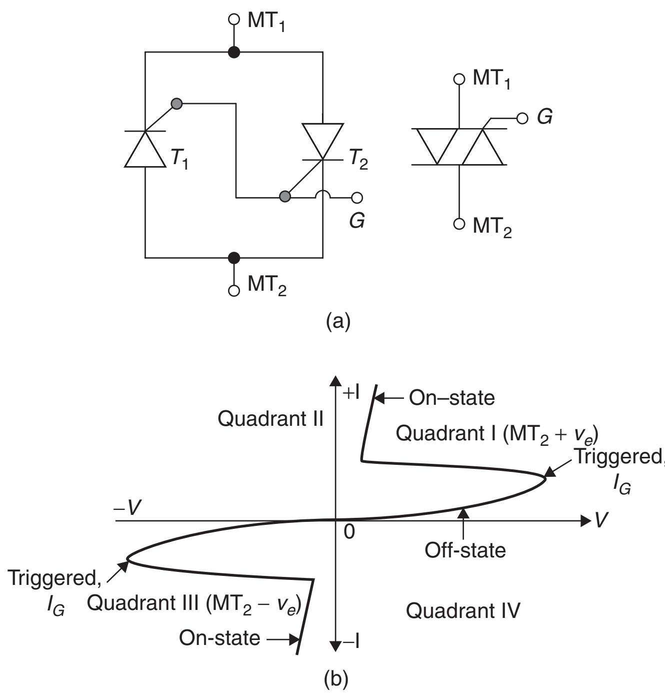


Figure 8 (a) Equivalent of TRIAC; (b) *V–I* characteristics

- The terminals of a TRIAC cannot be designated as anode and cathode because it is a bidirectional device.
- If terminal MT_2 is positive with respect to terminal MT_1, the TRIAC can be turned ON by applying a positive gate signal between gate G and terminal MT_1.
- If terminal MT_2 is negative with respect to terminal MT_1, it is turned ON by applying a negative gate signal between gate G and terminal MT_1.
- It is not necessary to have both polarities of gate signals and a TRIAC can be turned ON with either a positive or a negative gate signal.
- In practice, the sensitivities may vary from one quadrant to the another and TRIACs are normally operated in quadrant I^+ (positive gate voltage and gate current) and quadrant III^- (negative gate voltage and gate current).
- Individual SCRs are more flexible to use in advanced control systems; these are more commonly seen in circuits like motor drives.
- TRIACs are usually seen in simple low power applications like household dimmer switches.
- The TRIAC is easy to use and provides vast advantages over the use of two thyristors for many low power applications. Where higher power needed, two thyristors placed in is anti-parallel are almost always used.

Example 10: An incorrect statement regarding the disadvantages of a Triac is

(A) Triac is highly sensitive towards gate current.

(B) Triac protection requires a well-designed RC snubber circuit.

(C) Triac usage is difficult with inductive load due to lower rating of reapplied

$$\left(\frac{dV}{dt}\right)$$

(D) Storage effect of the minority carrier results in longer turn OFF time.

Solution: (A)

Gate current sensitivity of Triac is poorer compared to other Power semiconductor devices.

GTO's (Gate-turn-OFF Thyristor)

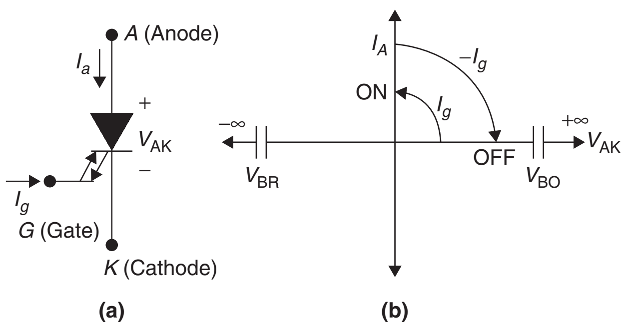


Figure 9 (a) Symbol; (b) Characteristics *V–I*

- The gate turn off thyristor is a PNPN device which can be turned on like an ordinary thyristor by a pulse of positive gate current.
- It can be easily turned off by a negative gate pulse of approximate amplitude.
- As no forced commutation circuitry is required for GTOs, these devices are compact and less costly.
- The negative gate current required to turn OFF GTO is quite a large percentage (20 to 30%) of anode current 800 A.
- GTO requires a negative current pulse of 200 A peak for turning it OFF.
- A Thyristor – transistor like behaviour of GTO can be explained by the two transistor analogy.
- If the transistor T_2 with current gain is designed to be near unity in the on state, and if negative gate current can completely divert the P–N–P collector T_{C_1} out of the gate, the device can be turned off successfully.
- Turn-off gain is defined as the ratio of anode current prior to turn OFF to the negative gate current required for turn-OFF. It is very low, typically between 3 and 5.

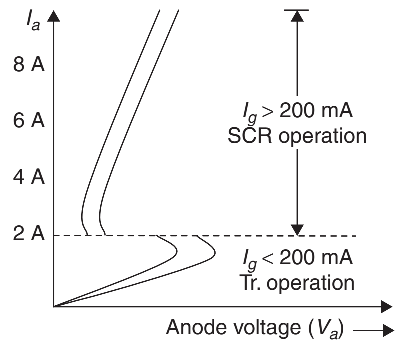


Figure 10 Static. *V–I* characteristics

Switching Characteristics

Turn-ON

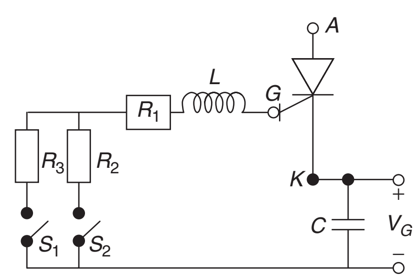
- A large initial gate trigger pulse is required to turn-on GTO since it has highly interdigitated gate structure with no regenerative gate.
- The rate of rise of $\frac{di}{dt}$ gate current affects the device turn-ON losses. A longer period is required, if the anode current $\frac{di}{dt}$ is low such that I_{GM} is maintained until a sufficient level of anode current is established.

On State

- Once the GTO is turned ON forward gate current must be continued for the whole of the conduction period to ensure the device remains in conduction.
- Otherwise the device cannot remain in conduction during the ON state period. The on state gate current should be at least 1% of the turn-ON pulse to ensure that the gate does not unlatch.

Turn-OFF

A turn-OFF circuit arrangement of a GTO is shown in the figure.



- Since a GTO requires a large turn-OFF current, a charged capacitor C is normally used to provide the required turn-off current. L limits the turn-OFF $\frac{di}{dt}$ of the gate current through the circuit formed but R_1, R_2, S_1 and L. The gate circuit supply voltage V_{GS} should be selected to give the required value of V_{GQ}.

- After the fall of the tail current to zero the gate should ideally be kept reverse biased and turn-OFF period begins.
- The reverse bias ensures maximum blocking capability, reverse bias can be obtained either by keeping S_1 closed during the whole OFF state period (or) by using a higher impedance circuit S_2 and R_3 provided a minimum negative voltage exits, it must also sink, the gate leakage current.
- GTOs are mostly used in voltage source converters in which a fast recovery antiparallel diode is required across each GTO. Thus GTOs normally do not need reverse voltage capabilities, such GTOs are known as asymmetric GTOs.
- Controllable peak on site current I_{TGQ} is the peak value of on state current that can be turned off by gate control.
- Once a GTO is turned OFF, the load current I_L, which is diverted through and charges the snubber capacitor determines the reapplied $\frac{di}{dt}$.

$$\frac{dV}{dt} = \frac{I_L}{C_s}$$

$C_s \rightarrow$ Snubber capacitance

- Gate drive design is very difficult due to very large reverse gate current at turn off

Ratings: Highest power ratings switch:
Voltage: $V_{AK} < 5$ kV
Current: $I_a < 5$ kA
Frequency < 5 kHz

MOSFETs (Metal Oxide Silicon Field Effect Transistor)

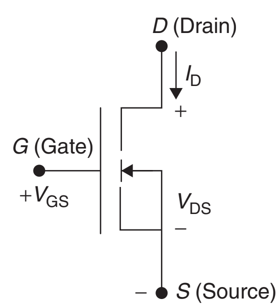


Figure 11 **MOSFET:** Symbol (n-channel)

Power MOSFET

- A power MOSFET is a voltage controlled device and requires only a small amount of input current.
- Switching speed is very high and switching times are of the order of nanoseconds.
- Two types of MOSFETs are
  1. Depletion MOSFET
  2. Enhancement MOSFET
- The three terminals are called gate, drain and source.
- With a positive voltage applied to the gate with respect to source (n-channel), it introduces an n-channel and permits electron current to flow from the source to the drain with applied voltage V_{DS}.
- Because of the SiO_2 isolation, the gate circuit impedance is extremely high, typically in the range of 10^9 W. This feature permits power MOSFET to drive directly from CMOS or TTL Logic.
- The devices have an integrated reverse rectifier, which permits free-wheeling current of the same magnitude as that of the main device.
- The MOSFET is used for low-power, high-frequency applications. Also DMOS structure is used for high-voltage devices.

n-channel Depletion-type MOSFET

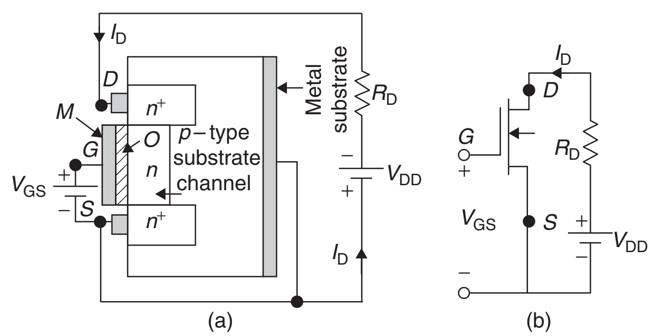


Figure 12 (a) Basic structure; (b) Symbol

p-channel Depletion-type MOSFET

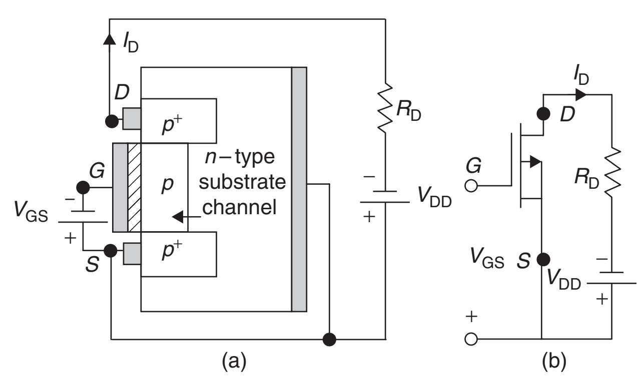
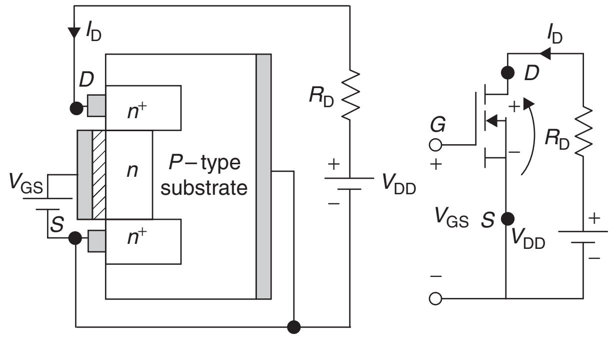
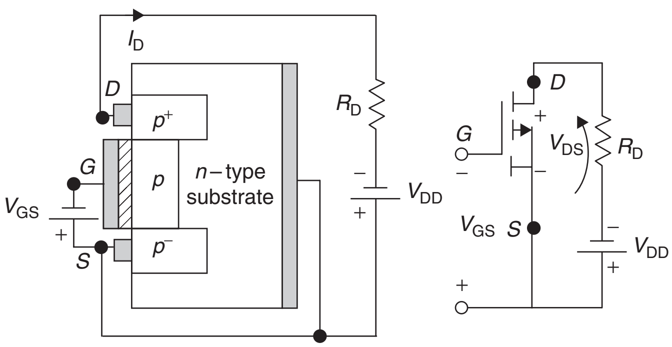


Figure 13 (a) Basic structure; (b) Symbol

n-channel Enhancement-type MOSFET

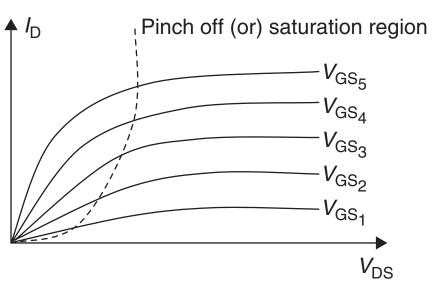


p-channel Enhancement-type MOSFET



Steady-State Characteristics

Drain-source steady-state characteristics are as shown below



The gate circuit has a threshold voltage, typically 2 to 4 V below which the drain current is very small. With V_{GS} beyond the threshold value $I_D - V_{DS}$ characteristics have two distinct regions, a constant resistance [$R_{DS(ON)}$] region and a constant current region.

- The [$R_{DS(ON)}$] of a MOSFET is a key parameter and determines the conduction voltage drop. For a device the [$R_{DS(ON)}$] increases with the voltage rating and has positive temperature coefficient.

Merits and Demerits when Compared to BJT

- Power MOSFET has lower switching losses but its ON-state resistance and conduction losses are more.
- At higher frequencies MOSFET is preferred and at lower frequencies BJT is preferred (30 kHz)
- MOSFET has positive temperature coefficient of resistance whereas BJT has negative temperature coefficient of resistance.
- In MOSFET secondary breakdown does not occur, because it has positive temperature coefficient of resistance.
- Power MOSFET of higher voltage rating has more conduction loss.

Ratings

Voltage $V_{DS} < 500$ V,
Current $I_{DS} < 300$ A,
Frequency $f > 100$ kHz

- For some low power devices (few hundred watts) may go up to MHz range.
- Turning ON and OFF is very simple.
- Gate drive circuit is simple.
- Power MOSFET is basically a low-voltage device. High-voltage device are available up to 600 V but with limited current.
- Can be paralleled quite easily for higher current capability.
- Internal (dynamic) resistance between drain and source during on state R_{DS} (ON), limits the power handling capability of MOSFET.
- High losses especially for high-voltage device due to R_{DS} (ON).
- Dominate in high-frequency application (>100 kHz) Biggest applications is in switched-mode power supplies.

Example 11: A power MOSFET would act as an amplifier in its

(A) Both linear and saturation regions
(B) Linear region only
(C) Saturation region only
(D) At the boundary of these regions.

Solution: (C)
Explained from the operating characteristics of MOSFET.

Example 12: Two parallel connected MOSFET'S carry a total current of 40 A. The drain source voltage and current storing series resistances of MOSFET 1 are $V_{DS_1} = 5$ V and $R_s = 1\ \Omega$ and that of MOSFET 2 are $V_{DS_2} = 6$ V and $R_{S_2} = 1\ \Omega$. The drain current of each transistor is

(A) 20 A, 20 A
(B) 15 A, 25 A
(C) 20.5 A, 19.5 A
(D) None of the above

Solution: (C)

$$I_T = I_{D_1} + I_{D_2}$$

$$V_{DS_1} + I_{D_1}R_{S_1} = V_{DS_2} + I_{D_2}R_{S_2}$$

[Due to Parallel connection]

$$= V_{DS_2} + (I_T - I_{D_1})R_{S_2}$$

$$I_{D_1} = \frac{V_{DS_2} - V_{DS_1} + I_T R_{S_2}}{R_{S_1} + R_{S_2}}$$

$$= \frac{6-5+40\times 1}{1+1} = 20.5$$

$$I_{DQ} = 40 - 20.5 = 19.5 \text{ A}$$

IGBTS (Insulated Gate Bipolar Transistor)

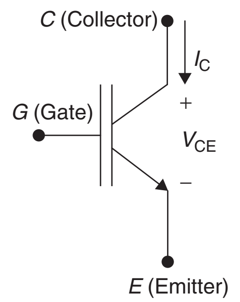
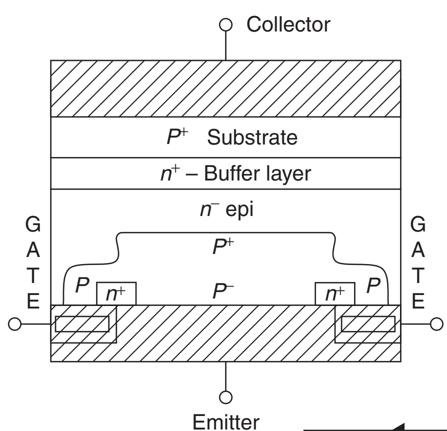
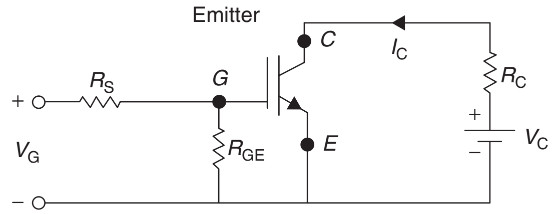


Figure 14 **IGBT:** Symbol

- Combination of BJT and MOSFET characteristics.
- Gate behaviour similar to MOSFET—easy to turn on and off.
- Low losses like BJT due to low on—state collector–emitter voltage (2–3 V).
- IGBT has high input impedance like a MOSFET and low ON state power loss as in a BJT.
- IGBT is virtually constructed in the same manner as a power MOSFET however there is a major difference in the substrate.





Symbol and Circuit for an IGBT

Ratings

Voltage: $V_{CE} < 3.3$ kV

Current $I_C < 1.2$ kA

Currently available

Latest: HVIGBT 4.5 kV/1.2 kA switching frequency up to 100 kHz.

Typical applications: 20–50 kHz.

- IGBTs are widely used in medium-power applications such as DC and AC motor devices, UPS Systems, power supplies and drives.

Comparison of IGBT with MOSFET

1. The terminals used in MOSFET are gate, source, drain, but in IGBT the terminals are represented by gate, emitter and collector.
2. The input impedance of both MOSFET and IGBT is high.

Insulated Gate-commutated Thyristor (IGCT)

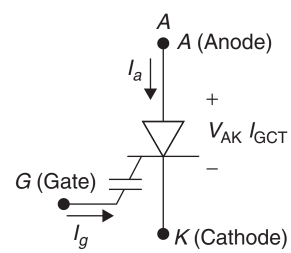


Figure 15 **IGCT:** Symbol

- Conducts like normal thyristor (latching) but can be turned off using gate signal, similar to IGBT turn off; 20 V is sufficient.
- Power switch is integrated with the gate drive unit.

Ratings

Voltage: $V_{AK} < 6.5$ kV

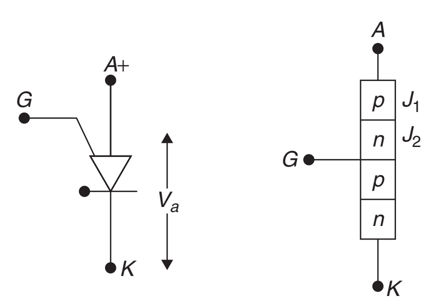
Current: $I_a < 4$ kA

Frequency < 1 kHz

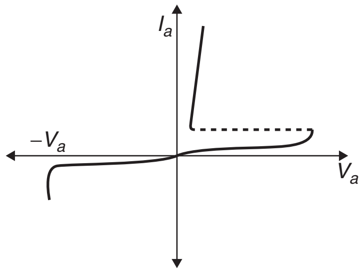
- Currently 10 kV device is being developed.
- Very low on-state voltage 2.7 V for 4 kA device.

Other Members of Thyristor Family

Programmable Unijunction Transistor (PUT)



- It is an ordinary unijunction transistor.
- V–I characteristics is almost similar to an ordinary UJT.



- It is a four layer P–N–P–N device with a gate connected directly to the sandwiched N-type layer.
- The term 'programmable' is applied because the inter base resistance R_{BB}, the intrinsic standoff ratio and peak point voltage V_p as defined in UJT can be programmed to any desired values through external base Resistors R_{B_1} and R_{B_2} and the supply voltage V_{BB}.
- Because of its superiority over ordinary unijunction transistors it is popularly used for relaxation oscillators, time delay, logic and SCR trigger circuits.
- Its largest rating is about 200 V and 1 A.

Silicon Unilateral Switch (SUS)

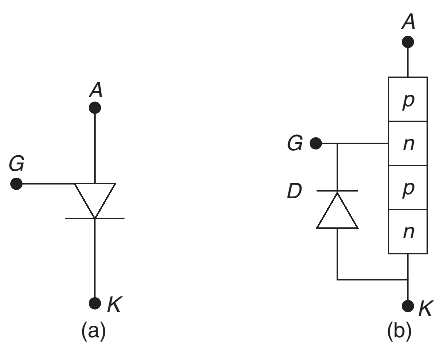
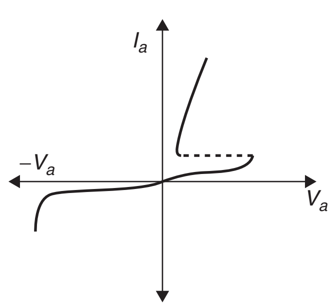


Figure 16 (a) Symbol; (b) Structure

- It is a type of thyristor used as a breakover device that conducts in only one direction; it has a third terminal that is used to alter the breakover voltage if connected to a zener diode



- It is an inbuilt low-voltage avalanche diode between gate and cathode.
- Mainly used in timing, logic and trigger circuits.
- Ratings are about 20 V and 0.5 A.

Silicon-controlled Switch (SCS)

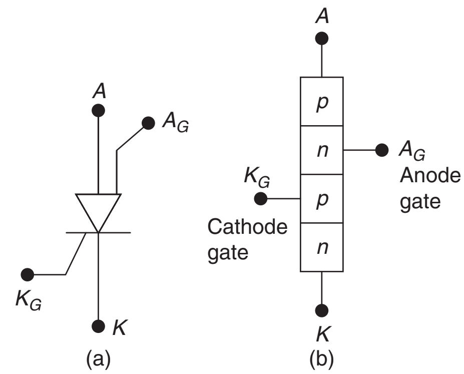


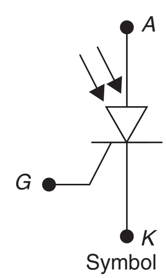
Figure 17 (a) Symbol; (b) Structure

- Like SCR, it is a unilateral, four layer three-junction P–N–P–N Silicon device with four electrodes, namely cathode, cathode gate G_1, anode gate G_2 and the anode A.
- Low-power device.
- Handles currents in milli amperes.
- A positive pulse at gate KG turns on the device.
- (Just like an SCR) and a negative pulse at AG turns it off (just like a GTO).

Ratings

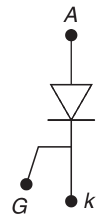
- 100 V and 200 mA.
- Can be operated like an OR gate.
- Used in timing, logic and triggering circuits, pulse generators, voltage sensors and oscillators.

Light-Activated Thyristor (LASCR)



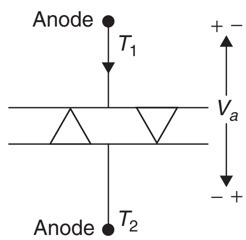
- It is an SCR whose state is controlled by the light falling upon a silicon semiconductor layer of the device.
- They are used in high-voltage high-current applications static reactive-power compensation, optical light controls, relays, phase control, motor control and a variety of computer application.
- The maximum currents 3.5 kA, and voltage 6 kV with on state voltage drop of about 2 V and with light – triggering requirements of 5 mW.
- Interesting application of an LASCR is in the AND & OR circuits.

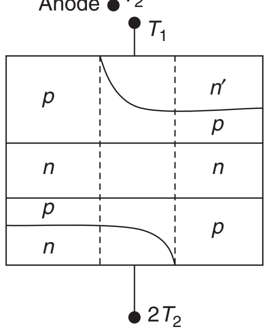
Static Induction Thyristors (SITHS)

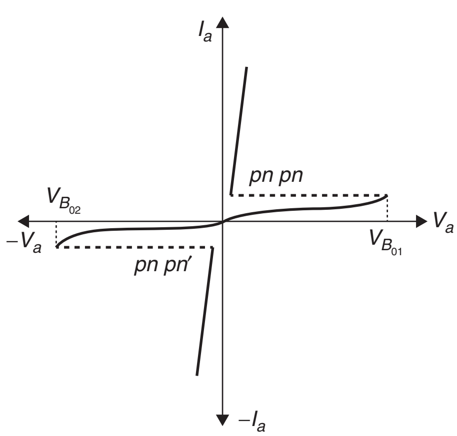


- Static induction thyristor is a thyristor with a buried gate structure in which the gate electrodes are placed in n-base region. Since they are normally on-state, gate electrodes must be negatively biased to hold-off-state.
- The V–I characteristics of a SITH are similar to those of an SCR.
- The ON state voltage drop is low.
- They are available up to about 2500 V, 500 A ratings.
- Used for medium-power converter with frequency range beyond that used for GTOs.

The DIAC (Bidirectional Thyristor Diode)







V–I Characteristics

- Diac is a two-electrode device; it can conduct in either direction.
- Diac stands for 'diode for AC'. The four layers are pn pn and pn pn′.
- It has symmetrical breakdown characteristics.
- Its leads are interchangeable. When conducting it acts like an open switch.
- It is sometimes called a gate less triac.
- Diac is mainly used for triggering triacs.
- A triac requires either positive or negative gate pulse for turning it on. This is provided by a Diac.

Asymmetrical Thyristor (ASCR)

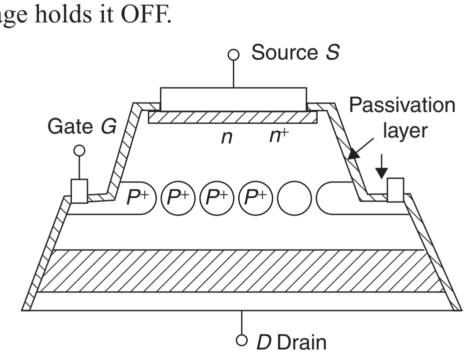
- Specially fabricated to have limited reverse voltage capability, by which it permits reduction in turn on time, turn off time and on-state voltage drop in SCR.
- The fast turn off ASCRs Permit high-frequency operation (20 kHz) in turn minimises the size weight and cost of commutating components with improved efficiency.

Reverse Conducting Thyristor (RCT)

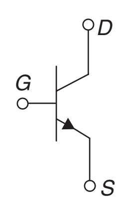
- It is a special case asymmetrical thyristor with a monolithically integrated anti parallel diode on the same silicon chip.

Static Induction Transistor (SIT)

- A SIT is a high-power, high-frequency device. It is essentially the solid state version of the triode vacuum tube. It is a vertical structure device with short multi channels. Hence it is not subject to area limitations and is suitable for high speed high power operations.
- A SIT has a short channel length, low gate series resistance, low gate source capacitance and small thermal resistance.
- A SIT normally is an ON device and a negative gate voltage holds it OFF.



Cross section

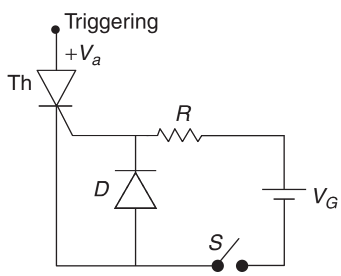


- Since SITs have a higher current and switching speed, it is most suitable for high-power and high-frequency applications.

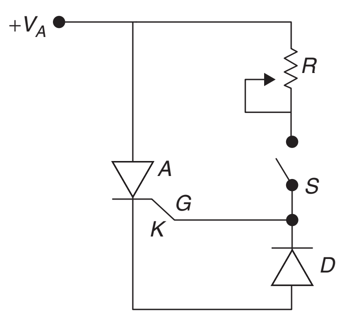
Thyristor-triggering Circuits

- Generally the thyristor gate circuits are within the low and high resistance values. It is a pn junction. The minimum level of voltage and current required to turn on the thyristor is a function of junction temperature.

Direct Current



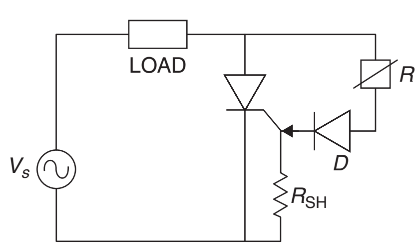
- A separate DC source, or the current tapped off from the main DC supply to the gate are used.



- When the thyristor conducts the forward voltage drop goes down about 1.5 V, then the positive voltage applied to the gate goes below the break over voltage.
- When the current is interrupted, then the reverse connected diode D prevents a large reverse bias at the gate-cathode terminals.

AC Signal Triggering

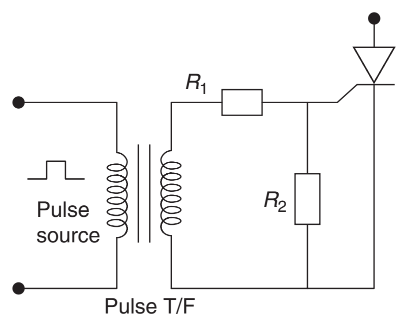
- Also known as phase control triggering.
- The firing instant can be manipulated to occur at any particular phase between 0 and p of the half cycle of an AC signal.



The firing angle is adjusted by variable resistance.

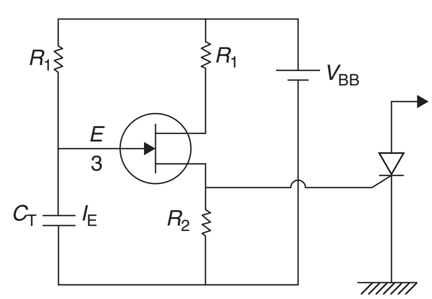
- The gate is not triggered when the variable resistance is high.
- When resistance is decreased, then I_G increases beyond latching current and SCR triggers.
- There is a delay by an angle a when a signal is applied to gate which causes the output load current to decrease.
- When the resistance is fully decreased to zero, a full positive angle of 180° is applied to the gate which causes large current to flow in the load.
- The drawback of the RC circuit is that R and C values have to be adjusted for different source voltages.
- This can be overcome by AC phase shift control vcircuit with a centre-tapped transformer.

Pulse Triggering



- To trigger a thyristor a pulse of current equal to forward break over voltage is required.
- Anode current should be greater than latching current.
- Reduces the power dissipation in the gate circuit.
- Conduction b can occur for only 90°.
- It has many defects as the turn-on angle ° may vary from cycle to cycle due to temperature variations.
- The turn on is slow.

UJT Trigger Circuit



- Due to simplicity low power consumption, high effective power gain, compactness and because of its combination of economy, UJT is mostly used for triggering SCRs.
- When voltage across capacitor after discharge fall below valley voltage V_V, UJT turns off.
- When $V_{CT} = V_P > \eta V_{BB} + V_r$, then I_E flows.

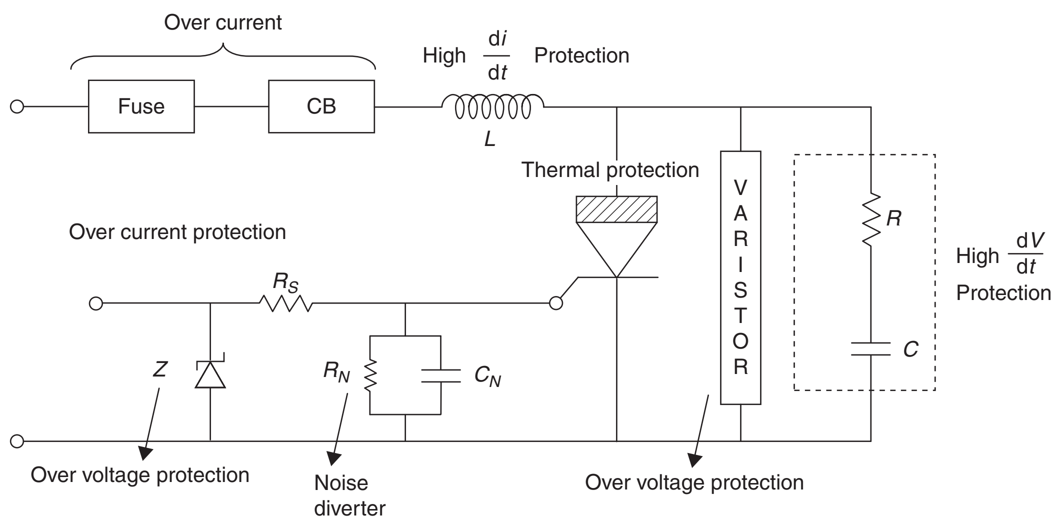
- For turning ON and OFF the UJT, the line of $I_E R_T$ should fall within the valley and peak point.

Protection of SCR

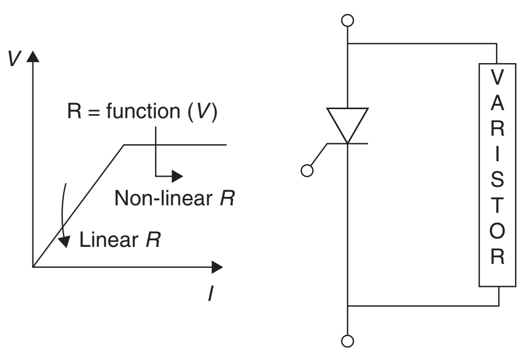
Generally protection is required against main circuit and Gate circuit.

Protection Circuit

1. **Main Circuit:**
   - Overvoltage
   - Overcurrent
   - Thermal
   - *dv*/*dt*
   - *di*/*dt*
2. **Gate Circuit:**
   - Overvoltage
   - Overcurrent
   - Noise
3. **Main Circuit Protection:**
   Overvoltage Protection: Overvoltages exist due to switching and lightning surges.



To reduce this VARISTORS are used. VARISTORS are non-linear resistor.



At higher voltages slope is less and VARISTORS operating with lesser resistance.

Overcurrent Protection

- They are fault currents or normal overload currents.
- Circuit breakers and fuses connected in series are used to protect.

Thermal Protection

- With the rise in temperature, insulation losses, which result in leakage current.
- Heat sinks made of aluminium discs are used with ventilating ducts.
- Coolants and hallow conductors are used.

dv/*dt* Protection

- When *dv*/*dt* is high without application of gate signal, then turn on of SCR takes place.
- Capacitors are used for *dv*/*dt* protection which delay the build-up of voltage.

di/*dt* Protection

- Series inductors reduces *di*/*dt* rate.

Gate Protection

Overcurrent protection: Connect the Resistor R_s to limit gate current with in permissible value.

Overvoltage protection: Voltage clampers are used for over voltage protection. Zener diode under reverse biased mode operates as voltage regulator.

Protection against noise: Noise signal produces the disturbance in the gate circuit due to the voltage transients of the power supply or due to the interference with the nearby communication lines. These noise signals may false turn-ON the SCR so that the gate loses control over itself.

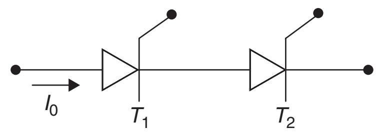
An RC parallel circuit is to be connected across the gate so that it will divert the noise signal without entering into the gate terminal.

$\downarrow\downarrow X_C = \dfrac{1}{\omega C \uparrow\uparrow}$, RC noise diverter, diverts the high-frequency noise signal and dissipates across R.

Series and Parallel Operation of SCRs

Series Operation

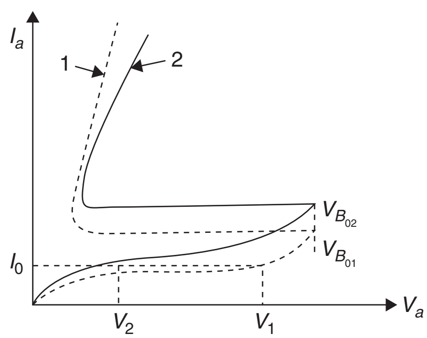
- It improves voltage rating



De-rating factor = 1 – String efficiency

String efficiency =

$$\frac{\text{Voltage (series) OR Current (parallel) rating of string}}{\text{No. of SCR in the string} \times \text{Voltage OR Current rating of each SCR}}$$



$$\eta_s = \frac{V_1 + V_2}{2V_1}$$

- Since the characteristics are not matching in forward-blocking mode, the efficiency is less than 1. To improve the efficiency this mismatch should be reduced.
- The SCR which offers more leakage resistance will block more voltage.
- With less leakage current blocks more voltage.
- Voltage distribution across the SCRs is proportional to the leakage resistance offered by each SCR.
- To make voltage distribution equal, leakage resistances should be made equal

Static equalizing resistance

$$R_s = \frac{\eta V_{bm} - V_s}{(n-1)\Delta I_b}$$

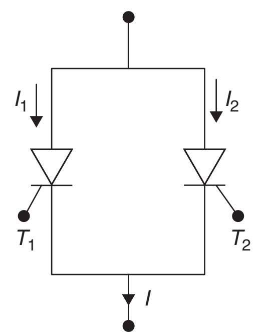
Dynamic equalizing capacitance

$$C = \frac{(n-1)\Delta Q}{nV_{bm} - V_s}$$

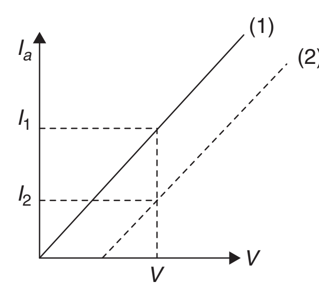
- An R in series with C acts as the snubber circuit for dV/dt protection as well as for dynamic equalization.

Parallel Operation

- Applied for SCRs with higher current ratings



$$M_S = \frac{I_1 + I_2}{2I_1}$$



- All SCRs should be mounted on heat sink in symmetrical positions.
- It is not compulsory that all SCRs should be mounted on the same heat sink to maintain constant temperature.
- A magnetic coupling is employed to equalize currents in parallel connected SCRs.

Exercises

Practice Problems 1

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. Which among the following, electronic switch employed in a power electronic converter which is uncontrollable is
(A) MOSFET (B) Diode
(C) Thyristor (D) BJT

2. An NPN transistor has a DC current gain (β) of 200. The base current required to switch resistance load of 3 mA would be
(A) 40 μA (B) 20 μ
(C) 30 μA (D) 10 μA

3. A power control switching is done using a BJT by basing it in the saturation region (or) cut off region. In the ON state for BJT
(A) Both emitter base and collector base junctions are reverse biased
(B) Emitter base junction is forward biased and collector base junction is reverse biased
(C) Both emitter base and collector base junctions are forward biased
(D) Emitter base junction is reverse biased and collector base junction is forward biased

4. A thyristor is categorized under a semi-controlled device because
(A) It conducts only during one half cycle of an AC wave.
(B) It can be switched ON but not OFF with a gate pulse
(C) It can be switched OFF but not ON with a gate pulse
(D) It conducts only during one half cycle of an alternating voltage wave.

5. The typical ratio of holding current to latching current in a 25 A thyristor is
(A) 5 (B) 2
(C) 1 (D) 0.5

6. The main switching element used in a switched mode power supply operating at 30 kHz to 90 kHz range preferably is
(A) UJT
(B) TRIAC
(C) Thyristor
(D) MOSFET

7. The ON-state condition of a MOSFET switch is equal to
(A) Capacitor (B) Battery
(C) Inductor (D) Resistor

8. For a power MOSFET, the characteristic curve drawn for conduction loss versus device current would follow the path of
(A) An exponentially decaying curve
(B) A parabola
(C) A rectangular hyperbola
(D) A straight line

9 The only non-current triggered, power semiconductor device among the following is
(A) Triac (B) Thyristor
(C) MOSFET (D) GTO

10. Combined characteristics of BJT and MOSFET, incorporated in a modern power semiconductor device would be
(A) An MCT (B) An FCT
(C) An IGBT (D) GTO

11. Which among the following parameters regarding an IGBT is true?
(1) High input impedance
(2) Combined attributes of BJT and MOSFET
(3) Inferior switching speed compared to MOSFET
(4) Low Forward Voltage Drop

(A) 1, 2, 3 and 4 (B) 1, 2 and 3
(C) 1, 2, and 4 (D) 3 and 4

12. Under steady-state conditions, between a MOSFET and BJT
(A) MOSFET requires lower control power
(B) BJT requires lower control power
(C) Both requires same range of control power
(D) MOSFET has an ON state voltage drop greater than that of BJT

13. In a thyristor, reverse anode to cathode voltage and forward gate current will cause
(A) Low forward current
(B) Large reverse current
(C) Large forward current
(D) Low reverse current

14. A TRIAC can be triggered by a gate pulse of ______ polarity
(A) Positive
(B) Negative
(C) Positive or Negative
(C) None

15. The Triac can be used only in
(A) Inverter
(B) Rectifier
(C) Multiquadrant chopper
(D) Cyclo converter

Practice Problems 2

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. A GTO thyristor
(A) Can be turned off by a positive current pulse at the gate.
(B) Can be turned off by a negative current pulse at the gate.
(C) Requires a special turn off thyristor.
(D) Can be turned off by removal of gate pulse.

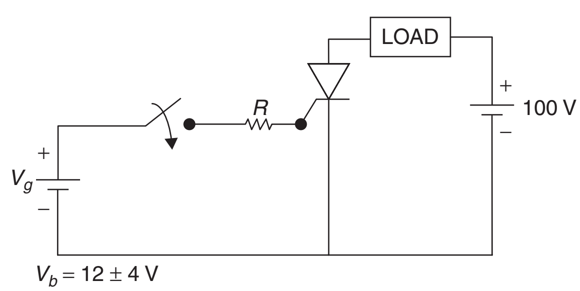
2. A gate turn-off thyristor (GTO) has the capacity to
(A) Amplify the gate current
(B) Turn-off when positive current pulse is given at the gate
(C) Turn-off when a gate pulse is given at the gate even though it is reverse biased
(D) Turn-off when a negative current pulse is given at the gate

3. A power semiconductor may undergo damage due to
(A) High di/dt (B) High $\frac{dv}{dt}$
(C) High gate current (D) Low $\frac{dv}{dt}$

4. A satisfactory turn off using a commutation circuit employed to turn off a Thyristor is obtained when
(A) Device turn off time > circuit turn off time
(B) Device turn off < circuit turn off time
(C) Device turn off time > circuit time constant
(D) Device turn off time < circuit time constant.

5. In synchronized UJT triggering of an SCR, voltage V_C across capacitor reaches UJT threshold voltage thrice in each half cycle so that there are three firing pulses during each half cycle. The firing angle of the SCR can be controlled
(A) Once in each half cycle
(B) Thrice in each half cycle
(C) Thrice in a full cycle
(D) Twice in a half cycle

6. The triggering circuit of a thyristor is shown in figure. The thyristor requires a gate current of 10 mA, for guaranteed turn-on. The value of R required for the thyristor to turn-on reliably under all conditions of V_g variation



(A) 10 kΩ (B) 1.6 kΩ
(C) 1.2 kΩ (D) 0.8 kΩ

7. Which of the following statements are true about power electronic systems?
(i) Tendency to generate harmonics in the supply system as well as in the load circuit
(ii) Fast dynamic response as compared to electromechanical converter systems
(iii) Low input power factor under certain operating conditions
(iv) Less efficiency as compared to electromechanical converter systems
(A) (i), (ii) and (iii)
(B) (i) and (iv)
(C) (ii) and (iv)
(D) (i) and (iii)

8. An IGBT has three terminals called
(A) Collector, emitter and base
(B) Drain, source and gate
(C) Drain, source and base
(D) Collector, emitter and gate

9. High-frequency operation of a circuit is limited by
(A) On-state loss in the device
(B) Off-state loss in the device
(C) Switching losses in the device
(D) Both (A) and (B)

10. For an SCR, dV/dt protection is achieved through the use of
(A) RL in parallel with SCR
(B) RC in series with SCR
(C) RL in series with SCR
(D) RC across SCR

11. Secondary breakdown occurs in
(A) MOSFET but not in BJT
(B) Both MOSFET and BJT
(C) BJT but not in MOSFET
(D) None of the above

12. Choose the correct statement
(A) MOSFET has positive temperature coefficient (TC) whereas BJT has negative TC
(B) Both MOSFET and BJT have positive TC
(C) Both MOSFET and BJT have negative TC
(D) MOSFET has negative TC whereas BJT has positive TC

13. Which of the following statements are true?
(1) Power MOSFET is a majority carrier device
(2) IGBT is a bipolar device
(3) BJT is a majority carrier device
(4) MCT is a unipolar device
(A) 1, 3 (B) 2, 3
(C) 2, 4 (D) 1, 2

14. The correct sequence of the given devices in the increasing order of their speed of operation is

[PMOSFET—Power MOSFET PBJT—Power BJT]

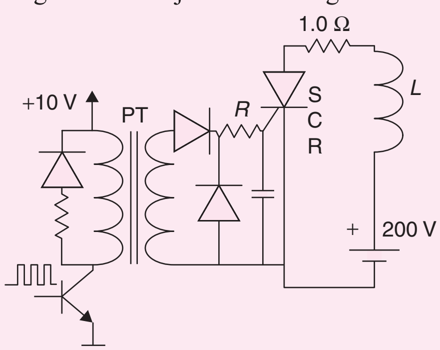
(A) SCR, IGBT, PMOSFET, PBJT
(B) SCR, PBJT, PMOSFET, IGBT
(C) PMOSFET, IGBT, PBJT, SCR
(D) SCR, PBJT, IGBT, PMOSFET

15. For a string voltage of 3300 V, there are six series connected SCRs, each of 600 V rating. Then the de-rating factor is

(A) 9.17%
(B) 91.7%
(C) 8.3%
(D) 10.9%

PREVIOUS YEARS' QUESTIONS

Common Data for Questions 1 and 2:
A 1:1 pulse transformer (PT) is used to trigger the SCR in the adjacent figure. The SCR is rated at 1.5 kV, 250 A with $I_L = 250$ mA, $I_H = 150$ mA, and $I_{Gmax} = 150$ mA, $I_{Gmin} = 100$ mA. The SCR is connected to an inductive load, where $L = 150$ mH in series with a small resistance and the supply voltage is 200 V DC. The forward drop of all transistors/diodes and gate-cathode junction during ON state is 1.0 V.



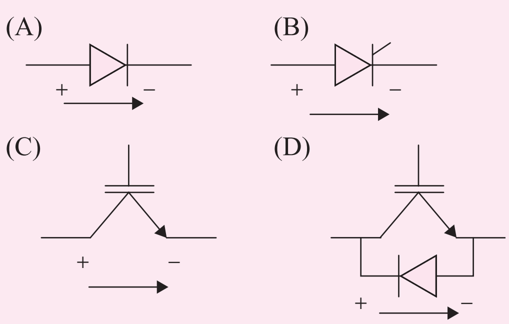
1. The resistance R should be **[2007]**

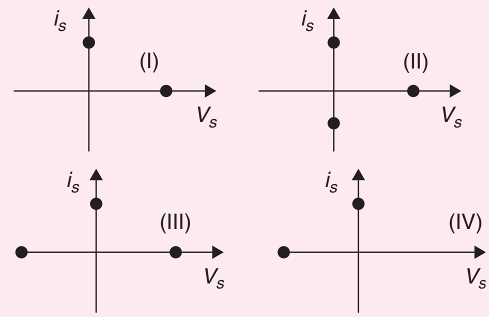
(A) 4.7 kΩ (B) 470 Ω
(C) 47 Ω (D) 4.7 Ω

2. The minimum approximate volt-second rating of the pulse transformer suitable for triggering the SCR should be: (volt-second rating is the maximum of product of the voltage and the width of the pulse that may be applied) **[2007]**

(A) 2000 μV-s (B) 200 μV-s
(C) 20 μV-s (D) 2.0 μV-s

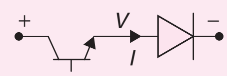
3. Match the switch arrangements on the top row to the steady-state V–I characteristics on the lower row. The steady-state operating points are shown by large black dots **[2009]**

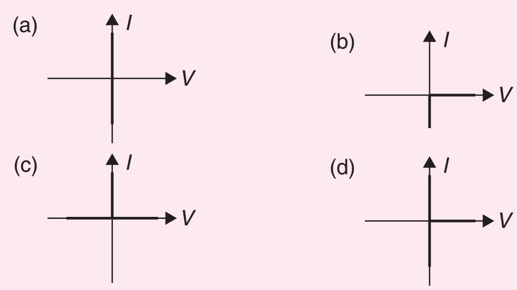




(A) A – I B – II C – III D – IV
(B) A – II B – IV C – I D – III
(C) A – IV B – III C – I D – II
(D) A – IV B – III C – II D – I

4. Figure shows a composite switch consisting of a power transistor (BJT) in series with a diode. Assuming that the transistor switch and the diode are ideal, the I–V characteristic of the composite switch is **[2010]**

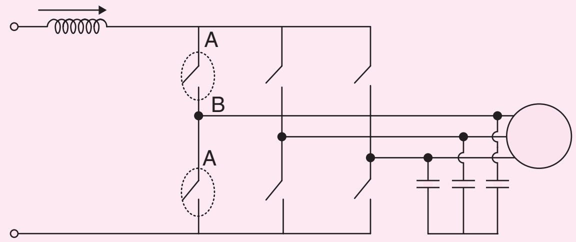




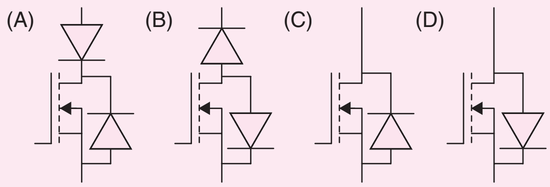
5. Circuit turn-off time of an SCR is defined as the time **[2011]**

(A) Taken by the SCR to turn off
(B) Tequired for the SCR current to become zero
(C) For which the SCR is reverse-biased by the commutation circuit.
(D) For which the SCR is reverse-biased to reduce its current below the holding current.

6. A three-phase current source inverter used for the speed control of an induction motor is realized using MOSFET switches as shown below. Switches S_1 to S_6 are identical switches. **[2011]**



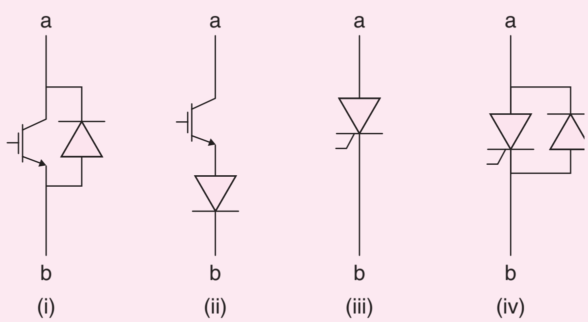
The proper configuration for realizing switches S_1 to S_6 is



7. The typical ratio of latching current to holding current in a 20 A thyristor is **[2012]**

(A) 5.0 (B) 2.0
(C) 1.0 (D) 0.5

8. Figure shows four electronic switches (i), (ii), (iii) and (iv). Which of the switches can block voltages of either polarity (applied between terminals 'a' and 'b') when the active device is in OFF state? **[2014]**

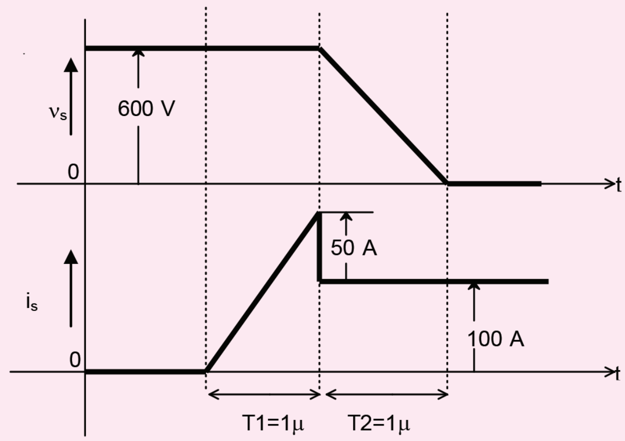


(A) (i), (ii) and (iii) (B) (ii), (iii) and (iv)
(C) (ii) and (iii) (D) (i) and (iv)

9. A single-phase thyristor-bridge rectifier is fed from a 230 V, 50 Hz, single-phase AC mains. If it is delivering a constant DC current of 10 A, at firing angle of 30°, then value of the power factor at AC mains is **[2016]**

(A) 0.87 (B) 0.9
(C) 0.78 (D) 0.45

10. The voltage (V_s) across and the current (I_s) through a semiconductor switch during a turn-ON transition are shown in figure. The energy sissipated during the turn-ON transition, in mJ is_______. **[2016]**



Answer Keys

Exercises

Practice Problems 1

1. D	**2.** C	**3.** C	**4.** B	**5.** D	**6.** D	**7.** A	**8.** B	**9.** C	**10.** C
11. A	**12.** A	**13.** D	**14.** C	**15.** C					

Practice Problems 2

1. B	**2.** D	**3.** A	**4.** B	**5.** A	**6.** D	**7.** A	**8.** D	**9.** C	**10.** D
11. A	**12.** A	**13.** D	**14.** D	**15.** B					

Previous Years' Questions

1. C	**2.** A	**3.** C	**4.** C	**5.** C	**6.** A	**7.** B	**8.** C	**9.** C	**10.** 75