THYRISTORS

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Contents:

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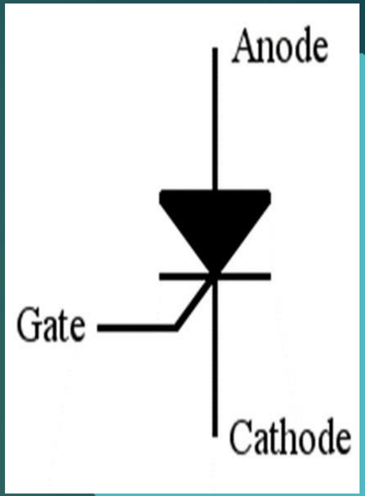
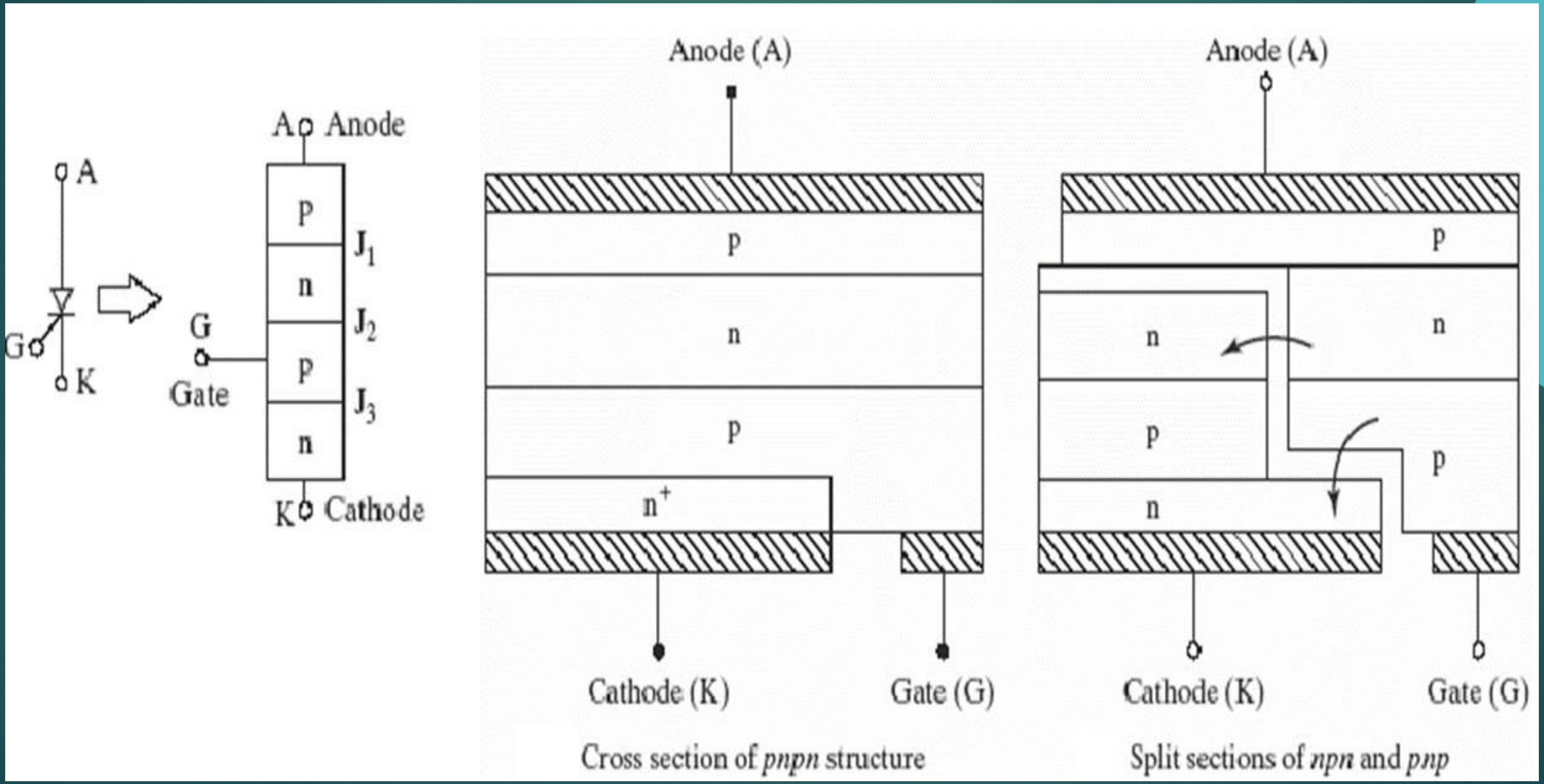
Introduction

- 4 – layer semiconductor device of alternating p- and n- material.
- The word Thyristor is coined from **THYR**atron and Trans**ISTOR**.
- Two – states: ON & OFF.
- Silicon Controlled Rectifier: SCR
- Trade Name of Thyristors commercialized by General Electric in 1957.
- 4-layered 3-terminal device.
- Have the highest power handling capability.
- Rating of 1200V / 1500A.
- Switching Frequency: 1KHz to 20KHz.
- Four states: Reverse blocking mode, reverse conduction mode, forward blocking mode, and forward conducting mode

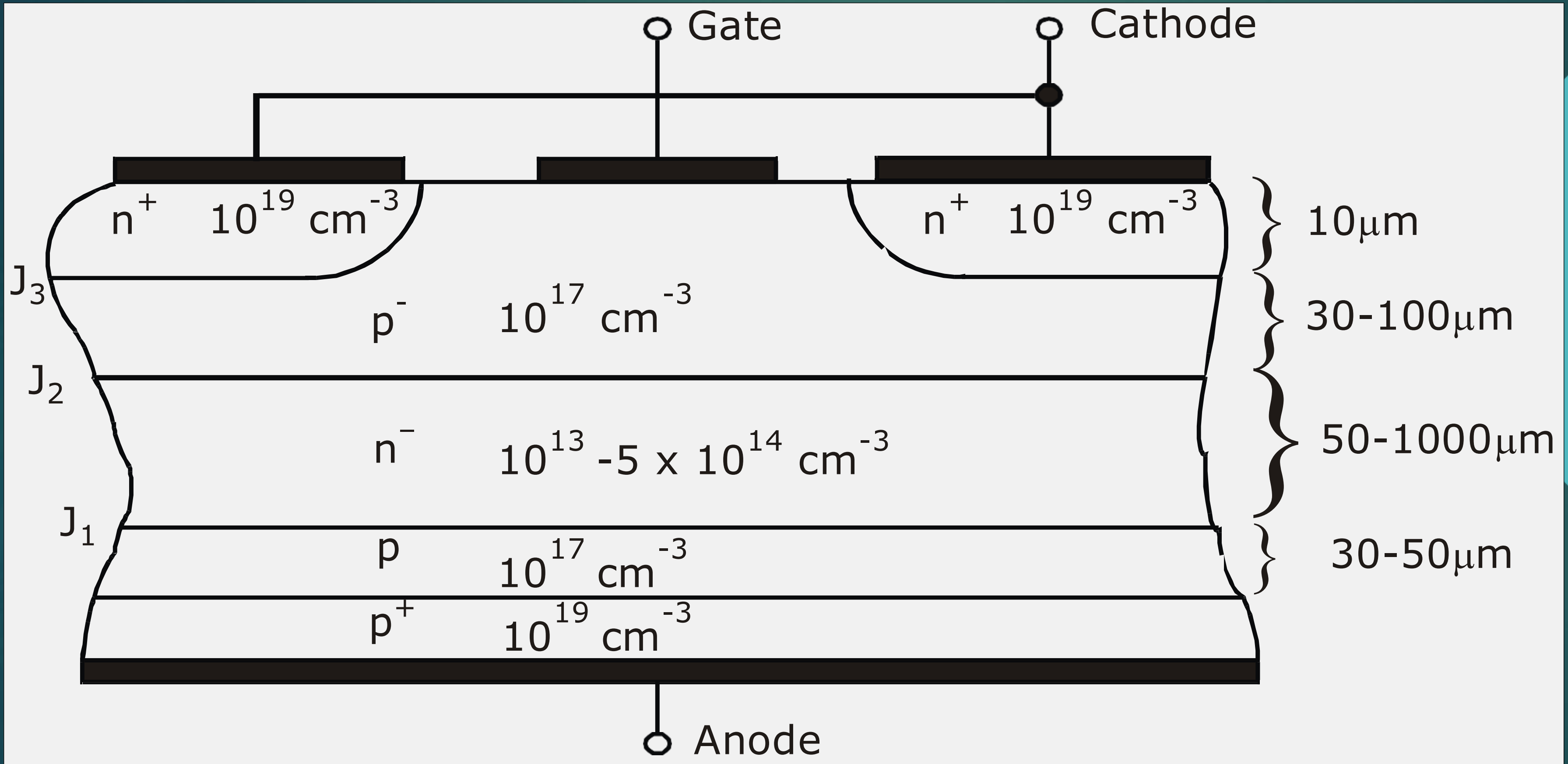


Symbol & Construction

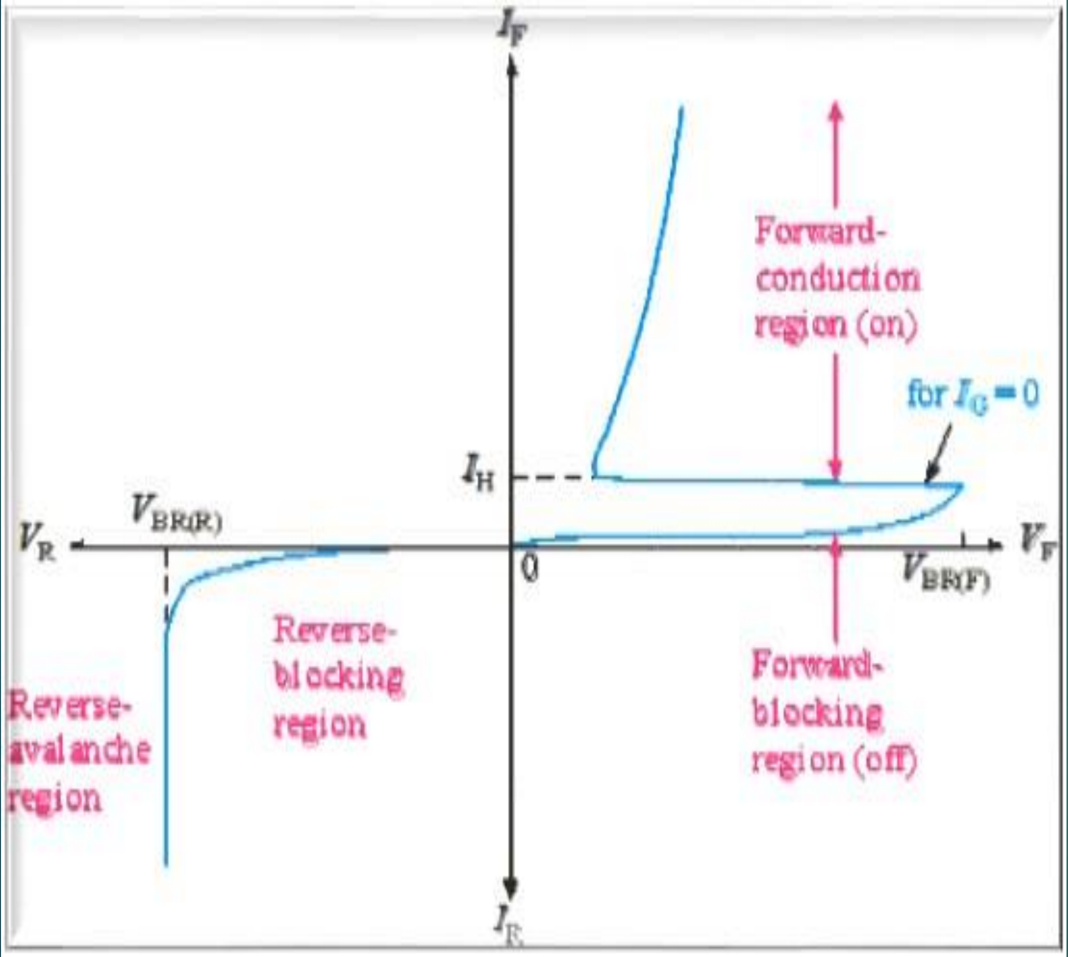
- Alternately N-type or P-type material, for example P-N-P-N.
- The control terminal, called the gate, is attached to p-type material near to the cathode.



Thyristor – Structure



Three important Thyrsitor Specifications:

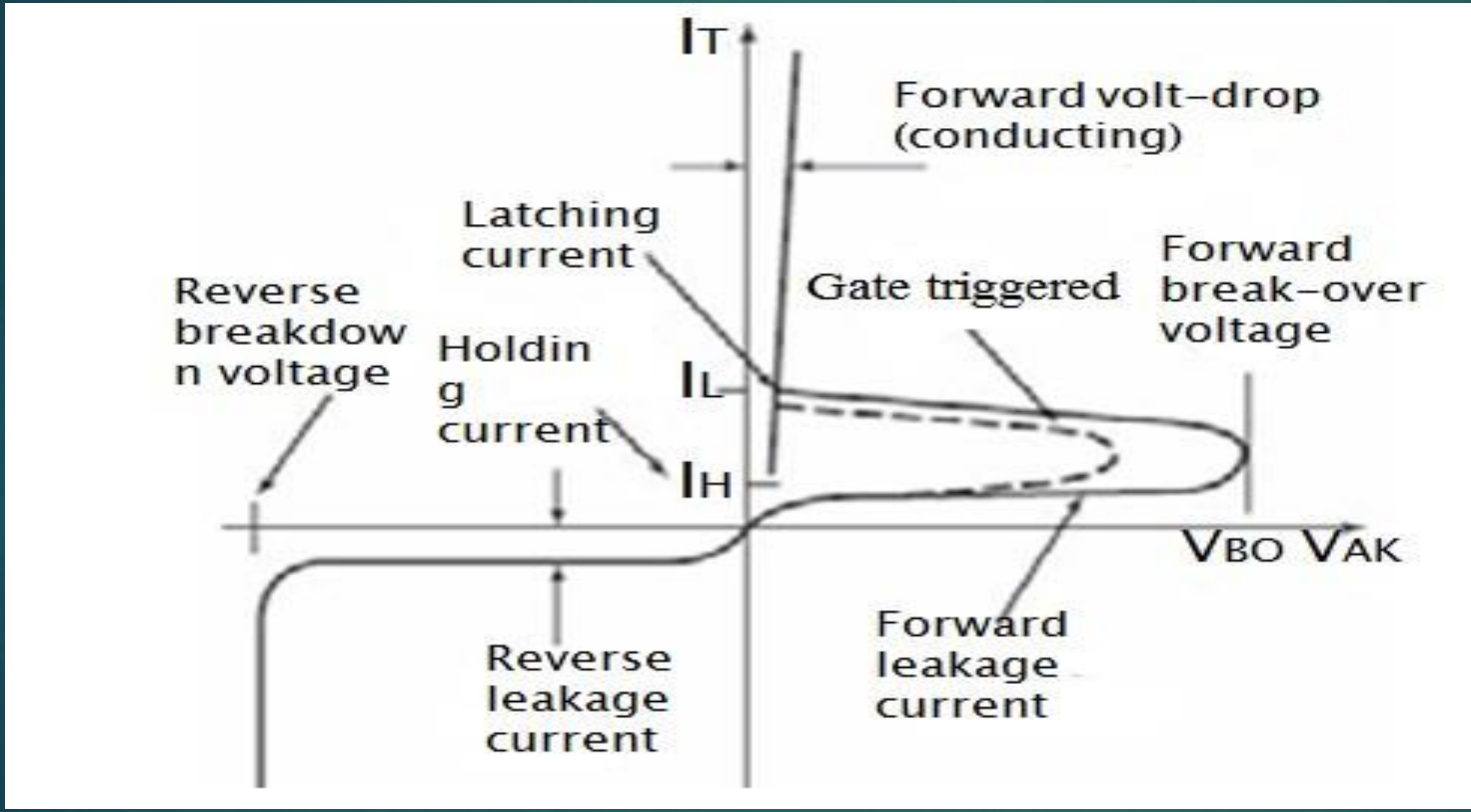


- Forward-break over voltage, **V_{BR}** (F): This is the voltage at which the SCR enters the forward-conduction region.
- Holding current, **I_H:** This is the value of anode current below which the SCR switches from the forward-conduction region to the forward-blocking region.
- Gate trigger current, **I_{GT}:** This is the value of gate current necessary to switch the SCR from the forward-blocking region to the forward-conduction region under specified conditions.

Characteristics of Thyristors

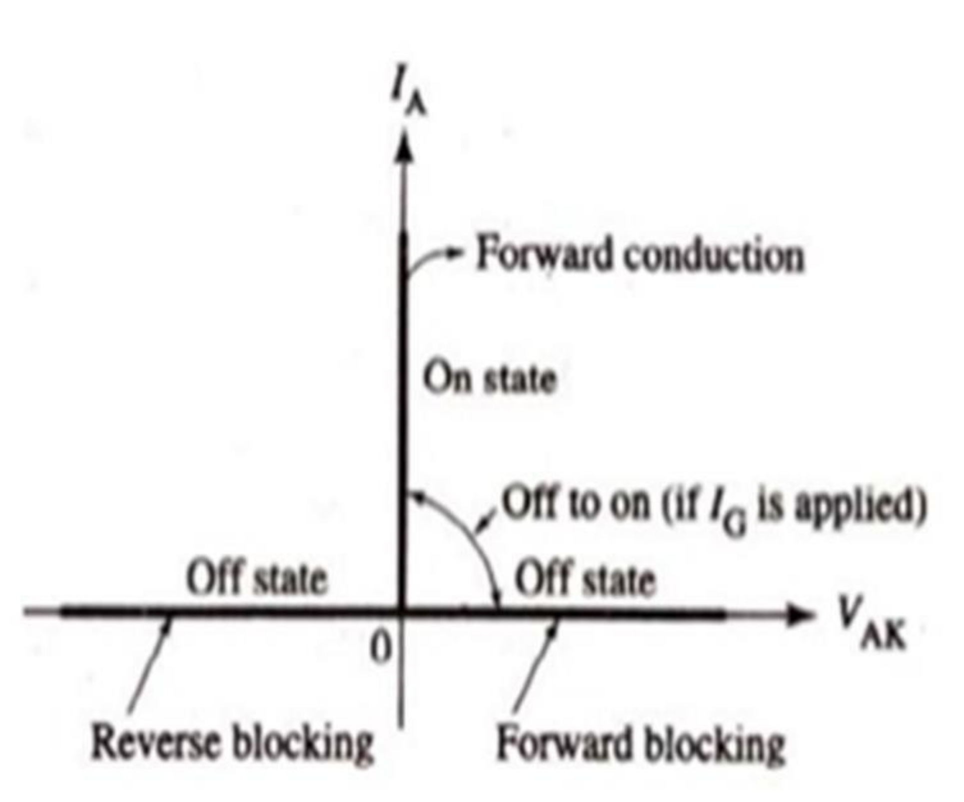
- When the anode is at a positive potential V_{AK} with respect to the cathode with no voltage applied at the gate, junctions J_1 and J_3 are forward biased, while junction J_2 is reverse biased. As J_2 is reverse biased, no conduction takes place.
- Now if V_{AK} is increased beyond the breakdown voltage V_{BO} of the thyristor, avalanche breakdown of J_2 takes place and the thyristor starts conducting.
- If a positive potential V_G is applied at the gate terminal with respect to the cathode, the breakdown of the junction J_2 occurs at a lower value of V_{AK}. By selecting an appropriate value of V_G, the thyristor can be switched into the on state suddenly.

Characteristic Curve – Thyristor



Ideal Switch

- An ideal switch behaves like a diode.
- 3 – states: Forward Blocking; Forward Conduction; Reverse Blocking.
- Gate signal switches ON the thyristor.



Types of Thyristors

- Unidirectional thyristor: The thyristors which conduct in forward direction only are known as unidirectional thyristors

Example: SCR- Silicon Controlled Rectifier; LASCR-Light Activated Silicon Controlled Rectifier

- Bidirectional Thyristor: The thyristors which can conduct in forward as well as in reverse direction are known as bidirectional thyristor

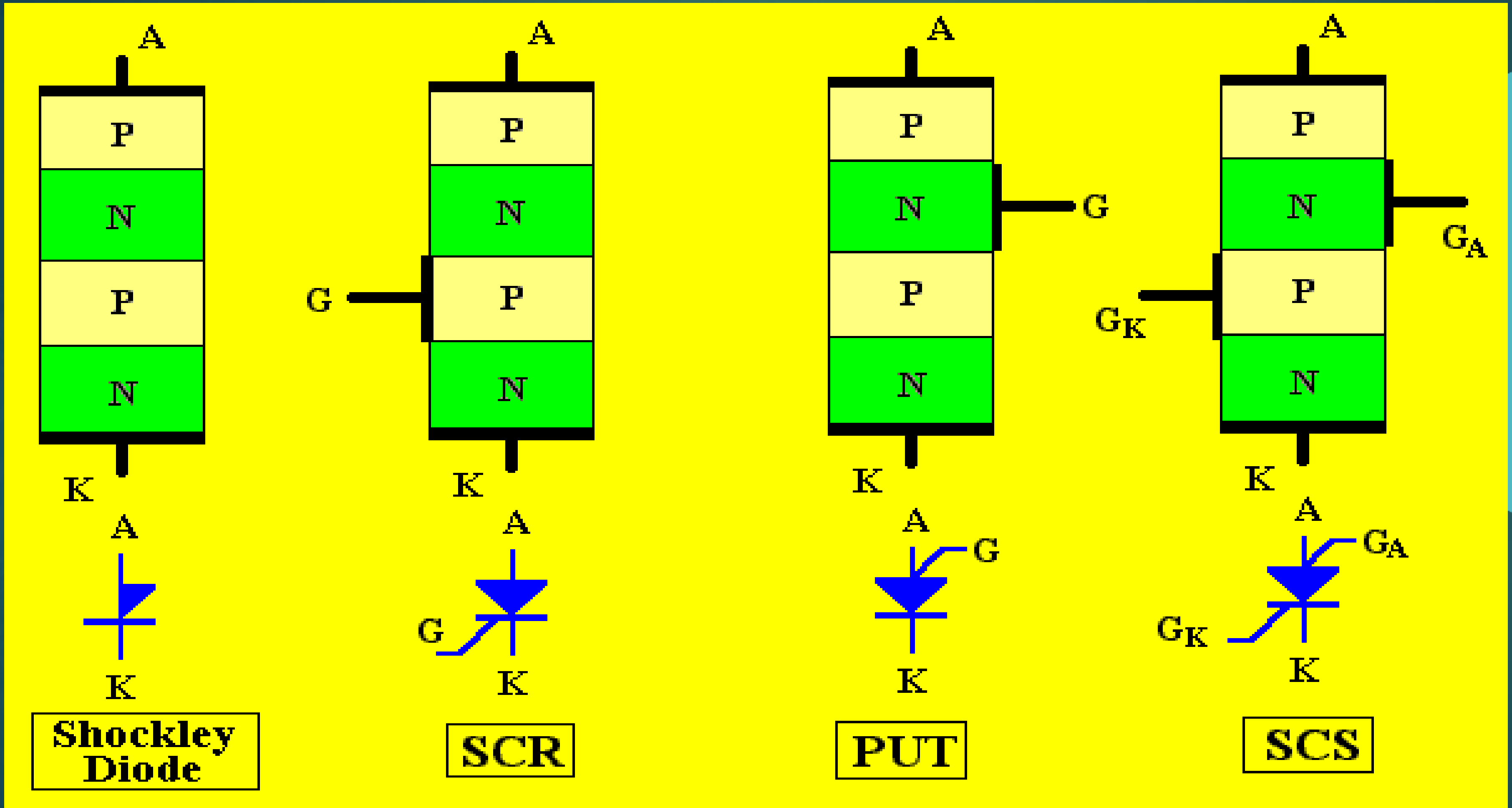
Ex: TRIAC - TRIode AC switch

- Triggering Devices: The devices which generate a control signal to switch the device from non-conducting to conducting state are known as triggering devices.

Ex: Diode AC Switch-DIAC,

UJT - UniJunction Transistor; SUS - Silicon Unilateral Switch; SBS - Silicon Bilateral Switch.

Few types of SCRs



Static Characteristics

- Blocking when reverse biased, no matter if there is gate current or not.
- Conducting only when forward biased and there is triggering current applied to the gate.
- Once triggered on, will be latched on conducting even when the gate current is no longer applied.
- Turning off: decreasing current to a near zero with the effect of external power circuit.
- If V_{AK} is further increased to a large value, the reverse biased junction will breakdown due to avalanche effect resulting in a large current through the device.
- The voltage at which this phenomenon occurs is called the **forward breakdown voltage (V_{BO})**

Two Important Current Terms

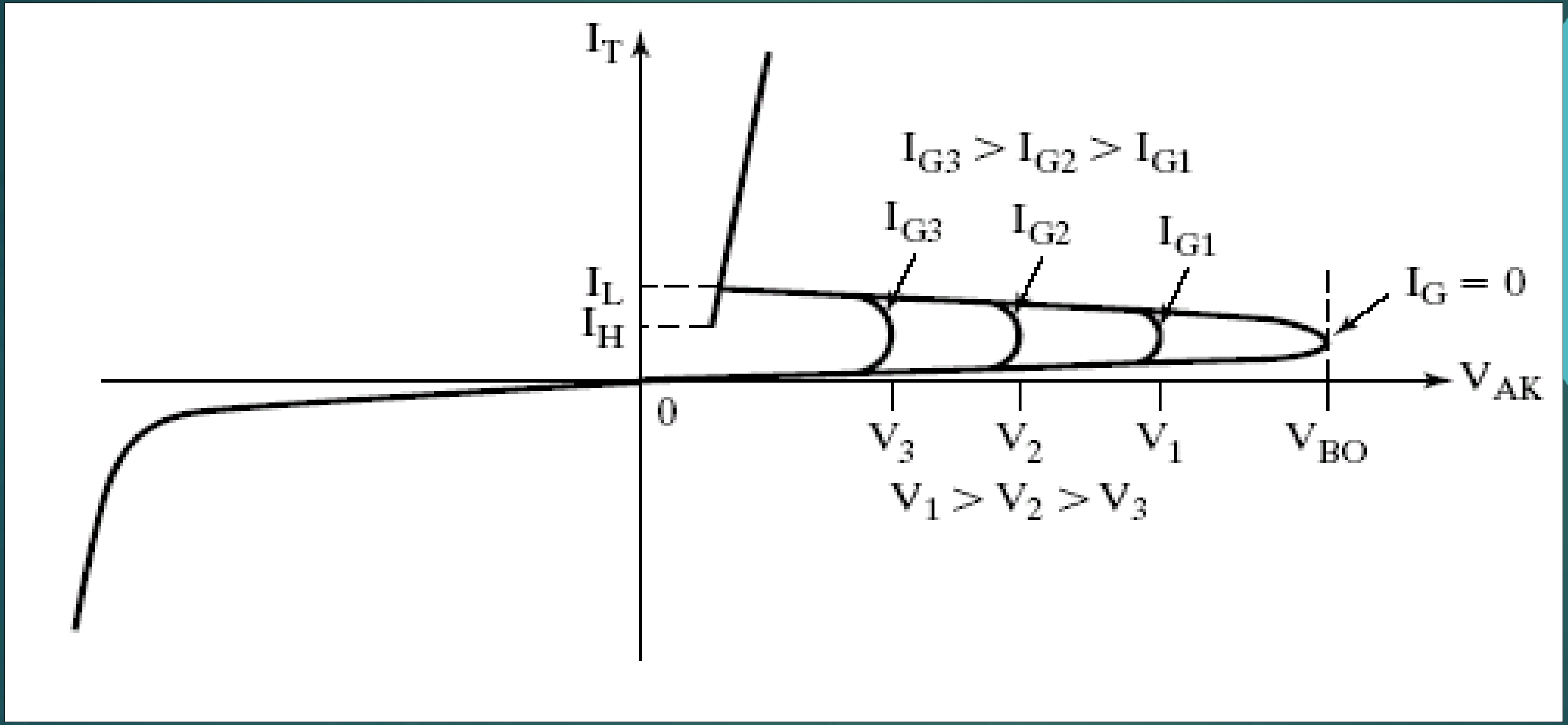
LATCHING CURRENT **(I_L)**

After the SCR has switched on, there is a minimum current required to sustain conduction even if the gate supply is removed. This current is called the latching current. associated with turn on and is usually greater than holding current.

HOLDING CURRENT **(I_H)**

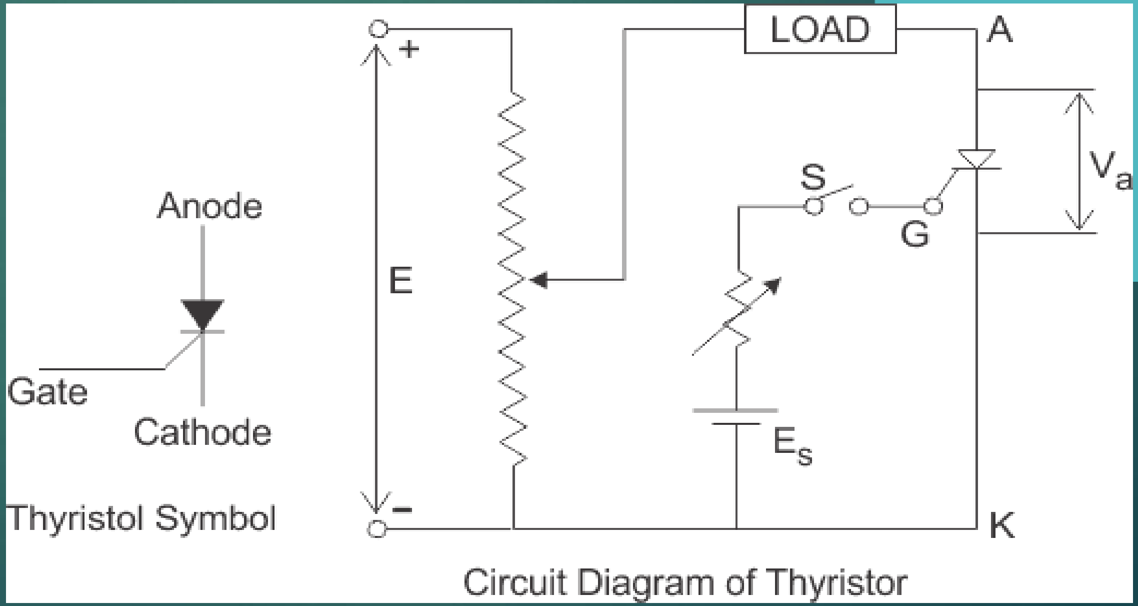
After an SCR has been switched to the on state a certain minimum value of anode current is required to maintain the Thyristor in ON state. If the anode current is reduced below the critical holding current value, the Thyristor cannot maintain the current through it and turns OFF.

Effects on Gate current on Forward Blocking Voltage



Four Modes in Thyristor Operation

- **Reverse Blocking Mode:** Thyristor Open Circuit
- **Reverse Conduction Mode:** Thyristor Closed Circuit
- **Forward Blocking Mode:** Thyristor Open Circuit
- **Forward Conduction Mode:** Thyristor Closed Circuit



Reverse Modes:

1. Reverse Blocking Mode [V_{AK} = -ve]

- When a negative voltage is applied to anode with respect to cathode, the junctions J1 and J3 are reverse biased, but the junction J2 is forward biased.
- The SCR is in its reverse blocking state. i.e. it acts as an open switch.
- As shown in figure a small amount of reverse leakage current flows through the device.

2. Reverse Conducting Mode:

- As the reverse voltage is further increased, at the reverse breakdown voltage(V_{BR}) Avalanche breakdown occurs at junction J1 and J3.
- SCR acts as a closed switch in reverse direction
- A large current gives more losses in SCR, dissipating in the form of heat, thereby damaging the SCR.

Forward Modes:

3. **Forward Blocking Mode [V_{AK} = +ve & V_G = 0]**

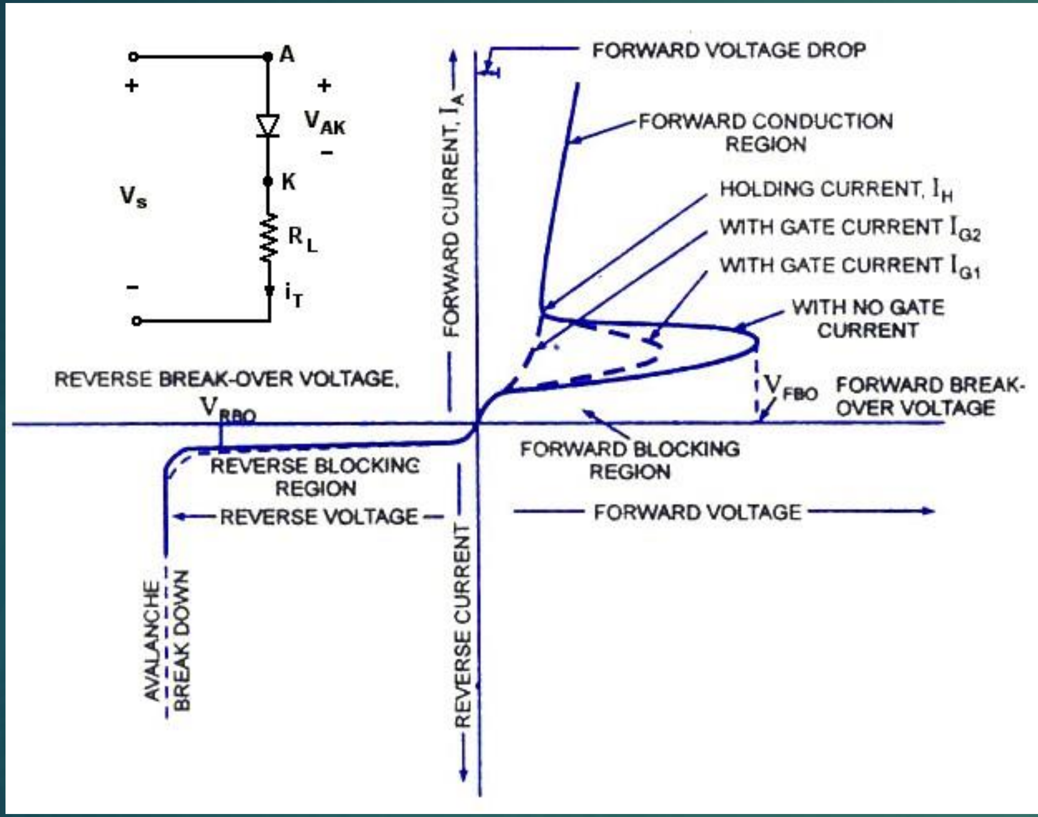
- When a positive voltage is applied to anode with respect to cathode, the junctions J1 and J3 are forward biased, junction J2 is reverse biased.
- The SCR is in Forward Blocking state. At this time the Gate signal is not applied.
- A depletion layer is formed in junction J2 and no current flows from anode to cathode.
- As shown in VI Characteristic, a small amount of current called *forward leakage current* flows through the device.

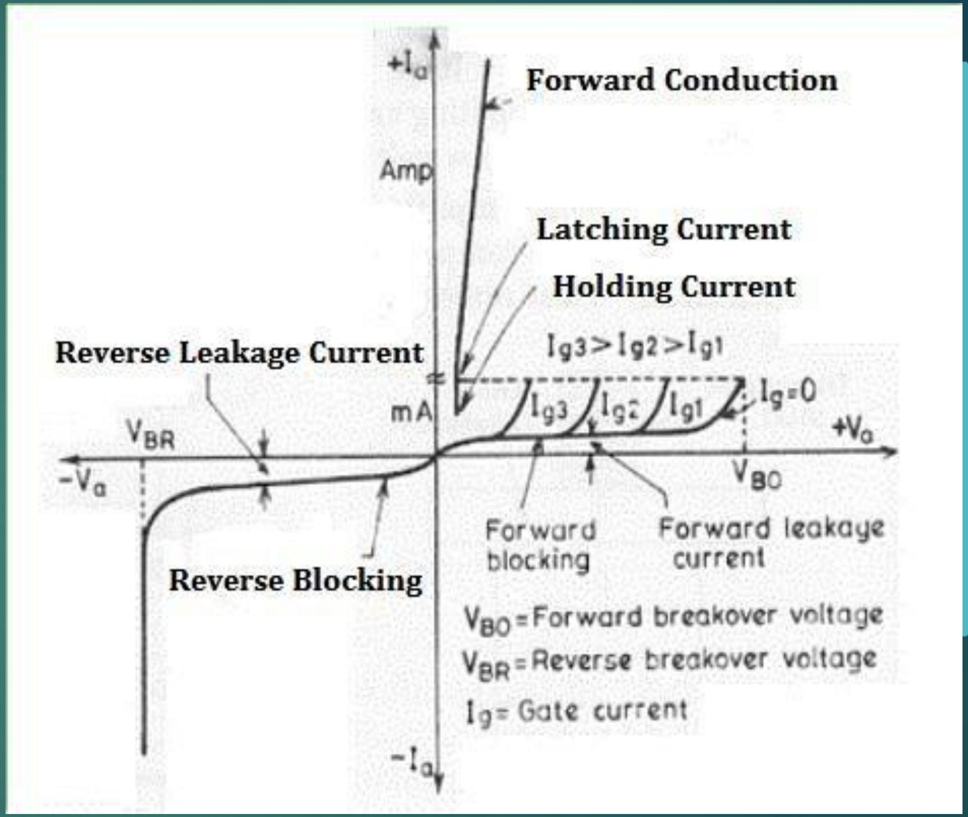
Forward Modes:

4. **Forward Conducting Mode [V_{AK} = +ve & V_G = +ve]**

- When the small amount of positive voltage is applied to gate terminal, while positive voltage is applied to anode with respect to cathode, the junction J3 becomes forward biased.
- So the SCR acts as a closed switch and conducts a large value of forward current with small voltage drop.
- With the application of gate signal, the SCR changes from forward blocking state to forward conducting state. It is known as *latching*.
- Without gate signal, SCR changes from forward blocking state to forward conducting state at *forward breakdown voltage (V_{fbd})*.
- When the gate signal value is increased, the latching happens for low V_{ak} voltages as mentioned in the figure.
- In the presence of forward current (i.e. after the thyristor is turned on by a suitable gate voltage) it will not turn off even after the gate voltage has been removed.
- The thyristor will only turn off when the forward current drops below holding current.

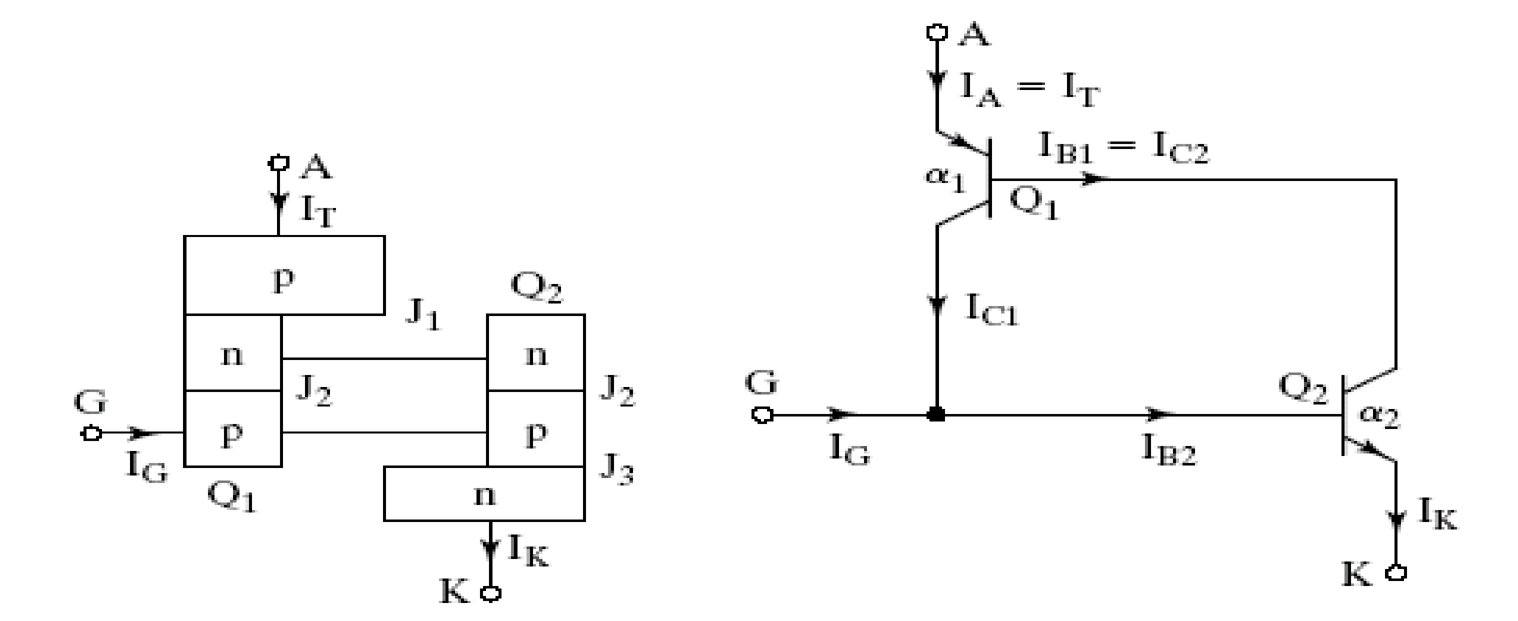
V – I Characteristics





Two Transistor Model

- An equivalent circuit of a pnp and an npn transistor.
- When forward biased, if there is sufficient leakage current in the upper pnp device, it acts as base to the lower npn.
- The lower npn then conducts bringing both transistors into saturation.



(a) Basic structure (b) Equivalent circuit

Derivation for Anode Current

General transistor equation is

$$I_C = \alpha I_E + I_{CBO}$$

For transistor 1

$I_{C1} = \alpha_1 I_{E1} + I_{CBO1}$; $I_{E1} = I_A$

Therefore $I_{C1} = \alpha_1 I_A + I_{CBO1}$

For transistor 2

$I_{C2} = \alpha_2 I_{E2} + I_{CBO2}$; $I_{E2} = I_K$

$I_K = I_A + I_G$

Therefore

$$I_{C2} = \alpha_2 (I_A + I_G) + I_{CBO2}$$

Two Transistor Model – Anode Current

$$I_C = \alpha I_E + I_{CBO}$$

α= common base current gain
I_{CBO}= common base leakage current

$$I_k = I_a + I_g$$

$$I_a = I_{C1} + I_{C2}$$

$$I_A = \alpha_1 I_A + I_{CBO_1} + \alpha_2 (I_A + I_G) + I_{CBO_2}$$

$$\therefore \quad I_{C_2} = I_{B_1}$$

$$\Rightarrow \quad I_A = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

Thyristor Turn – On Methods

- Temperature Triggering
- Light Triggering
- Forward Voltage Triggering
- $\frac{dv}{dt}$ Triggering
- Gate Triggering

Thermal Triggering

- The width of depletion layer of SCR decreases with increase in junction temperature.
- Therefore in SCR when V_{AK} is very near its breakdown voltage, the device is triggered by increasing the junction temperature.
- By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.
- This type of turn on may cause thermal run away and is usually avoided.
- The increase in temperature is within specified value, otherwise it may burn the device.

Light Triggering

- For light triggered SCRs a special terminal is made inside the inner P layer instead of gate terminal.
- When light is allowed to strike this terminal, free charge carriers are generated.
- When intensity of light becomes more than a normal value, the Thyristor starts conducting.
- These type of SCRs are called as LASCR.
- Energy is imparted by light radiation (neutrons or photons).
- Electron – hole pairs are generated increasing number of charge carriers.
- This leads to instantaneous flow of current and thyristor triggering.
- Should have high $\frac{dV}{d}$.

Forward Voltage Triggering

When A – K voltage is increased with G open, J2 suffers avalanche break down at forward break over voltage V_{BO}.

The thyristor is turned on with a high forward current.

Voltage is around 1 to 1.5 V.

Turn on time is divided into 3 periods.

$T_{on} = t_d + t_r + t_p$

t_d = delay time, t_p or t_s = peak time (or) spread time, t_r = rising time

Latching current: Minimum value of anode current which thyristor must attain during turn – on process when gate signal is removed.

Holding current: Minimum anode current below which thyristor turns OFF.

Forward Voltage Triggering

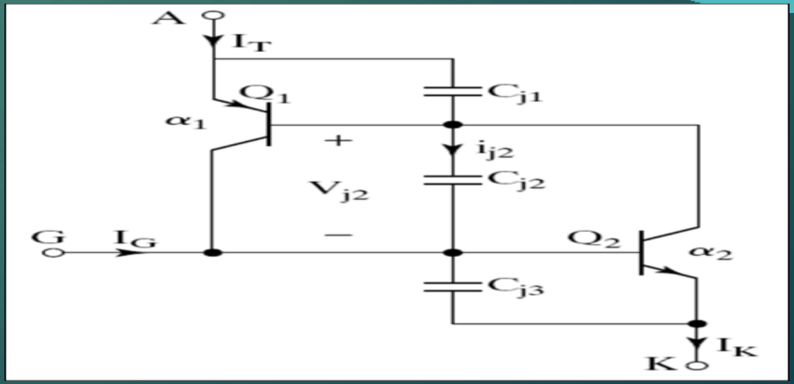
- In this mode, an additional forward voltage is applied between anode and cathode.
- When the anode terminal is positive with respect to cathode(V_{AK}) , Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- No current flows due to depletion region in J2 and it is reverse biased (except leakage current).
- As V_{AK} is further increased, at a voltage V_{BO} (Forward Break Over Voltage) the junction J2 undergoes avalanche breakdown and so a current flows and the device tends to turn ON(even when gate is open)
- This type of turn on is destructive and should be avoided.

$\frac{dv}{dt}$ Triggering

- With forward voltage across anode and cathode, the outer junctions J1 & J2 are forward biased but J2 is reversed biased. J2 behaves like capacitor due to the charges existing across the junction.

$$i_c = C_j \frac{dV_a}{dt}$$

- If the rate of rise of forward voltage is high, charging current i_c would be more, acting as gate current and triggering on the thyristor.
- Therefore when the rate of change of voltage across the device becomes large, the device may turn ON, even if the voltage across the device is small.



Gate Triggering

- Positive signal is applied at Gate terminal.
- By this, thyristor can be triggered much before break over voltage is reached.
- Conduction period can be controlled by varying Gate signal.
- Signal is applied between Gate and Cathode.
- When a positive voltage is applied at the gate terminal, charge carriers are injected in the inner P-layer, thereby reducing the depletion layer thickness.
- As the applied voltage increases, the carrier injection increases, therefore the voltage at which forward break-over occurs decreases.

Types of Gate Triggering

Three types of signals are used for gate triggering.

1. DC Gate Triggering
2. AC Gate Triggering
3. Pulse Gate Triggering

DC Gate Triggering

- A DC voltage of proper polarity is applied between gate and cathode (Gate terminal is positive with respect to Cathode).
- When applied voltage is sufficient to produce the required gate Current, the device starts conducting.
- One drawback of this scheme is that both power and control circuits are DC and there is no isolation between the two.
- Another disadvantages is that a continuous DC signal has to be applied. So gate power loss is high.

AC Gate Triggering

- AC gate triggering is most commonly used as it provides proper isolation.
- Firing angle control is obtained by changing the phase angle conveniently.
- Here AC source is used for gate signals.
- This scheme provides proper isolation between power and control circuit.
- Drawback of this scheme is that a separate transformer is required to step down AC supply.
- There are three methods of AC voltage triggering namely (i) R Triggering (ii) RC triggering iii) UJT Triggering.

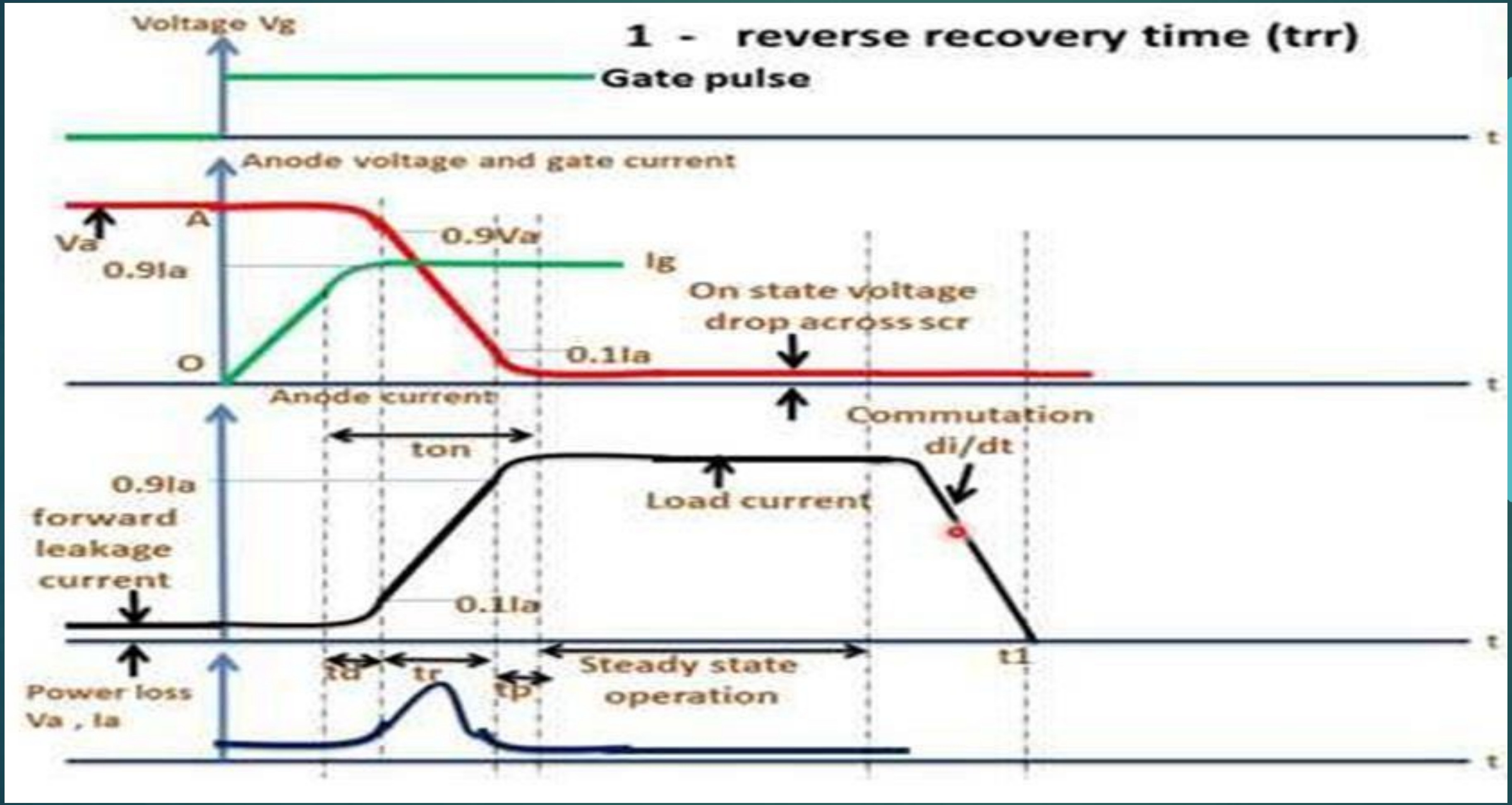
Pulse Gate Triggering

- Pulse triggering is the most popular.
- Pulse transformer is used for isolation.
- No need to apply continuous signal, therefore less loss.
- Sequence of high frequency pulse called "carrier frequency gating" is applied.
- In this method the gate drive consists of a single pulse appearing periodically (or) a sequence of high frequency pulses.
- This is known as carrier frequency gating.
- A pulse transformer is used for isolation.
- The main advantage is that there is no need of applying continuous signals, so the gate losses are reduced.

Switching Characteristics

- During Turn on and Turn off process a thyristor is subject to different voltages across it and different currents through it. The time variations of the voltage across a thyristor and the current through it during Turn on and Turn off constitute the switching characteristics of a thyristor.
- Turn on time $t_{ON} = t_d + t_r + t_p$
- Turn off time $t_{OFF} = t_{rr} + t_{gr,}$
- At t_1; current $I_A = 0$;
- After t_1; I_A builds up in the reverse direction, due to the charge carriers stored in the four layers.
- Reverse recovery current removes the excessive carriers from junctions J_1 and J_3 during the time t_1 to t_3. (Reverse recovery current flows due to sweeping out of holes from top p-layer and electrons from bottom n layer)

Switching Characteristics



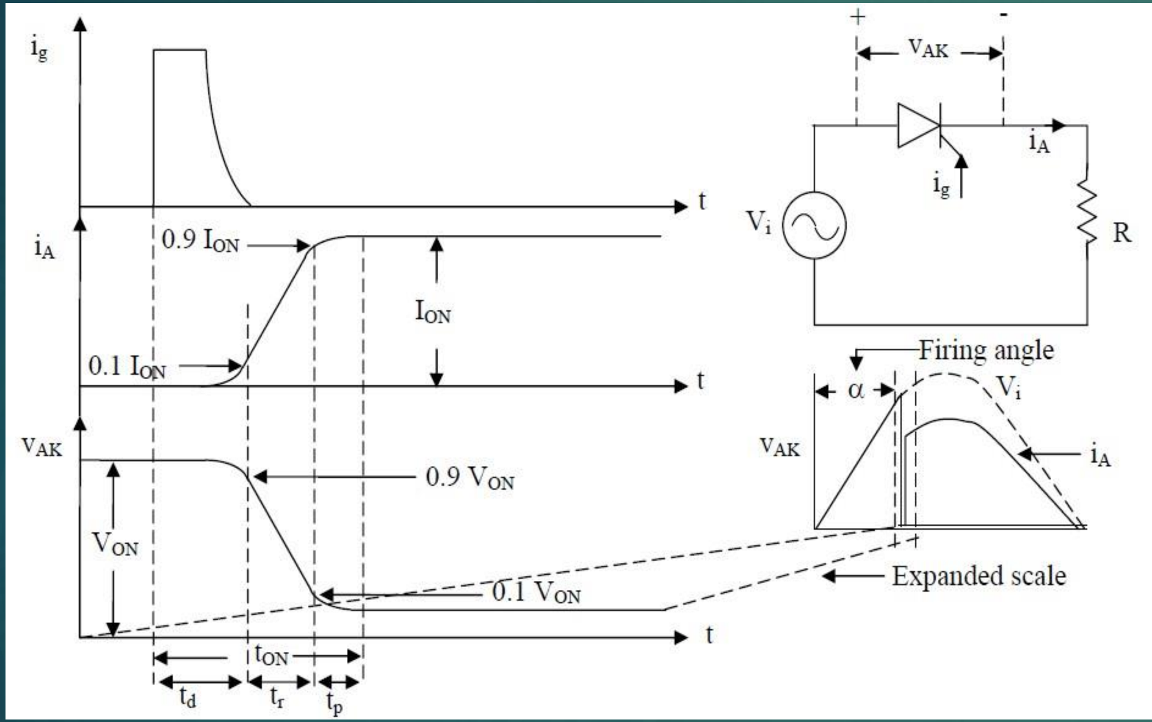
Switching Characteristics

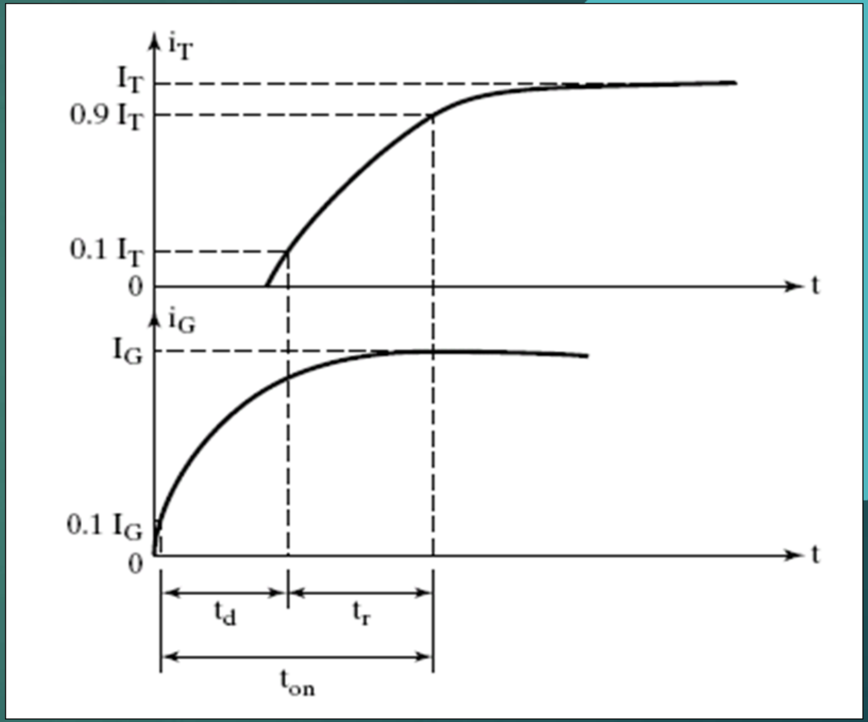
- **Reverse Recovery Time (t_{rr}):-**

1. It is the time taken for the removal of excessive carriers from top and bottom layer of the SCR.
2. At t_2: When nearly 60% of charges are removed from the outer two layers, the reverse recovery current decreases.
3. This decaying causes a reverse voltage to be applied across the SCR.
4. At t_3 all excessive carriers from J_1 and J_3 are removed.
5. The reverse voltage across SCR removes the excessive carriers from junction J_2.
6. Gate recovery process is the removal of excessive carriers from J_2 junction by application of reverse voltage.
7. Time taken for removal of trapped charges from J_2 is called gate recovery time (t_{gr}).
8. At t_4 all the carriers are removed and the device moves to the forward blocking mode.

Turn on Switching Characteristics

- Turn – On

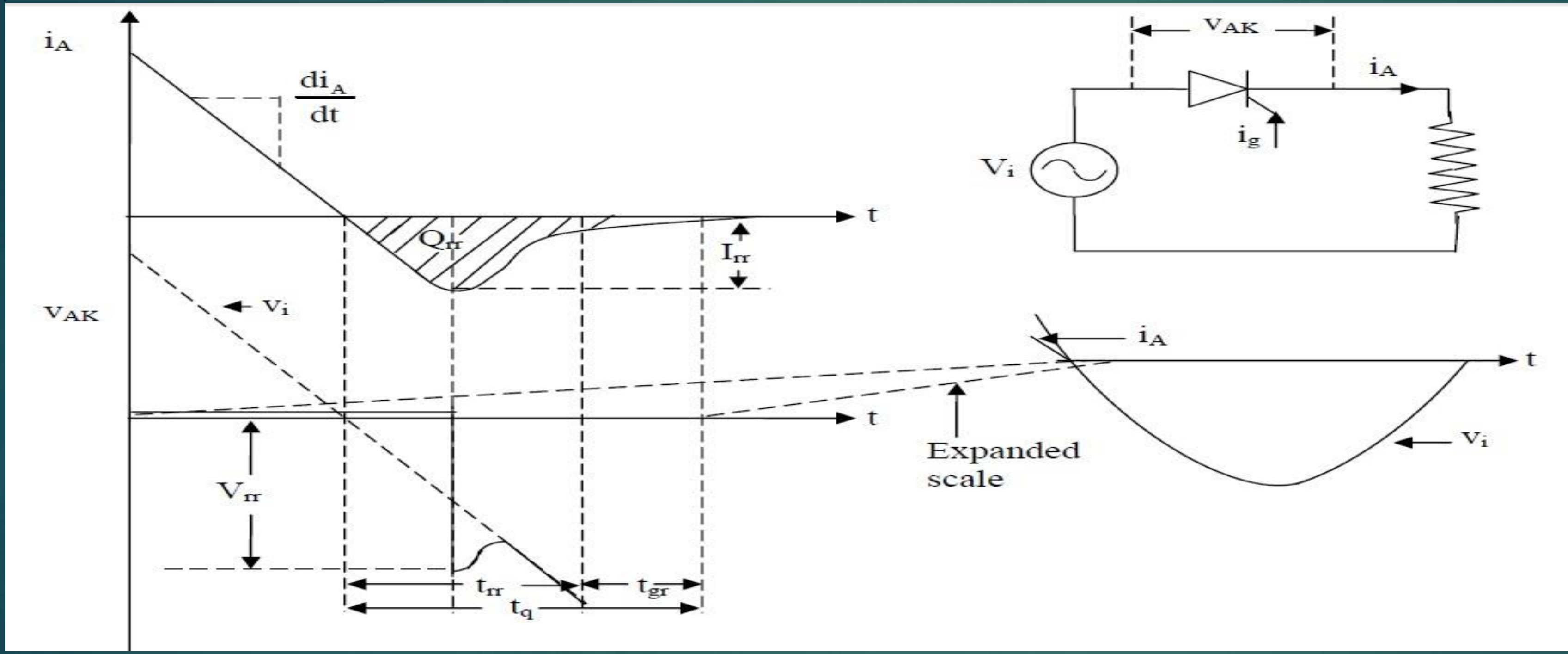




t_d = delay time; t_r = rise time; t_p = peak time

Turn off Switching Characteristics

- Turn Off



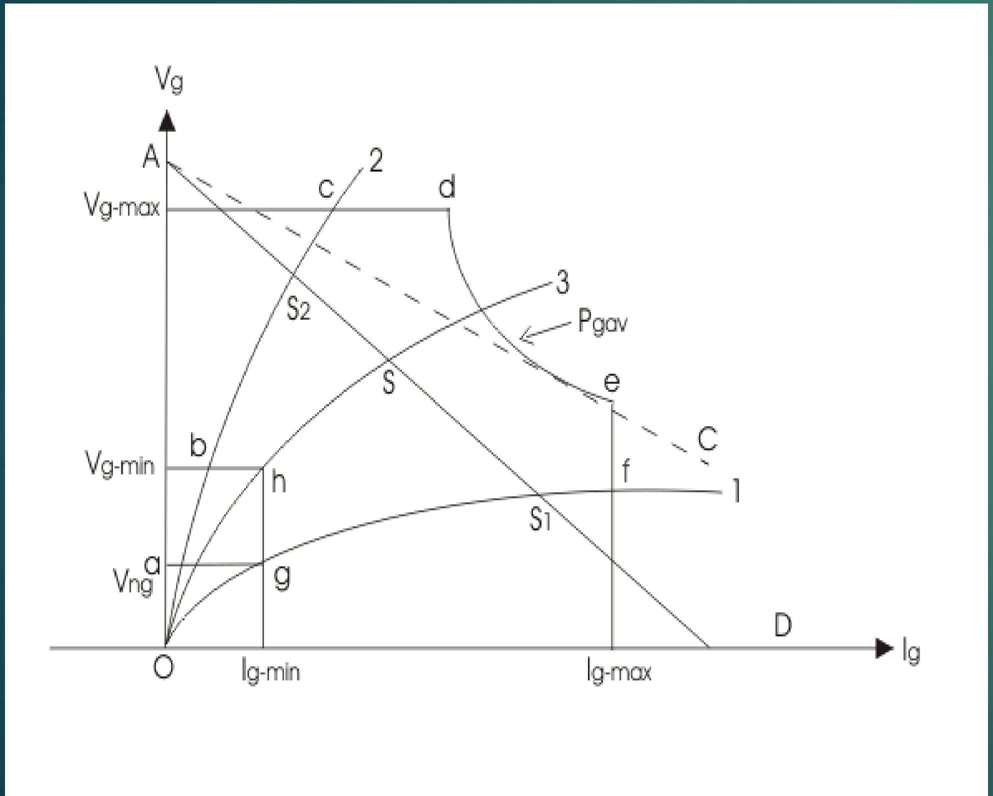
t_{rr} = reverse recovery time; t_{gr} = gate recovery time

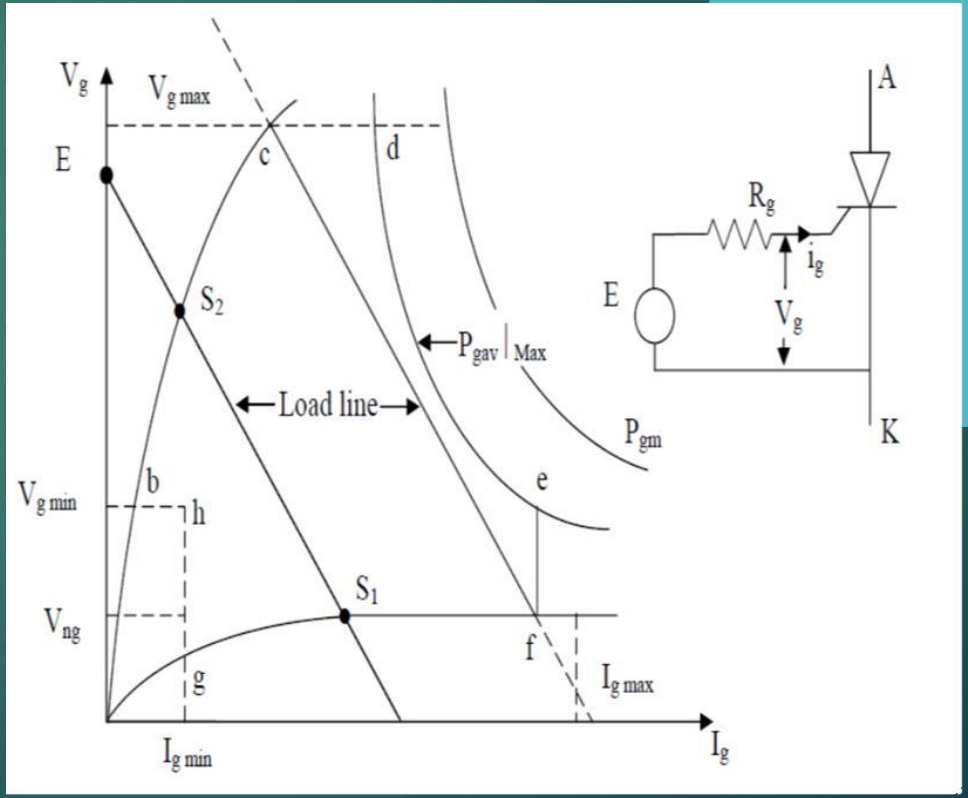
Gate Characteristics of SCR or Thyristor

- **Gate characteristic of thyristor or SCR** gives us a brief idea to operate it within a safe region of applied gate voltage and current.
- At the time of manufacturing each SCR or thyristor is specified with the maximum gate voltage limit ($V_{g\text{-}max}$), gate current limit ($I_{g\text{-}max}$) and maximum average gate power dissipation limit (P_{gav}).
- These limits should not be exceeded to protect the SCR from damage and there is also a specified minimum voltage ($V_{g\text{-}min}$) and minimum current ($I_{g\text{-}min}$) for proper operation of thyristor.
- A gate non triggering voltage (V ng) is also mentioned at the time of manufacturing of the device.
- V_{ng} is the non – triggering gate voltage and all spurious signals and noises should be less than this to stop the thyristor from unwanted triggering.

Gate Characteristics of SCR or Thyristor

- Curve 1 represents the lowest voltage values that must be applied to turn on the SCR and curve 2 represents the highest values of the voltage that can safely be applied.
- So from the figure we can see the safely operated area of SCR is b-c-d-e-f-g-h-b.





Gate Characteristics

- A load line of gate source voltage is drawn as AD where OA = Es and OD = Es/Rs which is trigger circuit or short circuit current.
- Now, let the V-I characteristic of gate circuit is given by curve 3.
- The intersection point of load line (AD) and curve 3 is called as operating point S.
- It is evident that S must lie between S1 and S2 on the load line.
- For decreasing the turn ON time and to avoid unwanted turn ON of the device, operating point should be as close to P_{gav} as possible.
- Slope of AD = source resistance R_s.
- Minimum amount of R_s can be determined by drawing a tangent to the P_{gav} curve from the point A.

Gate Characteristics

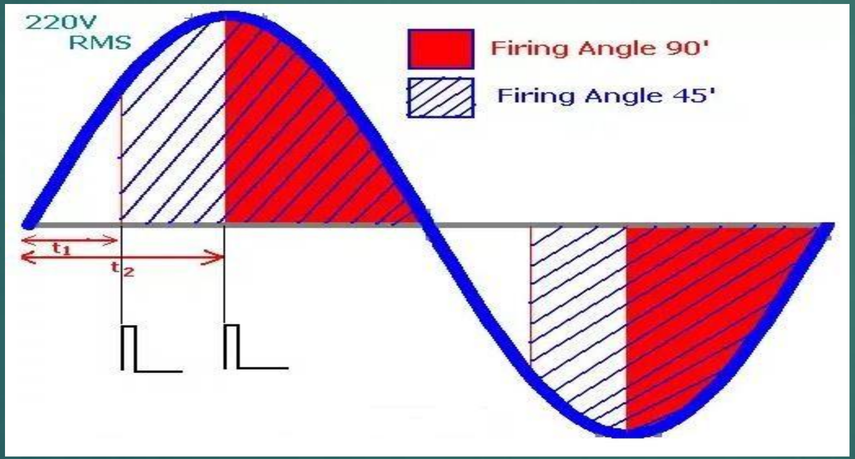
- Gate is connected to cathode behaving like a diode.
- Gate signal can be DC or AC.
- Gate signal facilitates reverse break down of J2 by increasing minority carriers.
- The magnitude of the gate voltage and current required for triggering a thyristor is inversely proportional to the junction temperature.
- $V_g = E - R_g i_g$; $P_g = V_g i_g$;
- When a thyristor is powered by an AC supply, the moment of the thyristor opening should be adjusted by shifting the control pulse relative to the starting point of the positive alternation of the anode voltage. This delay is called the “firing angle” denoted by $\boldsymbol{\alpha}$

$$\delta P_{gm} \leq P_{gav}\big|_{Max}$$

Where $\delta = T_{ON}\, f_p$, f_p = pulse frequency.

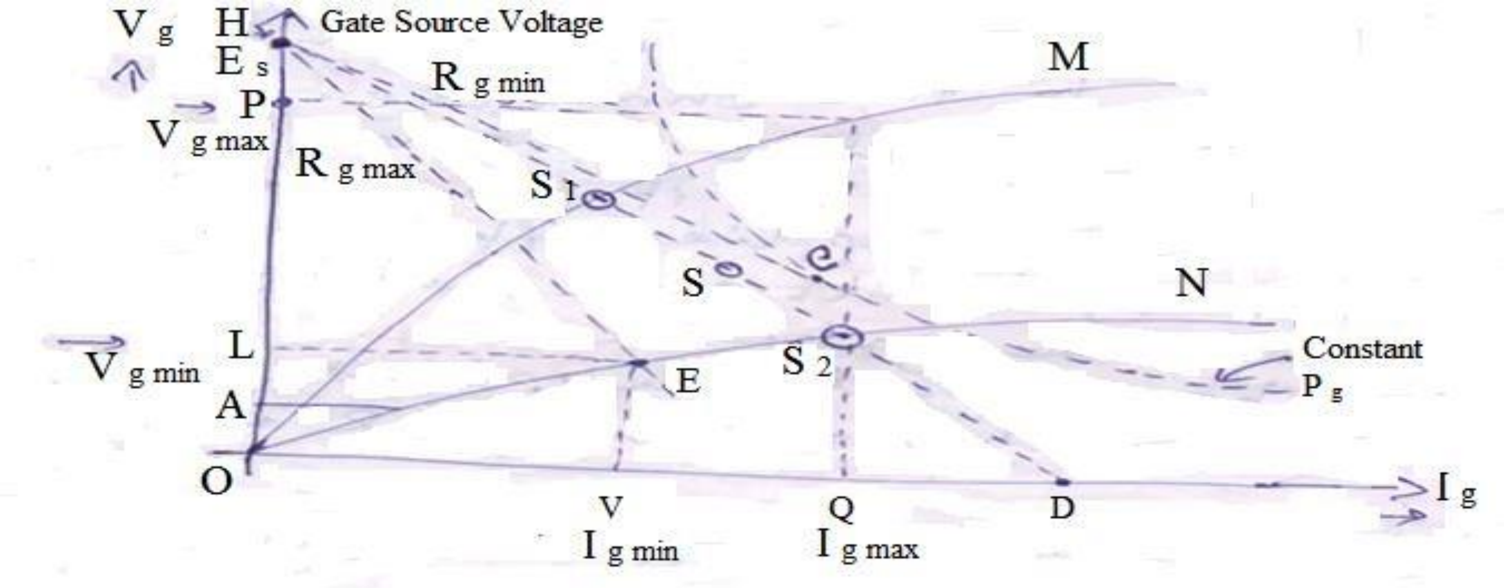
Firing Angle

- Firing Angle α: It is the angle after which the thyristor fires of conducts. It is normally done by either analog, digital or microprocessor controller circuits which sends the desired pulse to the thyristor gate drive circuit that will produce the actual gate drive pulse.
- Varying this angle changes the effective RMS values of voltage and current and hence power.



Three Regions

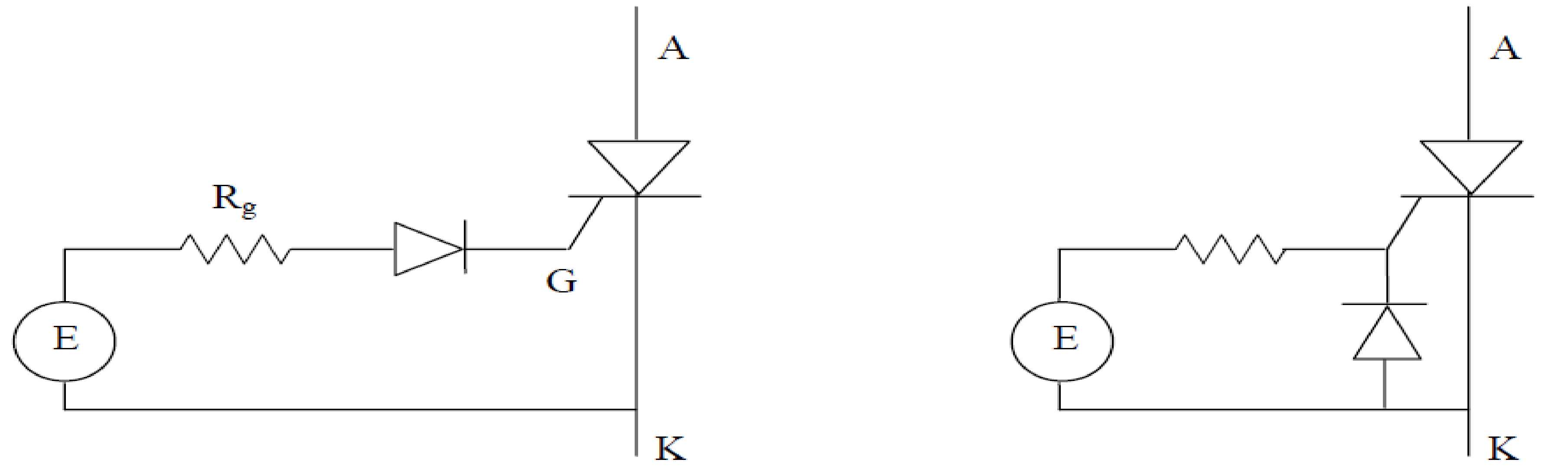
- Region I: OA lies near origin which is max. gate voltage that will trigger no device and this sets a limit to the false triggering signal.
- Region II: Marked by min value of gate voltage and gate current required to trigger all devices at min rated junction temperature.
- Region III: Marked by max voltage and max current for gate triggering for reliable firing. A signal on the lower left part of this section is adequate to trigger a thyristor.



Gate Characteristics

Gate Cathode Reverse Voltage Protection

- The gate cathode junction also has a maximum reverse (i.e. gate negative with respect to the cathode) voltage specification. If there is a possibility of the reverse gate cathode voltage exceeding this limit a reverse voltage protection using diode as shown.



(a) (b)

Gate Cathode Reverse Voltage Protection

Thyristor Protection

For reliable and satisfactory operation, the specified ratings of SCR should not exceed due to overload, voltage transients and other abnormalities.

Due to reverse process in SCR during turn OFF, the voltage overshoot occurs.

In case of short circuit, a large current flows through SCR which may damage the device.

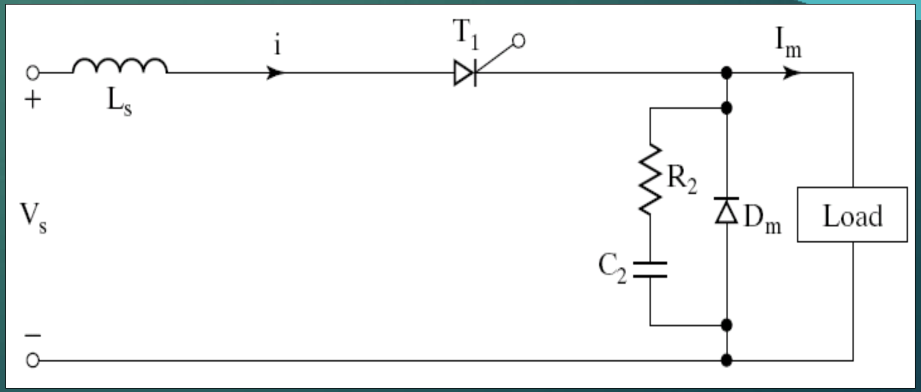
Various Protection Techniques of SCR

- di/dt Protection
- dv/dt Protection
- Over voltage Protection
- Over Current Protection
- Thermal protection.

di/dt Protection of SCR

- Here SCR is turned ON with application of gate signal, the anode current starts flowing through the SCR.
- It takes some time (finite) to spread across the SCR junctions.
- If (di/dt) i.e. rate of rise of anode current is high, current spreads in a non – uniform manner which leads to formation of local hot spots near gate – cathode junction, eventually it might damage the device by overheating it.
- In order to restrict this high (di/dt) , one inductor in series is connected with the thyristor. Typically, SCR di/dt ratings are in range between 20 and 500 Ampere/microseconds.

$$\frac{di}{dt} = \frac{V_S}{L_S}$$



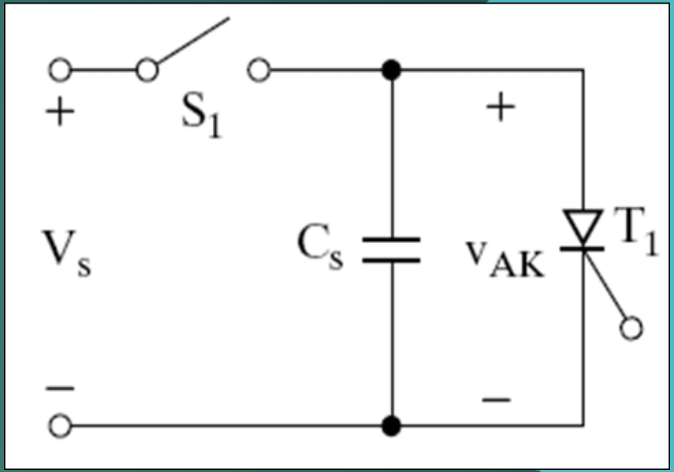
dv/dt Protection of SCR

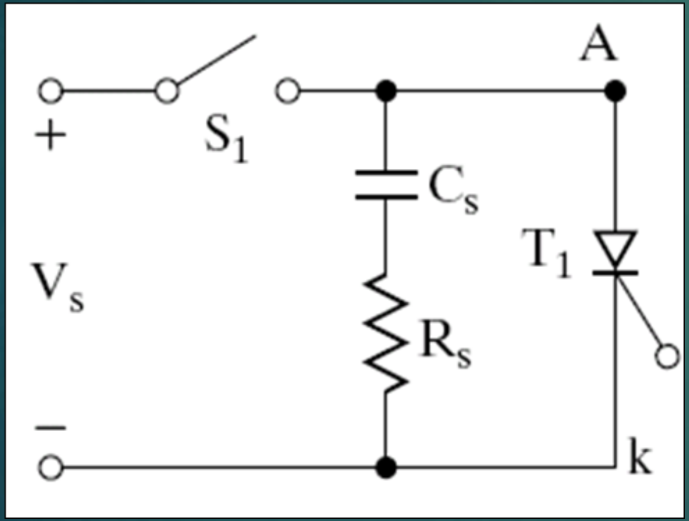
- As the SCR is forward biased, J1 and J3 junctions are also forward biased and J2 is reverse biased. This J2 acts as a capacitor.
- With the rate of forward voltage applied being very high across SCR, charging current starts flowing through J2 and it is sufficiently high to turn ON the SCR even without the gate signal.
- This is referred to as dv/dt triggering of SCR and this is not preferred as it may lead to false triggering process.
- This dv/dt triggering is kept in check with usage of RC snubber network across the SCR.
- If switch is closed at $t = 0$, the rate of rise of voltage across the Thyristor is limited by the capacitor .
- When Thyristor is turned on, the discharge current of the capacitor is limited by the resistor as shown in figure (b).

dv/dt Protection of SCR

- The voltage across the Thyristor will rise exponentially as shown in figure.

$$V_S = i(t)R_S + \frac{1}{C}\int i(t)dt + V_c(0)_{[for\ t=0]}$$





$$V_S = i(t)R_S + \frac{1}{C}\int i(t)dt$$

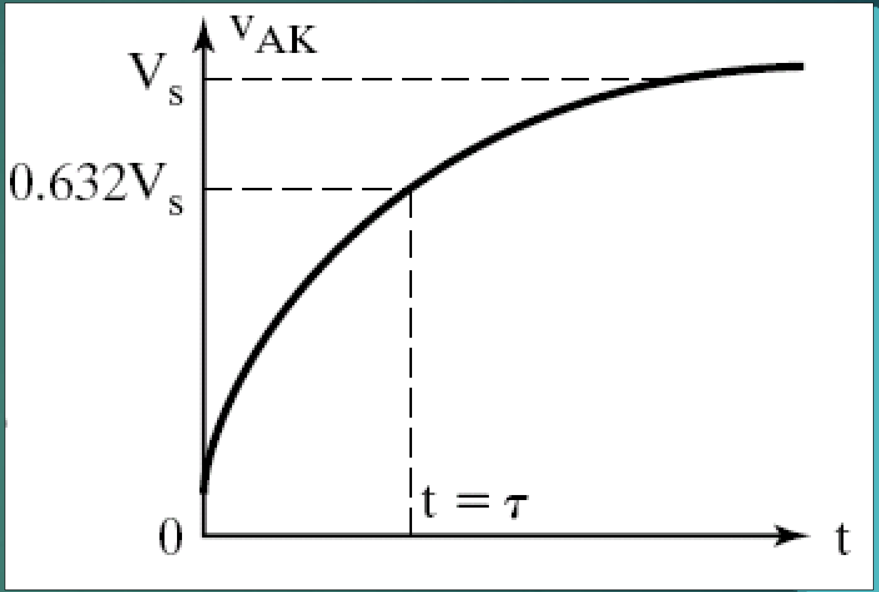
dv/dt Protection of SCR

- Now applying Laplace Transform

$$V_s = i(t)R_s + \frac{1}{C}\int i(t)\,dt$$

$$\frac{vs}{s} = RI(S) + \frac{1}{CS}I(S) \qquad \frac{vs}{s} = I(S)\left\{R + \frac{1}{CS}\right\}$$

$$I(S) = \frac{VS}{s\left\{R + \frac{1}{CS}\right\}} \qquad I(S) = \frac{VS}{R\left\{S + \frac{1}{RC}\right\}}$$



- Applying Inverse Laplace Transform

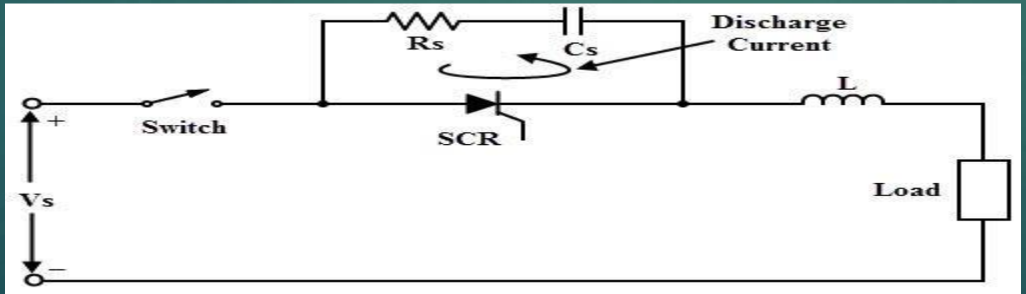
$$I(t) = \frac{VS}{R}\left\{e^{-\frac{t}{RC}}\right\} \qquad \tau_s = R_S C_S$$

$$Vc(t) = Vs - i(t)R$$

$$Vc(t) = V_s - V_s e^{-t/\tau_s} = V_s\left[1 - e^{-t/\tau_s}\right]$$

Snubber Circuit – dv/dt protection

- A snubber circuit comprises a series combination of capacitor and resistor connected across the SCR.
- It sometimes also consists of an inductor in series with SCR to prevent high di/dt.
- The value of the resistor is few hundred ohms.
- With the switch closed, the voltage that appears across the SCR is bypassed to the RC network as the capacitor acts as a short circuit, thus reducing the voltage to zero.
- With increment of time, the capacitor gets charged up at a slow rate which is significantly small to be able to turn on the SCR.
- Thus the dv/dt rating is always way lesser than the maximum dv/dt ratings.



Over Voltage Protection

- The major reason for SCR failure is overvoltage as this transient overvoltage leads to unscheduled turning ON of the SCR and sometimes the reverse transient voltage exceeds the reverse breakdown voltage.
- The reasons of this overvoltage may be commutation, chopping or lightening.
- **Internal Overvoltage:** During turn OFF, a reverse current continues to flow through the SCR after the anode current is decreased to zero. As this decaying current flows at a faster rate, due to inductance of the circuit, the high di/dt produces a high voltage which if crosses the SCR ratings will damage the SCR permanently.

Causes of External Overvoltage:

- External Overvoltage in a SCR circuit arises from the load or the supply source.
- When the SCR is in blocking mode in any converter circuit, there exists a small magnetic current that flows through the primary of the transformer. If the primary side switch is removed suddenly, the secondary of the transformer faces a high transient voltage which gets applied to the SCR. The voltage surge is multi fold than the SCR rating of the break over voltage.
- Lightening surges on the HVDC systems to which SCR converters are connected causes a very high magnitude of over voltages.
- If the SCR converter circuit is connected to a high inductive load, the sudden interruption of current generates a high voltage across the SCRs.
- If the switches are provided on DC side, a sudden operation of these switches produces arc voltages. This also gives rise the over voltage across the SCR.

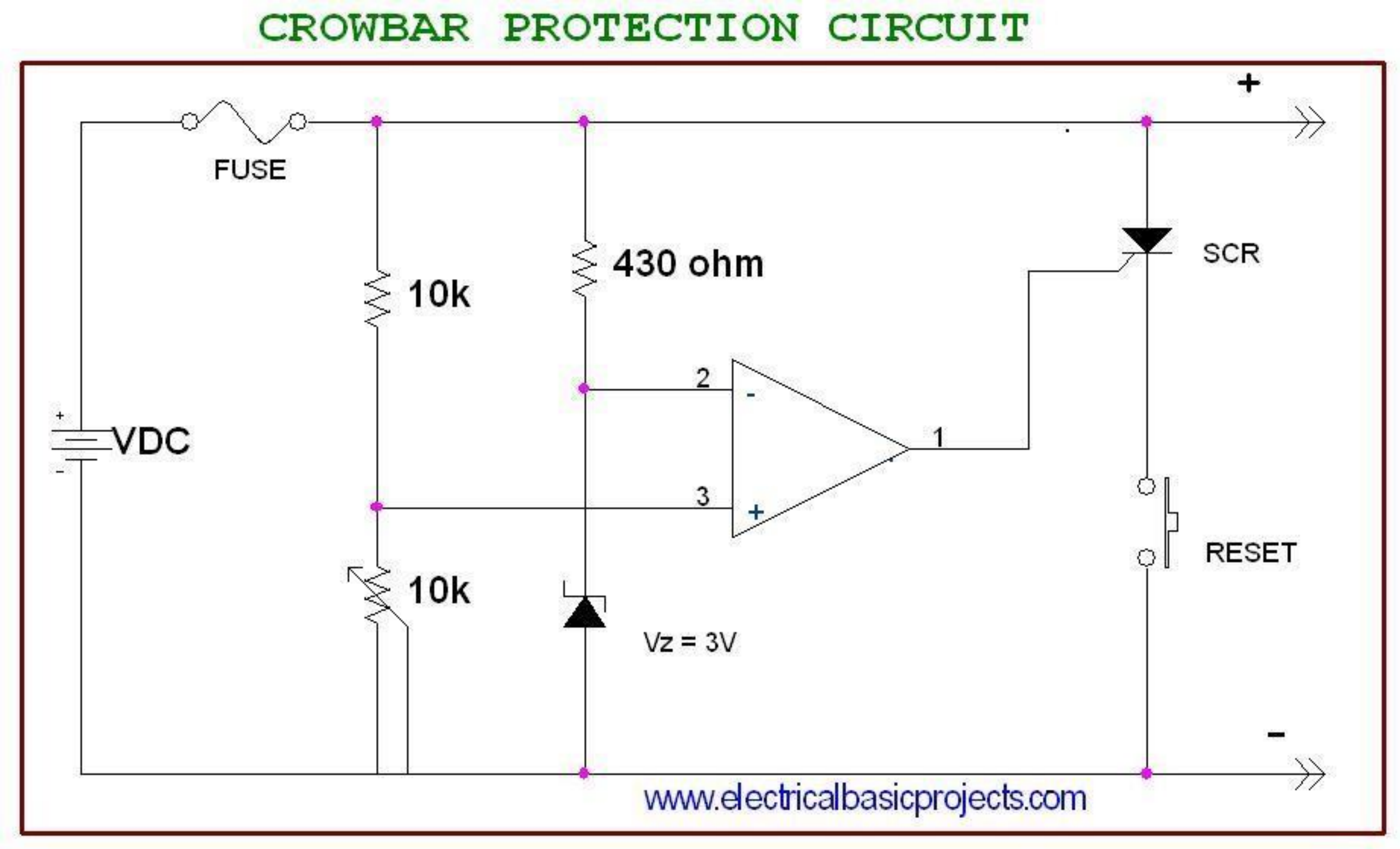
Protection Against Overvoltage

- To protect the SCR against the transient over voltages, a parallel R-C snubber network is provided for each SCR in a converter circuit.
- This snubber network protects the SCR against internal over voltages that are caused during the reverse recovery process.
- After the SCR is turned OFF or commutated, the reverse recover current is diverted to the snubber circuit which consists of energy storing elements.
- The lightening and switching surges at the input side may damage the converter or the transformer. And the effect of these voltages is minimized by using voltage clamping devices across the SCR.
- Therefore, voltage clamping devices like metal oxide varistors, selenium thyrector diodes and avalanche diode suppressors are most commonly employed.
- These devices have falling resistance characteristics with an increase in voltage. Therefore, these devices provide a low resistance path across the SCR when a surge voltage appears across the device.

Over Voltage - Crowbar Protection Circuit

- The Crowbar protection circuit is a fail-safe protection circuit.
- It protects the load against over voltages.
- It is placed across the power supply output terminals.
- The crowbar circuit mechanism contains crowbar device and sensing circuit (monitoring circuit).
- The two commonly used components for the crowbar device are Silicon Controlled Rectifier (SCR) and the MOSFET.
- A crowbar circuit is usually placed across the power supply’s output terminals, to protect the load against any overvoltage

Crowbar Circuit Operation



Crowbar Circuit - Normal Condition:

- Assume that the supply voltage is $V_{DC} = 6V$.
- The 10K resistor and the Potentiometer (POT) form the voltage divider circuit.
- Adjust the pot to 10K, so that the non-inverting input of op-amp is 3V.
- The Zener voltage of the Zener diode is $V_Z = 3V$ which is applied to the inverting input of the op-amp.
- As both the inputs are equal (3V) the output of the op-amp is zero. (Remember that here the op-amp act as a comparator.)
- In other words the gate voltage of the SCR is zero.
- So the SCR is in OFF state.

Crowbar Circuit - Faulty Condition:

- When overvoltage (Surge voltage) occurs, across the voltage divider circuit, the over voltage will appear which leads to high voltage at non-inverting input terminal of op-amp.
- The voltage at inverting input of op-amp is same as the Zener voltage $V_Z = 3V$.
- Now the comparator output is high, consequently voltage appeared at SCR gate terminal.
- Thus the crowbar SCR turns ON and shorts the circuit.
- Eventually the fuse will blow/trip the circuit breaker.

Advantages of Crowbar Protection Circuit

- Easy and cheap to construct.
- Prevent serious damage to sensitive and expensive electronic equipment.
- Has a low holding voltage, thus allows high fault currents to flow without dissipating much heat.
- It draws attention to the equipment or fault condition when it deactivates the protective devices by tripping the circuit breaker or blowing the fuse.

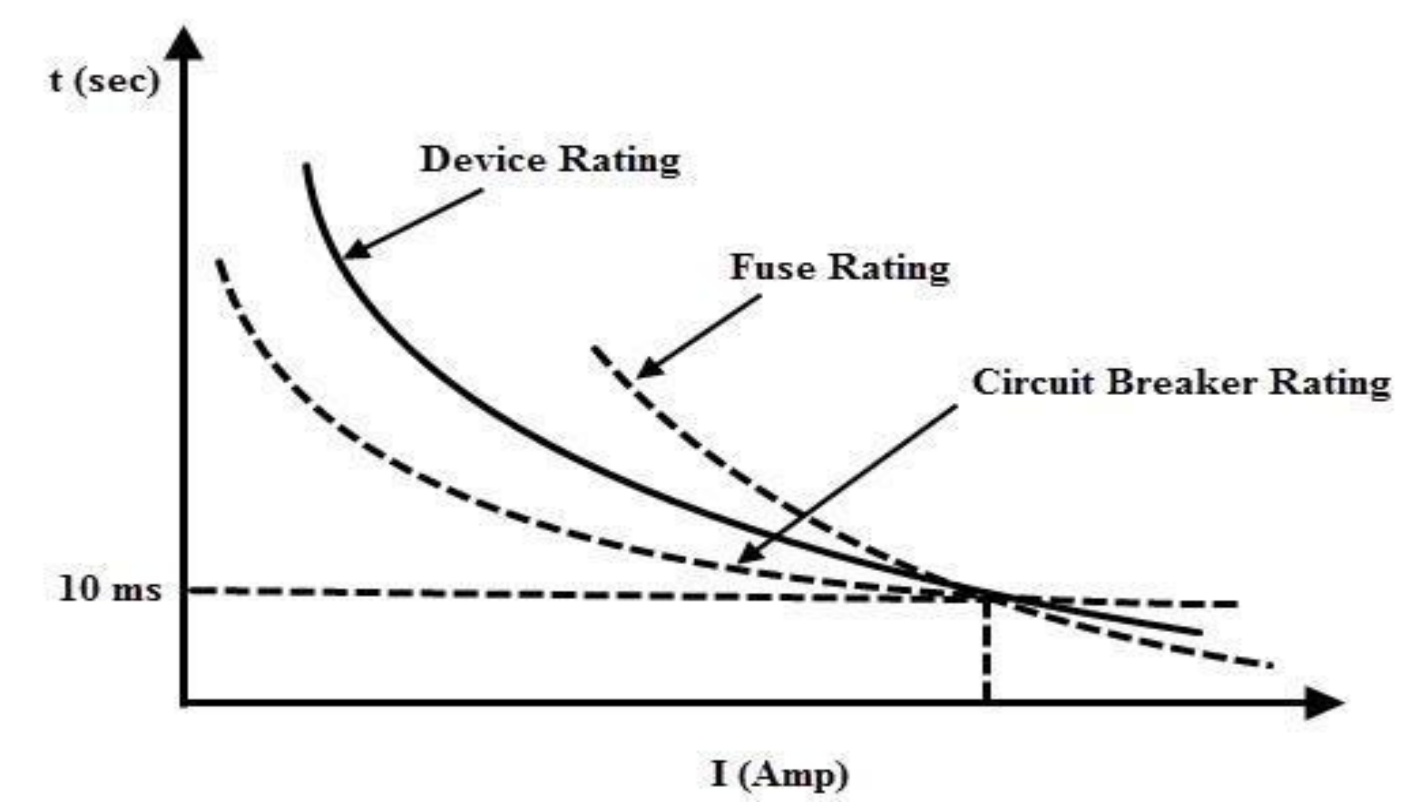
Over Current Protection

- During the short circuit conditions, over current flows through the SCR. These short circuits are either internal or external.
- The internal short circuits are caused by the reasons like failure of SCRs to block forward or reverse voltages, misalignment of firing pulses, short circuit of converter output terminals due to fault in connecting cables or the load, etc.
- The external short circuits are caused by sustained overloads and short circuit in the load.
- In the event of a short circuit, the fault current depends on the source impedance. If the source impedance is sufficient during the short circuit, then the fault current is limited below the multi-cycle surge rating of the SCR.
- In case of AC circuits, the fault occurs at the instant of peak voltages if the source resistance is neglected.
- In case of DC circuits, fault current is limited by the source resistance. Therefore, the fault current is very large if the source impedance is very low. The rapid rise of this current increases the junction temperature and hence the SCR may get damaged.
- Hence the fault must be cleared before occurrence of its first peak in other words fault current must be interrupted before the current zero position.

Protection Against Overcurrent

- The SCRs can be protected against the over currents using conventional over current protection devices like ordinary fuses (HRC fuse, rewireble fuse, semiconductor fuse, etc.), contractors, relays and circuit breakers.
- Generally for continuous overloads and surge currents of long duration, a circuit breaker is employed to protect the SCR due to its long tripping time.
- For an effective tripping of the circuit breaker, tripping time must be properly coordinated with SCR rating.
- Also, the large surge currents with short duration (are also called as sub-cycle surge currents) are limited by connecting the fast acting fuse in series with an SCR.
- So the proper coordination of fusing time and the sub-cycle rating must be selected for a reliable protection against over currents.
- Therefore, the proper coordination of fuse and circuit breaker is essential with the rating of the SCR.

Protection Against Overcurrent



Selection of fuse for protecting the SCR

- The selection of fuse for protecting the SCR must satisfy the following conditions.

1. Fuse must be rated to carry the full load current continuously plus a marginal overload current for a small period.
2. I2t rating of the fuse must be less than the I2t rating of the SCR
3. During arcing period, fuse voltage must be high in order to force down the current value.
4. After interrupting the current, fuse must withstand for any restricted voltage.

Thyristor Ratings

- Thyristors are provided with the minimum and maximum values of their voltage, current and power ratings within which they perform satisfactorily.
- Beyond these ratings, the devices may malfunction or get damaged.
- The devices are rate with subscripts.

Thyristor Ratings

- The first subscript indicates the state of the SCR as

F – Forward Bias

R – Reverse Bias

T – ON state

D – Forward blocking state with Gate open.

- The second subscript indicates the operating values as

T – Trigger

S – Surge or Non repetitive value

R – Repetitive value

W – Working value

Thyristor Voltage Rating

- **Peak Working Forward OFF state voltage (V_{DWM}):** It specifics the maximum forward (i.e. anode positive with respect to the cathode) blocking state voltage that a thyristor can withstand during working.
- **Peak repetitive off state forward voltage (V_{DRM}):** It refers to the peak forward transient voltage that a thyristor can block repeatedly in the OFF state.
- **Peak non-repetitive off state forward voltage (V_{DSM}):** It refers to the allowable peak value of the forward transient voltage that does not repeat.
- **Peak working reverse voltage (V_{RWM}):** It is the maximum reverse voltage (i.e. anode negative with respect to cathode) that a thyristor can with stand continuously.
- **Peak repetitive reverse voltage (V_{RRM}):** It specifies the peak reverse transient voltage that may occur repeatedly during reverse bias condition of the thyristor at the maximum junction temperature.

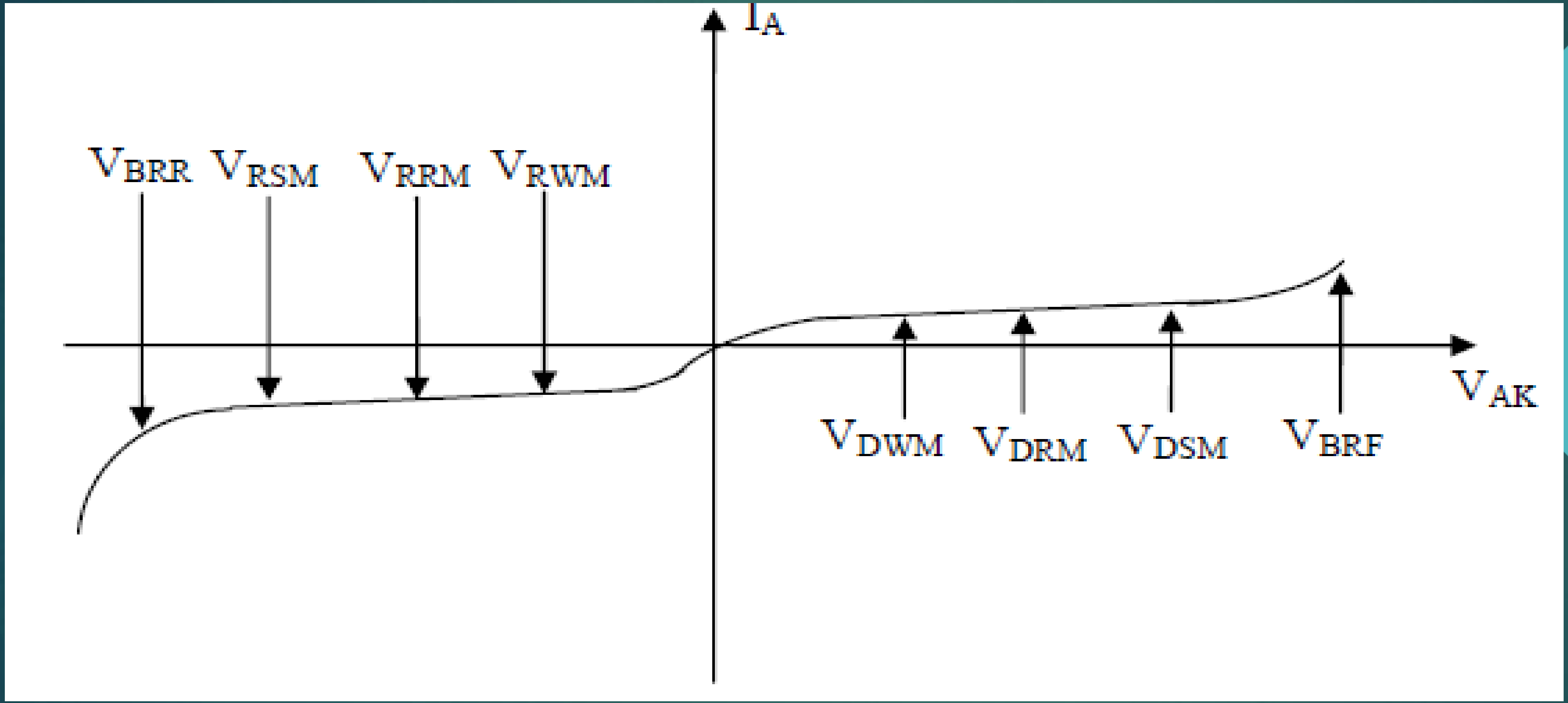
Thyristor Voltage Rating

- **Peak non-repetitive reverse voltage (V_{RSM}):** It represents the peak value of the reverse transient voltage that does not repeat.
- **ON-state Voltage V_T :** This is the voltage drop between the anode and cathode with specified junction temperature and ON-state forward current. Generally, this value is in the order of 1 to 1.5 Volts.
- **Gate Triggering Voltage V_{GT} :** This is the minimum voltage required by the gate to produce the gate trigger current.
- **Voltage Safety Factor V_f :** Generally, the operating voltage of the SCR is kept below the V_{RSM} to avoid the damage to the SCR due to uncertain conditions. Therefore, the voltage safety factor relates the operating voltage and V_{RSM} and is given as

$$V_f = V_{RSM} \ (RMS\ value\ of\ the\ input\ voltage * \sqrt{2})$$

Finger Voltage of SCR (V_{FV}): Minimum value of voltage which must be applied between anode and cathode for turning off the device by gate triggering. Generally this voltage is little more than normal ON state voltage drop.

Thyristor Voltage Rating



Voltage ratings of a thyristor.

Thyristor Current Rating

- **Average ON-state Current Rating (I_{AV}):** It is the maximum repetitive average forward current through the SCR. The power loss of SCR is completely dependent on this value.
- **Maximum RMS current** (I_{rms})**:** This is the maximum repetitive RMS current specified at a maximum junction temperature that can flow through the SCR. For a direct current, both RMS and average currents are same. Rating is required to prevent excessive heating in leads.
- **Maximum Surge current** (I_{SM})**:** It specifies the maximum non-repetitive or surge current that the SCR can withstand for a limited number of times during its life span. It is provided to accommodate the abnormal conditions of SCR due to short circuits and faults.
- **Maximum Squared Current integral ($\int i^2 dt$):** It is used for determining the thermal energy absorption of the device for a small time and choice of fuse.

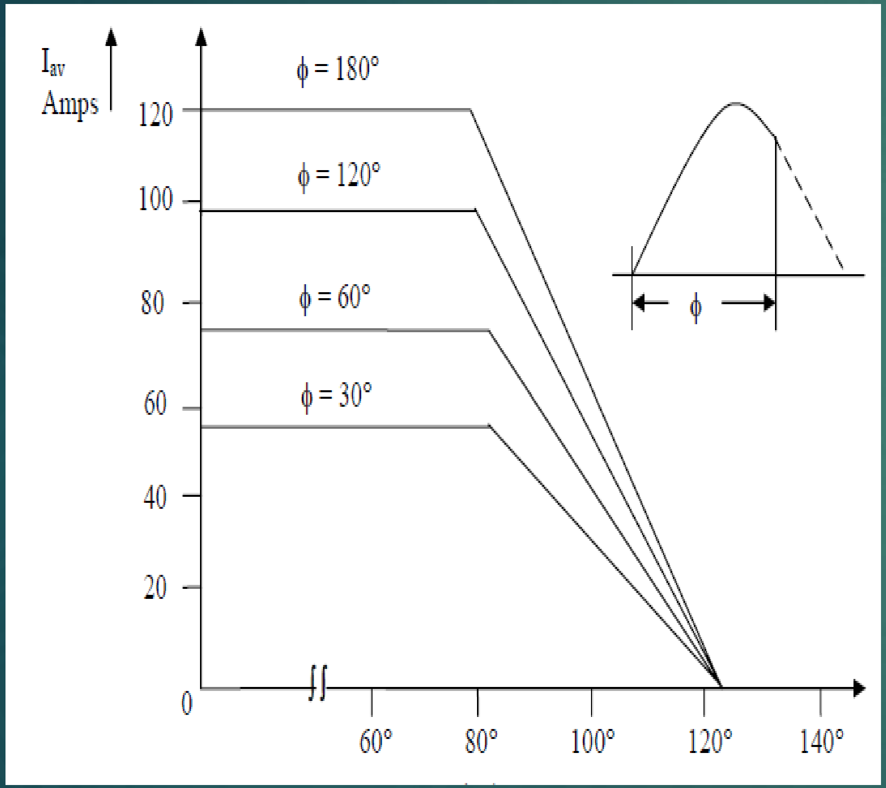
Thyristor Current Rating

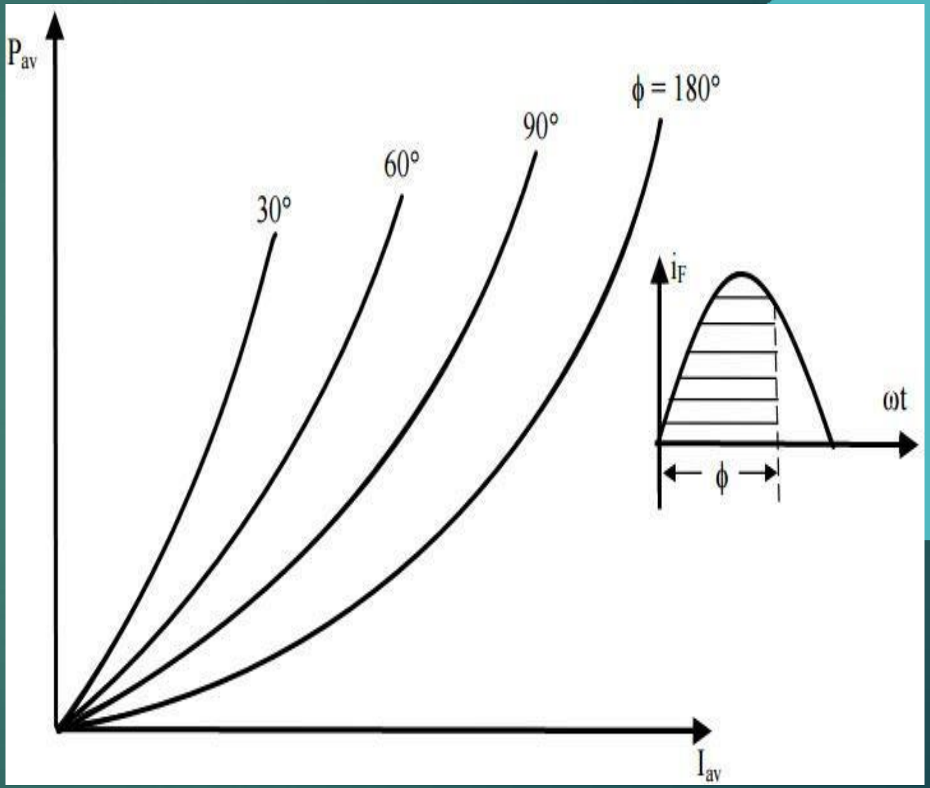
- **Latching Current (I_L):** The minimum anode current required to maintain the thyristor in the On – state immediately after it is turned on and the gate signal has been removed.
- **Holding Current (I_H):** The minimum anode current to maintain the thyristor in the On – State.

$$I_L > I_H$$

- **Gate Current** (I_G): The minimum and maximum Gate Current that can be applied to the SCR for safe turning On. Between these two limits, the conduction angle of the SCR is controlled.
- **Average Power Dissipation** (P_{av})**:** The product od average anode current and forward voltage drop across the SCR. It is the major source of junction heating for normal duty cycle. Device may get damaged if rating is exceeded.

Thyristor Current Rating





Current and Power Rating

Improvement of Thyristor Characteristics

- Improvement in di/dt rating.
- Higher Current gain
- Structural modification of the device.
- Improvement in dv/dt

Merits & Demerits of Thyristors

- **Merits of SCR:**

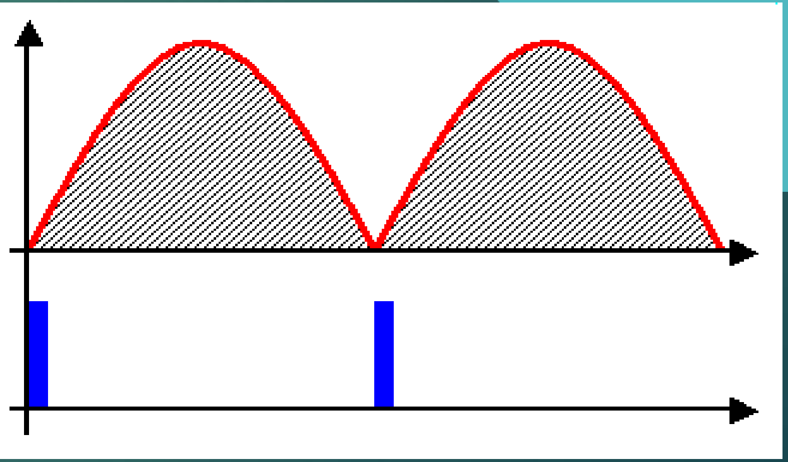
1. SCRs with high voltage and current ratings are available.
2. On state losses in SCRs are reduced.
3. Very small amount of gate drive is required since SCR is a regenerative device.

- **Demerits of SCR:**

1. Gate has no control after the SCR is turned ON.
2. External circuits are required to turn OFF the SCR.
3. Operating frequencies are very low.
4. Snubber circuits are required for dv/dt protection.

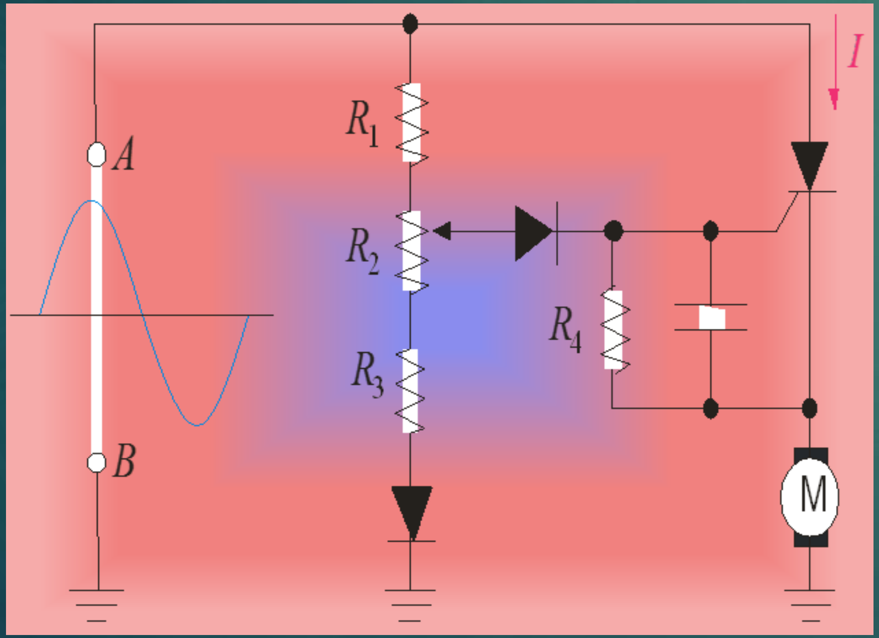
Applications:

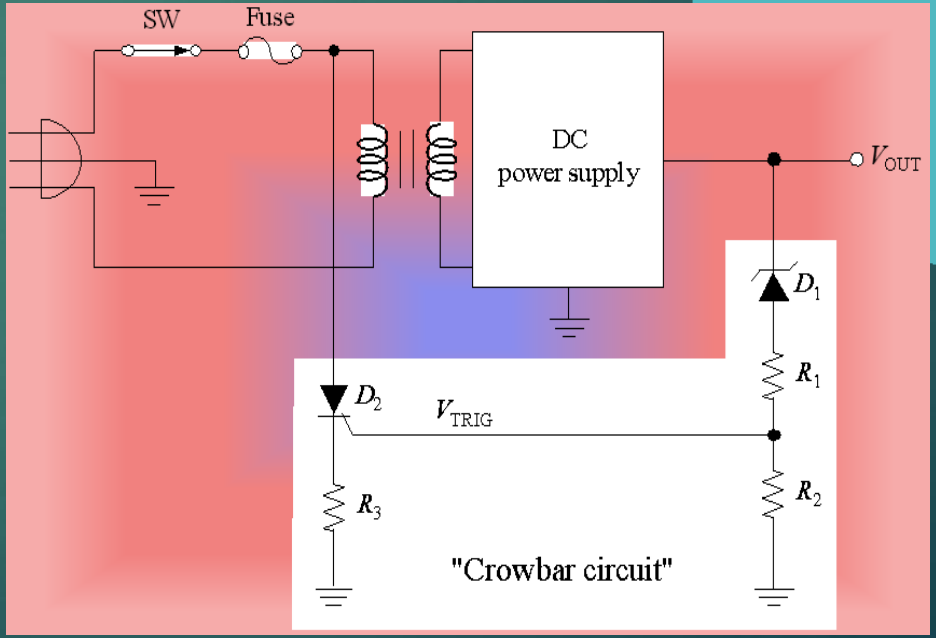
- High Current High Voltage Applications.
- Controlling alternating currents, where the change of polarity of the current causes the device to switch off automatically; referred to as Zero Cross operation.
- Phase angle triggered controllers, also known as phase fired controllers.
- “Circuit breaker" or “Crowbar" to prevent a failure in the power supply from damaging downstream components, by shorting the power supply output to ground.
- Load voltage regulated by thyristor phase control.
- Red trace: load voltage
- Blue trace: trigger signal.



Summary:

- The SCR is triggered on the positive cycle and turns off on the negative cycle.
- A circuit like this is useful for speed control for fans or power tools and other related applications.
- The SCR can handle a large current, which causes the fuse (or circuit breaker) to open.





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