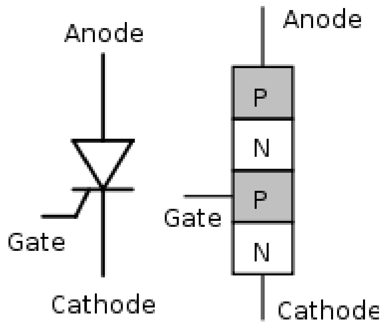
Module-3

Thyristors: *Introduction, Thyristor Characteristics, Two-Transistor Model of Thyristor, Thyristor Turn- On, Thyristor Turn-Off, A brief study on Thyristor Types, Series Operation of Thyristors, Parallel Operation of Thyristors, di/dt Protection, dv/dt Protection, Thyristor Firing Circuits, Unijunction Transistor.*

Introduction:



A thyristor is a four-layer, three-joint p-n-p-n semiconductor switching device with three terminals: anode, cathode, and gate. The figure shows the thyristor symbol and a sectional view of a three-pn junction.

The terminal connected to the outer p region is called anode(A), the terminal connected to outer n region is called cathode(K) and that connected to inner p region is called the Gate(G).

For large current applications, thyristor need better cooling, this is achieved to a great extent by mounting them onto heat sinks SCR ratings has an improved of voltage rating 10kv and an rms current rating of 300 A with corresponding power handling capability of 30 MW are available.

An SCR is so called silicon carbide Rectifier because silicon is used for its construction and its operation as a rectifier unlike the diode, a thyristor also blocks the current from anode to cathode until it is triggered into conduction by a proper gate signal between gate and cathode terminals.

Static VI Characteristics of SCR:

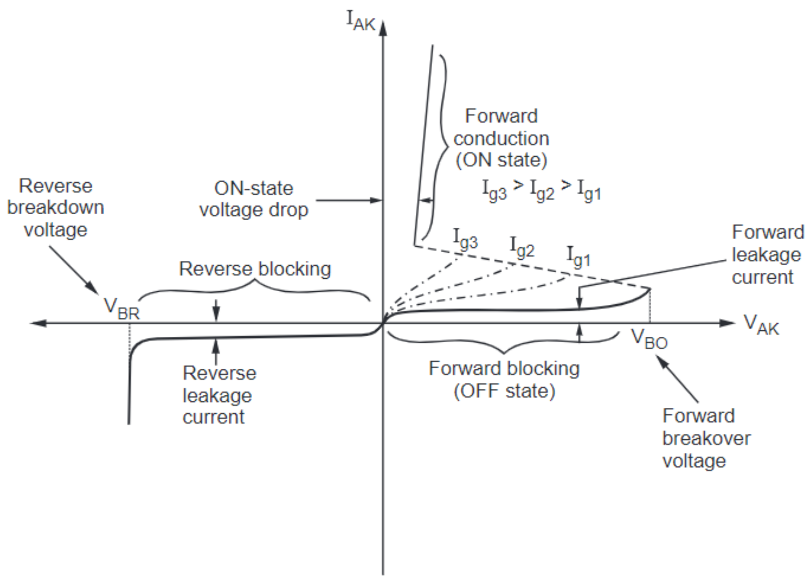


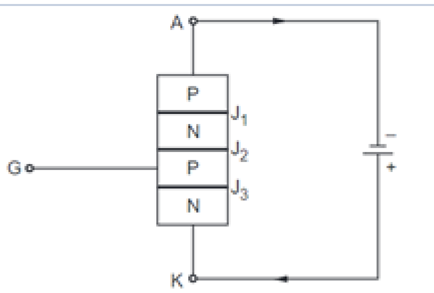
Fig 1. Static V-I characteristics of a thyristor (SCR)

The characteristics shown in the above figure are called static characteristics. The anode to cathode current I_{AK} is plotted with respect to anode to cathode voltage V_{AK}. The voltage 'V_{BO}' is the forward breakover voltage. 'V_{BR}' is the reverse break-down voltage. And I_{gl}, I_{g2} , I_{g3} are the gate currents applied to the thyristor.

The working of the terrestrial can be discussed into 3 modes

1. Reverse blocking mode
2. Forward blocking mode and
3. Forward conduction mode

Reverse blocking mode:

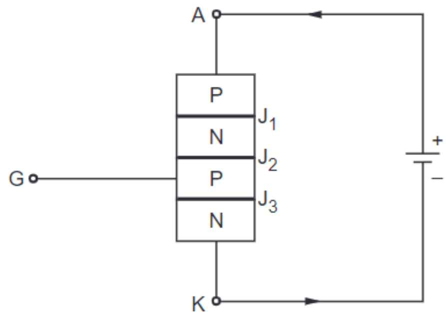


A reverse biased thyristor

Fig. shows the situation when the thyristor will be in reverse blocking mode. In the above figure, observe that the anode (A) is made negative with respect to cathode (K). The gate is kept open. There are three PN junctions in the thyristor J_1,J_2 and J_3. Due to this reverse bias, junctions J_1 and J_3 are also reverse biased. And junction J_2 is forward biased. The thyristor does not conduct due to this reverse bias. A very small current flows from cathode to anode. This current is called reverse leakage current of the thyristor. This mode is called reverse blocking mode. Fig.1 shows the characteristic of thyristor in reverse blocking mode. Observe that reverse voltage increases but very small current flows. At reverse break down voltage (V_{BR}), the reverse current increases rapidly. At the time of reverse breakdown, the high voltage is present across the thyristor and heavy current flows through it. Hence large power dissipation takes place in the thyristor. Due to this dissipation, the junction temperature exceeds the permissible value and the thyristor is damaged. Hence a reverse voltage across the thyristor should never exceed V_{BO}.

During the reverse blocking mode, the positive gate signal should not be applied. If the positive signal is applied between gate and cathode, junction J_3 is forward biased. Hence current starts flowing through it. This current adds to reverse leakage current of the thyristor. Hence dissipation is also increased.

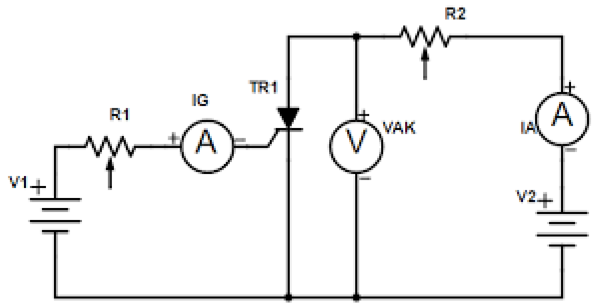
Forward Blocking Mode: The thyristor is said to be forward biased when anode is made positive with respect to cathode As shown in the fig. Due to this the junction J_1 & J_3 are forward biased and J_2 is reverse biased. A very small current flows from anode to cathode called forward leakage current and it is in order of few milliamperes. In this mode, the thyristor is forward biased but it does not turn-on. The V_{AK} can be increased till V_{BO} then the thyristor will turn on and the thyristor goes from forward blocking mode to forward conduction mode even if gate drive is not applied. Thus thyristor is not damaged if $V_{AK} > V_{BO}$, rather it is turned on.



Thyristor in forward biased condition

Forward Conduction Mode:

In this mode, the thyristor conducts current from anode to cathode with a very small drop across it. A thyristor is brought from forward blocking mode to forward conduction mode by turning it on by exceeding the V_{BO} or by applying a gate pulse between gate and cathode. In this mode, thyristor is in on state and behaves like a closed switch. The voltage drop across thyristor in the on state in of the order of 1 to 2v depending on the rating of SCR.



The voltage drop increases slightly with an increase in anode current in conduction mode anode current is limited by load impedance alone as voltage drop across SCR is quite small. This small voltage drop across the device is due ohmic drop in the four layers.

Latching Current(I_L): Latching current is the minimum forward current that flows through the thyristor to keep it in forward conduction mode (ON state) at the time of triggering if the forward current is less than the latching current thyristor doesn't turn on. Latching current is of the order of 10 to 15 milliamperes

Holding Current(I_h): Holding current is the minimum forward current that flows through the thyristor to keep it in forward conduction mode when forward current reduces below holding current thyristor turn off.

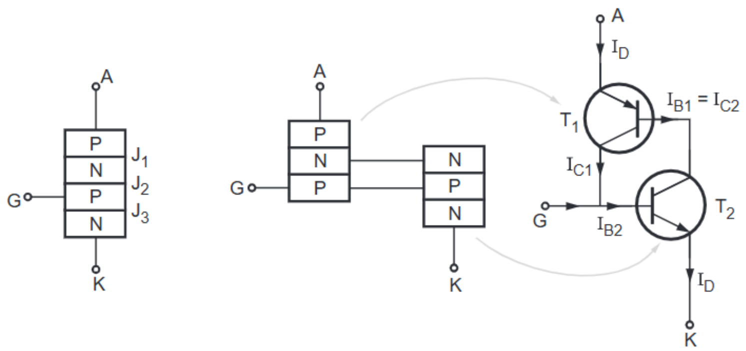
The holding current of the thyristor is of the order of 8 to 10 milliamperes.

Comparison (difference) between holding and latching currents

The definitions of holding current and latching current appear similar but they are totally different. The differences are mentioned below :

1. Latching current is effective at the time of turning-ON, whereas holding current is effective at the time of turning-OFF the thyristor.
2. Latching current is the minimum current that should flow at the time of triggering to turn-ON the thyristor. Whereas once the thyristor is already in ON-state, its current should not reduce below holding current otherwise it turns-OFF.
3. Latching current is greater than holding current even though their magnitudes are much related.

Two Transistor Model of Thyristor: The operation of the thyristor can be explained with the help of two transistor model. Fig. shows how the two transistor model of the thyristor is formed.



(a) Four layer structure of thyristor (b) Middle two layers split into two separate parts (c) Two transistor mode of the thyristor from fig (b)

A two transistor model of the thyristor

As shown in Fig. (b), the middle two layers are split into two separate parts. Because of this, the two transistors are formed. These transistor are shown in Fig.(c). The transistor Tl is pnp, whereas T2 is npn. The base of Tl is connected to collector of T2. Similarly base of T2 is connected to collector of T1. These transistors are in common base configuration. When the thyristor is forward biased and gate is open, various currents flow as shown in Fig.(c). As shown in this figure, the anode to cathode current is ID. The collector current, emitter current and leakage currents of Tl are related as,

$$I_{C1} = \alpha_1 I_{E1} + I_{CO1} \qquad \text{............(1)}$$

Here $I_{E1} = I_D$ and I_{CO1} is leakage current of T_1. Similarly for T_2,

$$I_{C2} = \alpha_2 I_{E2} + I_{CO2} \qquad \text{............(2)}$$

Here $I_{E2} = I_D$ and I_{CO2} is leakage current of T_2.

Therefore equation (1) & (2) can be written as,

$$\left.\begin{aligned} I_{C1} &= \alpha_1 I_D + I_{CO1} \\ I_{C2} &= \alpha_2 I_D + I_{CO2} \end{aligned}\right\} \qquad \text{............(3)}$$

In Fig. (c), observe that the current ID flows through the collectors of Tl and T2. Hence we can write,

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

Putting the values from equation (3) in above equation,

$$I_D = \alpha_1 I_D + I_{CO1} + \alpha_2 I_D + I_{CO2}$$

$$\therefore \quad I_D = (\alpha_1 + \alpha_2) I_D + I_{CO1} + I_{CO2}$$

$$\therefore \quad I_D = \frac{I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)} \quad \text{........(4)}$$

$I_{CO1} + I_{CO2}$ can be considered as total reverse leakage current of junction J_2. This current can be denoted by the I_{CO}. Then above equation can be written as,

$$I_D = \frac{I_{CO}}{1-(\alpha_1+\alpha_2)} \quad \text{.......(5)}$$

Here I_{CO} is the reverse leakage current of the reverse biased junction J_2. And α_1 is the common base current gain of T_1 and α_2 is common base current gain of T_2. Initially when forward voltage is small, $(\alpha_1 + \alpha_2)$ is very small and less than 1. Hence forward blocking current as given by equation (5) is also small. As forward voltage applied across the thyristor increases, the values of α_1 and α_2 also increase. When $(\alpha_1 + \alpha_2)$ tends unity, then I_D approaches infinity as given by equation (5) At this instant, internal regeneration starts and the thyristor goes into forward conduction (ON-state) mode. The current through the thyristor is only limited by the external load.

Once the thyristor goes into conduction, the two transistor model is no more applicable. Here note that the internal regeneration takes place in the thyristor due to avalanche breakdown of reverse biased junction J_2. It does not take place when thyristor is reverse biased. When the current through the thyristor falls below holding current, the forward blocking state is regained. Then α_1 and α_2 of transistors are also reduced to small values.

When the gate current I_g is applied, then equation 3.2.7 will be written as,

$$I_D = \frac{I_{CO} + I_g}{1-(\alpha_1+\alpha_2)} \quad \text{.........(8)}$$

Thus the forward leakage current (I_D) is increased due to gate drive (I_g). This leakage current flows through junction J_2 and its avalanche break-down occurs at lower forward voltage. Thus with the gate drive, the SCR is turned on at voltages less than V_{BO}. Hence gate becomes convenient way of triggering the thyristor. Once the thyristor is turned-on, the gate has no control over its conduction.

Thyristor Turn-on and Turn-off:

Different Ways to Turn-on the Thyristor:

1. Gate drive: Thyristor can be turned on by applying positive gate-cathode voltage. Injected gate carriers increase the anode current and regenerative action starts. $(\alpha_1 + \alpha_2)$ approaches unit and anode current (I_D) becomes large. It is limited only by external load. Once the thyristor is turned-on, there is no need of gate drive. Hence it can be removed. Normally pulsed gate drive is applied to reduce losses in the thyristor gate.

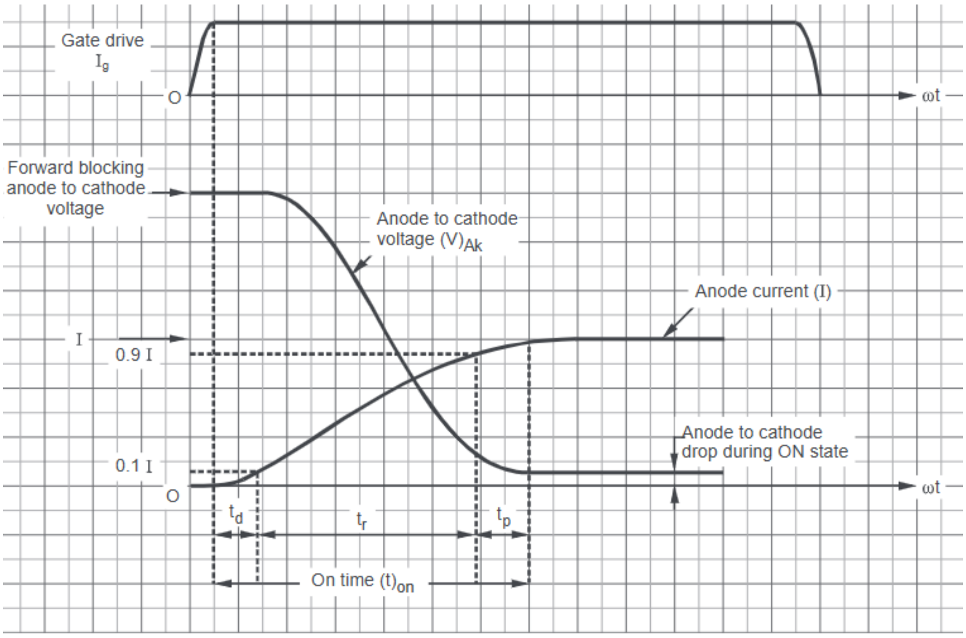
2. High forward voltage: Thyristor turns on when its anode-cathode voltage exceeds forward breakover voltage, i.e. $V_{Ak} > V_{BO}$. At these voltages, the leakage current is so high, that internal regeneration starts in the device.

3. dv/dt: Thyristor can be thought of as a capacitor in the forward biased state. When the anode-cathode voltage changes rapidly, leakage current thought the device increases due to internal capacitor. The leads to turn-on of the thyristor.

4. Light: Thyristor can be turned on by light, when it falls on gate cathode junction of the thyristor light induces electronic hole pairs and it helps to increases leakage current.

5. High temperature: Tyristor turns on due to increased temperature AT higher temperature, there are more electron-hole pairs across junctions. This inverses the leakage current and the thyristor turns on.

Turn-on Dynamic Characteristics:



Dynamic characteristics of thyristor during turn-on

The gate pulse is applied at t = 0. During the delay time (td), the anode current rises very slowly and flows only near the narrow region of the gate. Observe that anode to cathode does not reduce during td. It remains to the forward blocking value. During the rise time (tr), the anode current increases rapidly and anode to cathode voltage falls rapidly. The high voltage and current are present in the thyristor. Hence large dissipation takes place in the thyristor.

This power dissipation is called switching loss of the thyristor. The current starts spreading in the remaining area of the thyristor. During the spread time (tp), the conduction spreads over the complete cross-section of the thyristor. The anode current reaches to its maximum value. And the anode to cathode voltage falls to lowest value (i.e. less than 2 V). The dissipation in the thyristor is also reduced. The turn on time (ton) of the thyristor is given as total of td,tr and tp. Thus,

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

The turn on time can be defined as,

The turn-on time of the thyristor is defined as the time from initiation of gate drive to the time when anode current reaches to its full value.

The turn-on time of the thyristors is about I to 3 microseconds. The turn-on time can be effectively reduced by applying higher values of gate currents. Because of high gate currents, more electron-holes are injected near junction J2. Hence avalanche break-down of J 2 takes place fast. Therefore anode current rises fast. Thus effective turn-on time is reduced. To turn-on the thyristor, the gate pulse is thus sufficient.

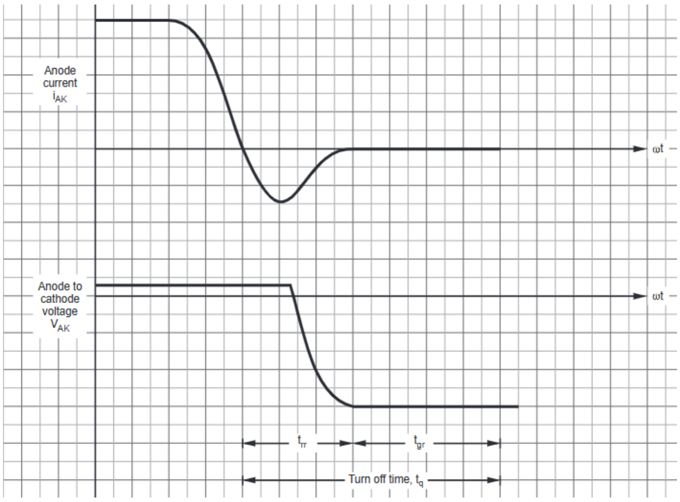
Thyristor Turn-off:

The thyristor can be turned-off, when its forward current falls below holding current. The can be done by two methods i) Natural commutation and ii) Forced commutation.

i) Natural commutation: In this type of turn-off, the supply voltage becomes zero or negative, Hence thyristor is reverse biased. Therefore it is turned-off.

ii) Forced commutation: When the supply voltage is DC, then external commutation component are used to turn-off the thriystor. The commutation components apply reverse bias across the thyristor temporarily or pass impulse of negative current. Therefore thyristor turns-off.

Turn-off Dynamic Characteristics:



The thyristors are not turned off by gate. They need external circuit for turn-off. These circuits are called commutation circuits. These commutation circuits has to hold negative voltage across the thyristor during turn-off period. The thyristor is said to be turned-off when it regains forward blocking capability after forward conduction. In the below figure observe that anode current falls and then it becomes negative. The negative pulse of current flows through the thyristor for short period. During the conducting state, the thyristor is flooded with carriers and it acts as short circuit. The negative anode current flows through the thyristor till all these carriers are removed. Then junctions Jl and J 3 achieve their forward blocking state. The time required for this is called reverse recovery time (try At the end of trr, reverse voltage appears across the thyristor and anode current becomes zero. This is shown in Fig. But still, the thyristor is not turned-on. The commutation circuit has to hold negative voltage across the thyristor for gate recovery time (tgr During this time, the excess carriers near junction J2 are recombined. If negative voltage is removed by commutation circuit before t then thyristor may turn-on again due to these excess carrier near junction J2. Because they act like gate drive to the thyristor. Hence the turn-off is complete at the end of gate recovery time. The thyristor regains its forward blocking capability. The negative voltage imposed by commutation circuit can be removed at the end of tgr. The turn-off time (tq) of the thyristor is the total time required by reverse recovery and gate recovery. i.e.,

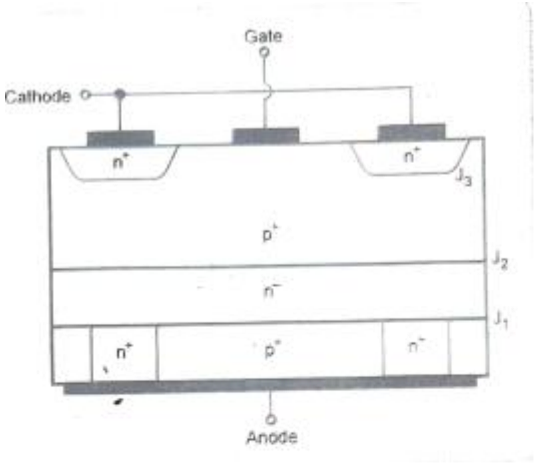
$$t_q = t_{rr} + t_{gr}$$

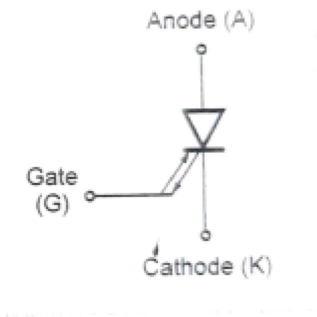
The turn-off time of the thyristor is the time required to achieve forward blocking capability after commutation is initiated.

The turn-off time of the thyristor varies from 5 to 200 microseconds. The turn-off time of the commutation circuit is called circuit turn-off time (tc). And hence circuit turn-off time must be greater than the turn-off time of the thyristor (tc > tq).

A Brief Study on Thyristor Types:

Gate Turn-off Thyristor (GTO):





The SCR is most commonly used member thyristor family. But needs external circuits for turn-off. GTO can be turned-off by gate drive, gate has full control over the operation of GTO. Fig. shows the structure of GTO.

The Structure of GTO is almost similar to SCR, but significant differences make GTO different from SCR. These differences are

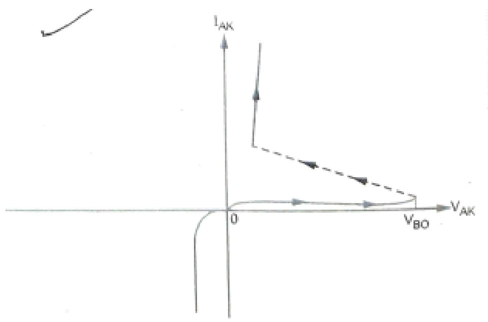
1. Gate and cathode are highly interdigitated with various geometric forms. This maximizes the periphery of cathode and minimize distance.
2. There are n + regions at regular intervals in the p + anode layer. This n + layer makes direct contact with n - layer This is called anode short. This speeds up turn-off mechanism of GTO.
3. The operation of GTO can be explained with the help of two transistor analogy. The gain of pnp transistor is reduced. This reduces the regenerative action. Hence turn-off of GTO can be achieved by negative current from gate.

The double arrow on the gate indicates the bidirectional current flows through the gate. The rest of the symbol is similar to SCR.

Characteristics of GTO:

The V-I Characteristics of GTO in forward direction are similar to that of SCR. But in reverse direction GTO has virtually no blocking capability Observe that GTO starts conducting in direction after very small reverse (20 to 30 V) voltage. This is because of the short structure.

The junction blocks reverse voltages. But J3 has very small reverse breakdown voltage. Thus GTO has asymmetric voltage blocking capability.



Advantages, Limitations and Applications of GTO:

Advantages:

1. Higher voltage blocking capability.
2. Gate has full control over the Of GTO
3. Low on-state loss.
4. High ratio of surge current to average current.
5. High on-state gain.

Limitations

1. GTOs require large negative gate currents for turn-off. Hence they are suitable for low-power applications.
2. Very small reverse voltage blocking capability.
3. Switching frequencies are very small.

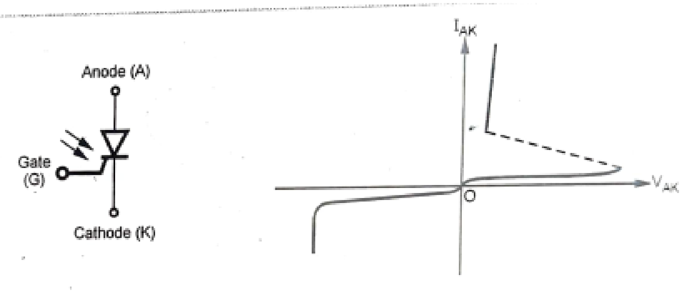
Applications

1. GTOs are suitable mainly For low power applications.
2. Induction heating and motor drives.

Light Activated SCR (LASCR):

The light-activated SCRs can be triggered using a beam of light: Their gate region is photosensitive.

The photons of light induce electrons in the gate cathode junction. Because of these electrons, current starts flowing across J3 and SCR turns-on. Once the SCR is turned on, gate has no control over its operation.



(a) Symbol of LASCR (b) V-I characteristics of LASCR

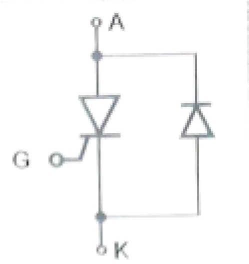
Advantages

1. It can turned-on by a beam of light. Hence isolation is provided between control circuit and SCR.
2. Because of optical triggering, effects of noise are reduced.

Applications

1. Used in high-power applications like HVDC transmission, VAR compensation etc.
2. Used in noise environments for better-triggering control.

Reverse Conducting Thyristor (RCT):

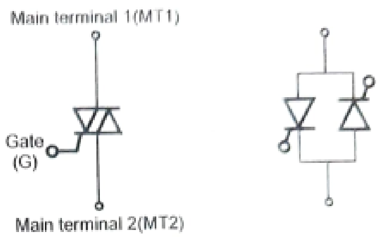


In most of the applications, an antiparallel diode is connected across the thyristor, For example in chopper and inverter circuits, the antiparallel diode improves the turn-off requirement of the circuit. The antiparallel diode is also useful in case of inductive loads to provide the path for feedback currents. A reverse conducting thyristor (RCT) is similar to an SCR with an antiparallel diode. Fig. shows the equivalent circuit of RCT. The RCT is also called as thyristor or ASCR. It conducts in the reverse direction without any control. The conduction in the forward direction is controlled by the gate. The characteristics are similar to SCR in the forward direction. And the characteristics are similar to diode in reverse direction.

Triac (Bidirectional Triode Thyristors):

The triac is the bidirectional device. It conducts in both directions. SCR is conducted only in one direction. The tria is equivalent to the two antiparallel SCRs.

The triac has three terminals: Main Terminal 1 (MT1), Main Terminal 2 (MT2), and Gate (G). The symbol pf antiparallel devices. The current flows from MT1 to MT2 when MT1 is forward biased with respect to MT2. Similarly, current flows from MT2 to MT1 when MT2 is forward biased with respect to MT1. The current flows (the triac is switched on) whenever the gate drive is applied.



(a) Triac symbol (b) Triac equivalent circuit

The Triac is the best device for AC phase control. The input and load are both AC. The power is to be controlled in positive and negative half cycles. The tria is then triggered in every half cycle. The triac turns off when the current falls to zero in every half cycle. Thus the necessity of antiparallel SCRs is eliminated by triac.

Merits, Limitations and Applications of Triac:

Merits of Triac:

1. Triac is a bidirectional device, i,e it conducts in both directions.
2. Triac turns off when voltage is reversed.
3. Single gate controls conduction is both directions.
4. Triac with high voltage and current ratings are available.

Demerits if Tria:

1. Tria are latching devices like SCR. Hence, they are not suitable for DC power applications.
2. Gate has no control over the conduction once triac is turned on.
3. Triac have very small switching frequencies.

Applications of Triac:

1. AC power controllers and heater, fan etc. controller.
2. Triggering device for SCRs.

Diac:

The diac is the two terminal and four layer device. It is mainly used for triggering triacs. Fig(a) shows the symbols of diac. The symbol shown in Fig(b) has arrows in both the directions. This means it conducts in either direction, The terminals are not named. It can be used in any direction. It is low low-power triggering device. There is no control terminal on the diac.

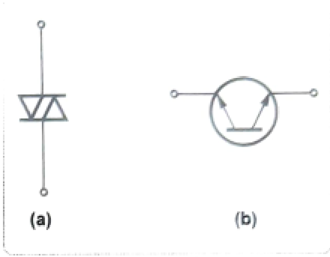
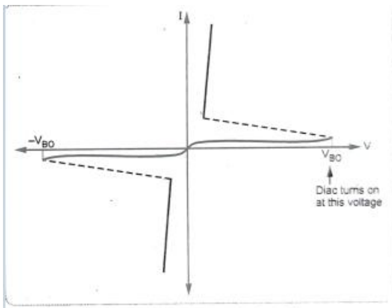


Fig (a)Two different symbols used for diac

VI Characteristics of Diac: Fig. shows the V-I characteristics of diac. The current through the diac is plotted with respect to voltage across it. Diac remains Off till voltage is less than V_{BO}. When voltage exceeds V_{BO}, diac turns 'on' and conducts heavily. Observe that the characteristic is exactly similar for positive as well as negative values of voltage and current. Once the diac turns on, the voltage across it drops to negligible value.

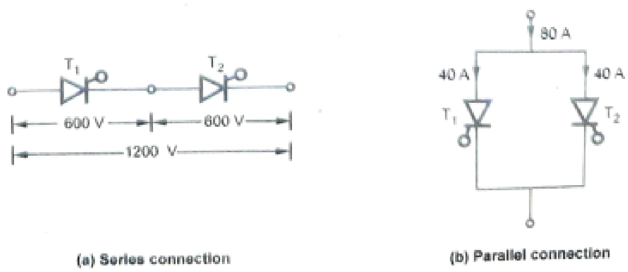


Fig(b) V-I characteristic of diac

Series and Parallel Operation of Thyristors:

Necessity of Series and Parallel Operation:

Series connection of the devices is often required to increase the overall voltage rating. For example the thyristor is to be operated at 1000 volts. But we have thyristors of rating 600 volts. Then the circuit can be implemented by connecting two thyristors in series



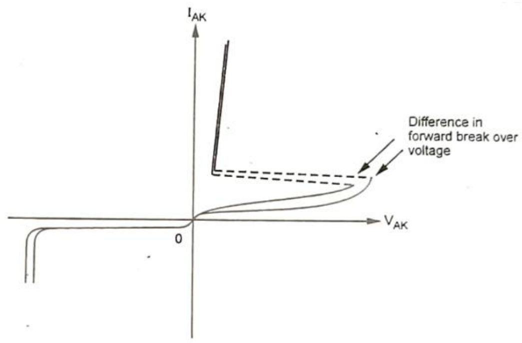
(a) Series connection (b) Parallel connection

Similarly, parallel connection is used to increase current ratings. For example, current in the circuit is 80 A. But we have a thyristor of rating 50 A. Then the problem can be solved by connecting two thyristors in parallel as shown in Fig. (b). This makes the current sharing among two thyristors and each one carries 80/2 = 40 A. Thus series and parallel connections are most widely used to cater the need of higher voltage and currents.

Series Connection of Thyristors:

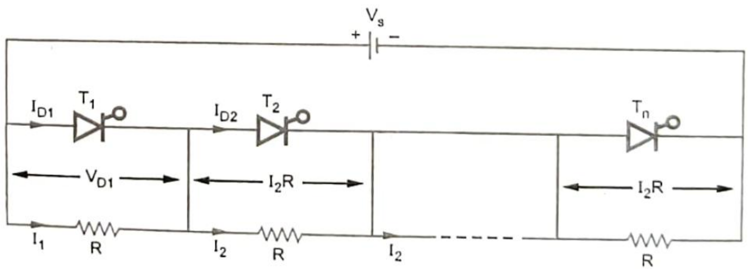
Problems Encountered in Series Connection:

When the thyristors are connected in series, they have small differences in their ratings. Fig shows the V-I characteristics of two thyristors of same ratings. Observe that there are minor differences between the characteristics. Forward break-over voltages, internal resistance, leakage current etc are not exactly same. The thyristor with highest internal resistance will have minimum leakage current. Hence high voltage will appear across it in off state. This creates voltage imbalance in the series connection. Hence equalization is necessary in the series connection.



Equalizing Components:

Consider that 'n' number of thyristors are connected in series. An equalizing resistance 'R' is connected across each thyristor as shown in Fig. Let us assume that Tl has maximum internal resistance in off state. Hence its leakage current I_{D1} is minimum. Let the internal resistance of other devices is same. Hence their leakage current is also same, i.e. I_{D2} current I_1 flows through R. Since other thyristors have same internal resistance, current through their theie resistors will be same, i.e. I_2. From above circuit we can write,



$$I_{D_1} + I_1 = I_{D_2} + I_2$$

$$I_2 = I_1 - I_{D_1} - I_{D_2} = I_1 - \Delta I_D \quad \text{............(1)}$$

Here ΔI_D is the difference in leakage currents of two thyristors. Voltage across T_1 is $V_{D1} = I_1$, R and voltage across T_2, T_3,…..T_n is same i.e. I_2R. Therefore we can write,

$$V_s = I_1 R + I_2 R(n-1) = V_{D_1} + (n-1) I_2 R$$

Putting for I_2 from equation (1),

$$V_s = V_{D_1} + (n-1)(I_1 - \Delta I_D) R = V_{D_1} + n I_1 R - n \Delta I_D R - I_1 R + \Delta I_D R$$

$$= V_{D_1} + n V_{D_1} - V_{D_1} - (n-1) \Delta I_D R = n V_{D_1} - (n-1) \Delta I_D R$$

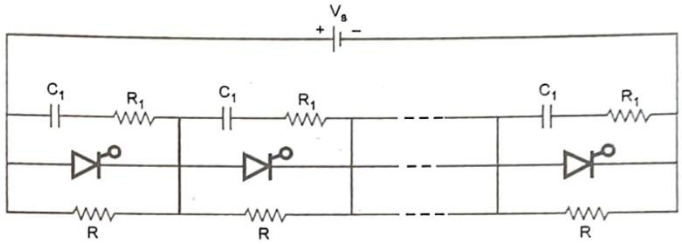
$$V_{D_1} = \frac{V_s + (n-1) \Delta I_D R}{n} \quad \text{.......(2)}$$

Maximum value Of V_{D1} will occur when ΔI_D is maximum. Value of R can be obtained from above equation as,

$$R = \frac{n V_{D_1} - V_s}{(n-1) \Delta I_D} \quad \text{......(3)}$$

Dynamic Equalization Circuit:

When all thyristors are in forward blocking state. There can be some difference in the turn-on and turn-off times of the thyristors. When trigger is given to all the thyristors, they start turning-on. Higher voltage will appear across the thyristor which turns-on late. Hence its maximum voltage rating may be exceeded. This problem can be overcome by dynamic equalizing circuit.



An R-C circuit is placed across each thyristor. C_l provides the equalization during turn-on and turn-off. Resistance R_l is used to limit the discharge current of C_l.

Value of C_l

$$V = \frac{Q}{C}$$

If V is ΔV, then

$$\Delta V = \frac{\Delta Q}{C}$$

We Know that

$$V_{D_1} = \frac{V_s + (n-1)\Delta I_D R}{n}$$

If ΔQ indicates the difference in charge stored in C_l and C_2, then ΔV will indicate the voltage difference across T_l and T_2. Hence we have $\Delta V = \Delta I_D R$. Therefore above equation becomes,

$$V_{D_1} = \frac{V_s + (n-1)\Delta V}{n}$$

Since $\Delta V = \frac{\Delta Q}{C_1}$,

$$V_{D_1} = \frac{V_s + (n-1)\Delta Q / C_1}{n} \quad \text{........(1)}$$

This equation gives the voltage imbalance across T_l. Value of C_l can be obtained as,

$$C_1 = \frac{(n-1)\Delta Q}{nV_{D_1} - V_s} \quad \text{.....(2)}$$

Derating factor of the string: The derating factor (D) indicates the amount by which string is derated. It is given by

$$\% D = \left[1 - \frac{V_s}{nV_{D_1}}\right] \times 100$$

String efficiency (n): Sting efficiency indicates the amount by which the string is utilized. It is given as,

$$\% \eta = (1-D) \times 100$$

$$= \frac{V_s}{\eta V_{D_1}} \times 100$$

Parallel Connection of Thyristors:

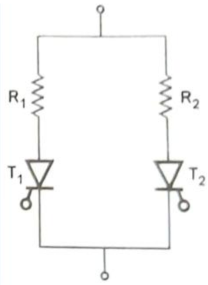
The parallel connection of thyristor is used to provide high current demands.

Problems Occurred In Parallel Connection: The devices used in parallel connection do not have exactly similar characteristics. The thyristor carrying higher current will have more power dissipation. This will increase its temperature and reduce the internal resistance. Therefore the current further increases. This process continues till thyristor damages.

Equalizing Arrangements:

Heat sharing can be done by using common heat sinks for all the devices. This will maintain all the devices at same temperature.

Static Current Sharing: Two resistors connected in series with the thyristors. R_1 and R_2 try to equalize the currents through T_1 and T_2. But power dissipation in R_1 and R_2 is very high.

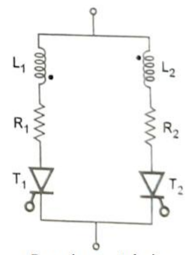


Static current sharing

Dynamic Current Sharing: The inductors are placed in series with thyristors.

These inductors are magnetically coupled. But they are connected in opposite direction.

Hence if current in T_1 tries to Increase, then a voltage of opposite polarity will be induced in L2. This Increases the current in T_2. Thus current balance is maintained.



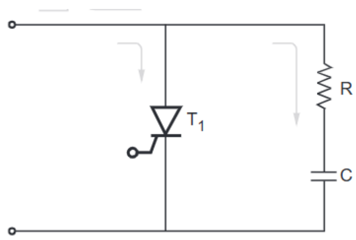
Dynamic current sharing

di/dt and dv/dt Protection:

In the power controllers, there is a chance of exceeding some rating of the device. The device and the complete controller may be damaged when such ratings are exceeded. Such fault conditions can be avoided by protecting the devices against exceeding the ratings. The current, voltage etc are regularly monitored and the device is protected by some means such as fast acting fuse, snubber, disabling the gate drives etc.

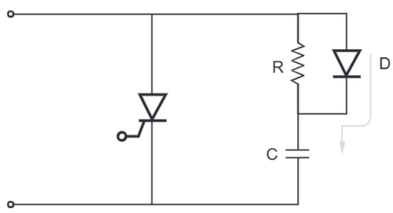
Snubber for Protection Against dv/dt and Over Voltages:

Transient Voltage: The transient over voltages can switch on the thyristor. In some cases the thyristor can be damaged due to these transient voltages. These transient voltages are very common when the converter is having inductive loads. The thyristors can be protected against transient voltages by a RC network as shown in Fig. This RC network is connected in parallel across the thyristor. It is called snubber circuit. The resistance has the value of few hundred ohms. Whenever there is a large spike or voltage transient across the thyristor, it is absorbed by the RC circuit. The RC circuit (snubber) acts as a lowpass filter for this voltage transient. The resistance has normally low value so that the transient is absorbed by the capacitor quickly. Thus the thyristor is protected against voltage transients. The RC snubber circuit is very commonly used for protection of thyristors against transient voltages.



A snubber (RC) network is used for transient voltage protection

dv/dt: dv/dt also generates large voltage transients. These rapid voltage variations can also be suppressed by snubber circuit. The capacitor acts as a short for these dv/dt variations. The snubber can be made more effective by connecting a diode across the resistance as shown in Fig.



Snubber is used for dv/dt protection

In case of voltage transient, the current flows through diode and capacitor. The capacitor acts as a short for the voltage transient. Thus it is suppressed. When thyristor turns-on, the capacitor discharges through resistance R. The R, C and diode snubber is more commonly used because it is very effective for dv/dt and other voltage transients.

Design of snubber:

The value of capacitor is given as,

$$C = \frac{1}{2L}\left(\frac{0.564\, V_m}{\frac{dv}{dt}}\right)^2 \qquad \text{......(1)}$$

Here V_m is the peak value of supply voltage

$\frac{dv}{dt}$ is the permissible $\frac{dv}{dt}$.

L is the source inductance.

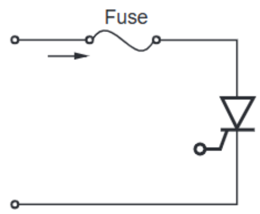
And resistance is given as,

$$R = 2\sigma\sqrt{\frac{L}{C}} \qquad \text{.......(2)}$$

Here σ is the damping factor. It's value is normally taken as 0.65.

Overcurrent Protection:

The over currents flow in the thyristor circuits due to short circuits. The short circuits can take place because of short circuited load, misalignment of firing pulses failure of the thyristors due to over voltages etc. The short circuit currents can be protected automatically because of load or supply transformers appear in the circuit. However the thyristors must be protected against over currents in the circuit. Normally fast acting fuse are used for the protection of thyristor against over currents. These fuses melt at comparatively lower currents than current rating of the thyristor. Thus fuse melts and disconnects the circuit and the thyristor is protected. This is shown in Fig. The fuse should be selected such that it should not melt or disconnect the circuit at normal load currents.



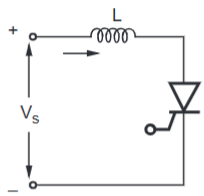
Fast acting fuse is used to protect thyristor against overcurrent

di/dt Protection:

At the time of turn-on, anode current increases rapidly. This rapid variation of anode current does not spread across the junction area of the thyristor. This creates the local hot-spots in the junction and increases the junction temperature. If the junction temperature exceeds permissible value, then the thyristor is damaged.

The rapid variations of the thyristor current are also called di/dt. Every thyristor has maximum permissible value of di/dt.

The thyristor can be protected from excessive di/dt by using an inductor in series as shown in Fig. The inductance opposes for rapid current variation di/dt. Whenever there is rapid current variation, the inductor smooths it and protects the thyristor from damage.



An inductance in series with the thyristor provides protection against di/dt

The value of inductance can be calculated as,

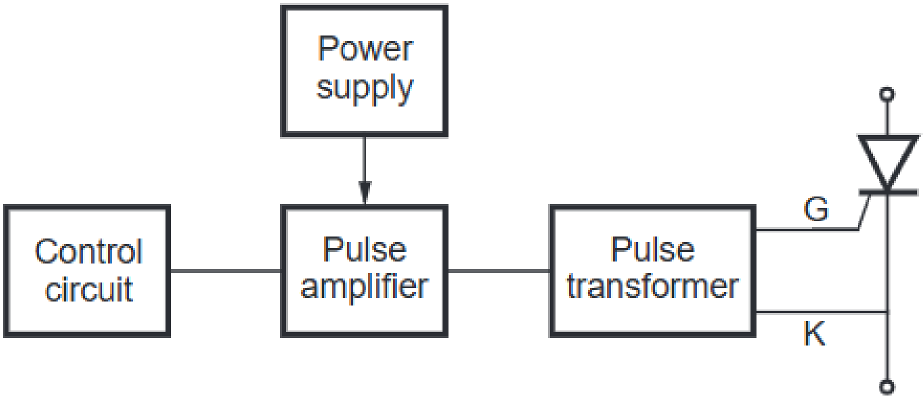
$$L \geq \frac{V_s}{\frac{di}{dt}}$$

Here di/dt is the maximum value and L is the series inductance including stray inductance.

Firing Circuits:

1. Forward break over voltage
2. dv/dt triggering
3. Exceeding internal device temperature
4. Focusing light beam on the junction
5. Gate triggering.

Features of Firing Circuits: The triggering circuits are called firing circuits. The following features must be fulfilled by the firing circuit.



Main blocks of firing circuit

1. The firing circuit should produce the triggering pulses for every thyristor at ppropriate instants.
2. The triggering pulses generated by the control circuit need to be amplified and passed through the isolation circuit. The triggering pulses generated by the control circuit have very small power. Hence their power is increased by pulse amplifier. Fig. shows the scheme. The firing circuit operates at low voltage levels (5 to 20 volts). And the thyristor operates at high voltage levels (greater than 250 volts). Hence there must be electrical isolation between firing circuit and thyristor. This isolation is provided by the pulse transformer or optocouplers.

R-Firing Circuit:

Fig. 1 shows the simple R-firing circuit.

The resistance R_{min} is used to limit the gate current to its maximum value. If $I_{g(max)}$ is maximum gate current and V_m is the peak supply voltage, then R_{min} will be,

$$R_{min} \geq \frac{V_m}{I_{g(max)}}$$

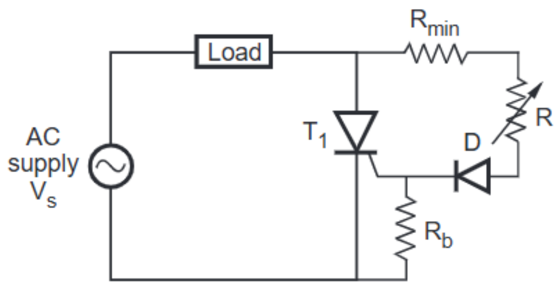


Fig. 1 R-firing circuit

The resistance R_b is the stabilizing resistance. The voltage across R_b should not exceed minimum gate voltage $\left(V_{g(min)}\right)$, otherwise thyristor will turn-on directly.

Then the variable resistance R is used to trigger the thyristor T_1. When 'R' is zero, the triggering angle is minimum. The triggering angle increases as value of 'R' is increased. Fig. 2 shows the waveforms of this circuit.

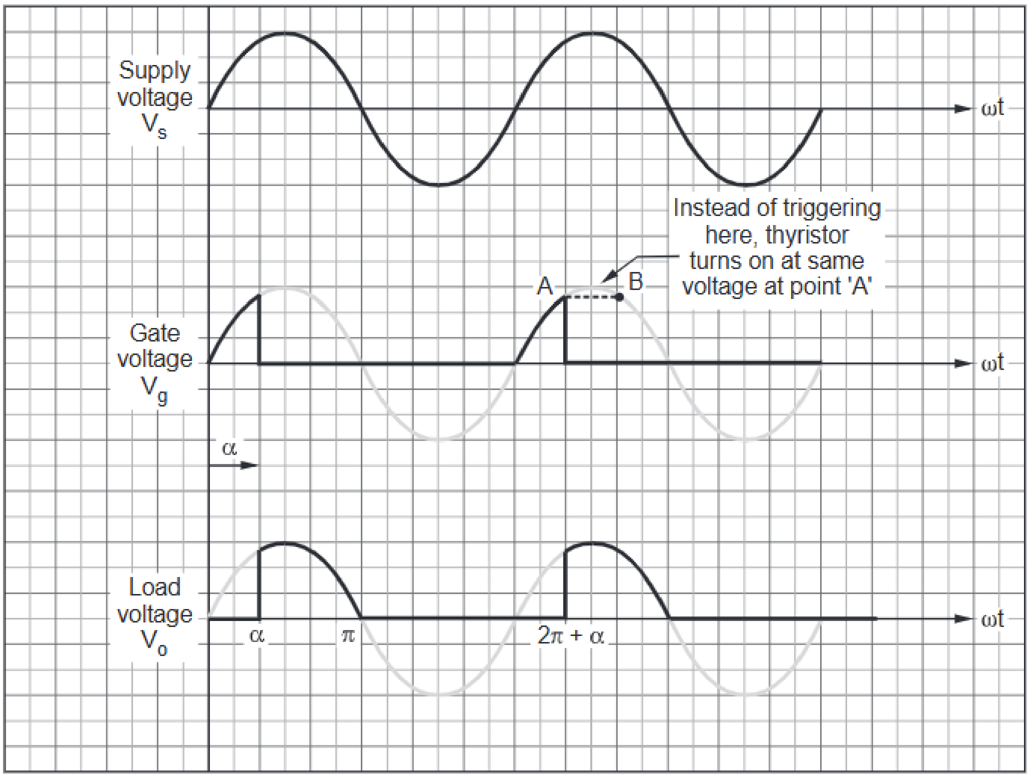


Fig. 2 Waveforms of R-firing circuit

The anode to cathode voltage and the gate current are in phase. Hence the triggering angle of T_1 cannot be delayed beyond 90°. In the above waveforms, observe that at points 'A' and 'B' gate voltage is same.

If it is desired to trigger thyristor at point 'B', similar voltage appears at point 'A'. Hence thyristor will turn-on at point 'A' only. Hence maximum triggering angle will be 90°. This is because the gate current and anode voltage are in phase.

RC Firing Circuit:

Fig. 1 shows the circuit diagram of RC firing circuit. In the negative half cycle, the capacitor charges through diode D_2 to negative supply voltage. The capacitor charges to $-V_m$ (i.e. negative peak) of the supply. This is shown in waveforms of Fig. 2 The capacitor then discharges (i.e. charges towards positive) through resistance R during the positive half cycle of the supply. The thyristor triggers when capacitor charges to value greater than $v_{g(\min)}$. Observe the capacitor voltage and load voltage waveforms in Fig. 2 The diode D_1 prevents the negative capacitor

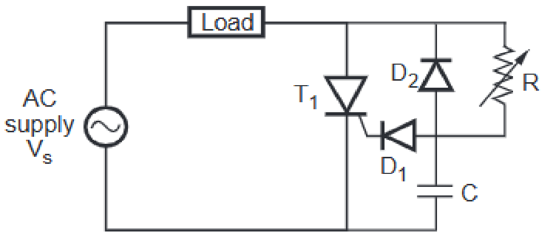


Fig. 1 RC half wave firing circuit

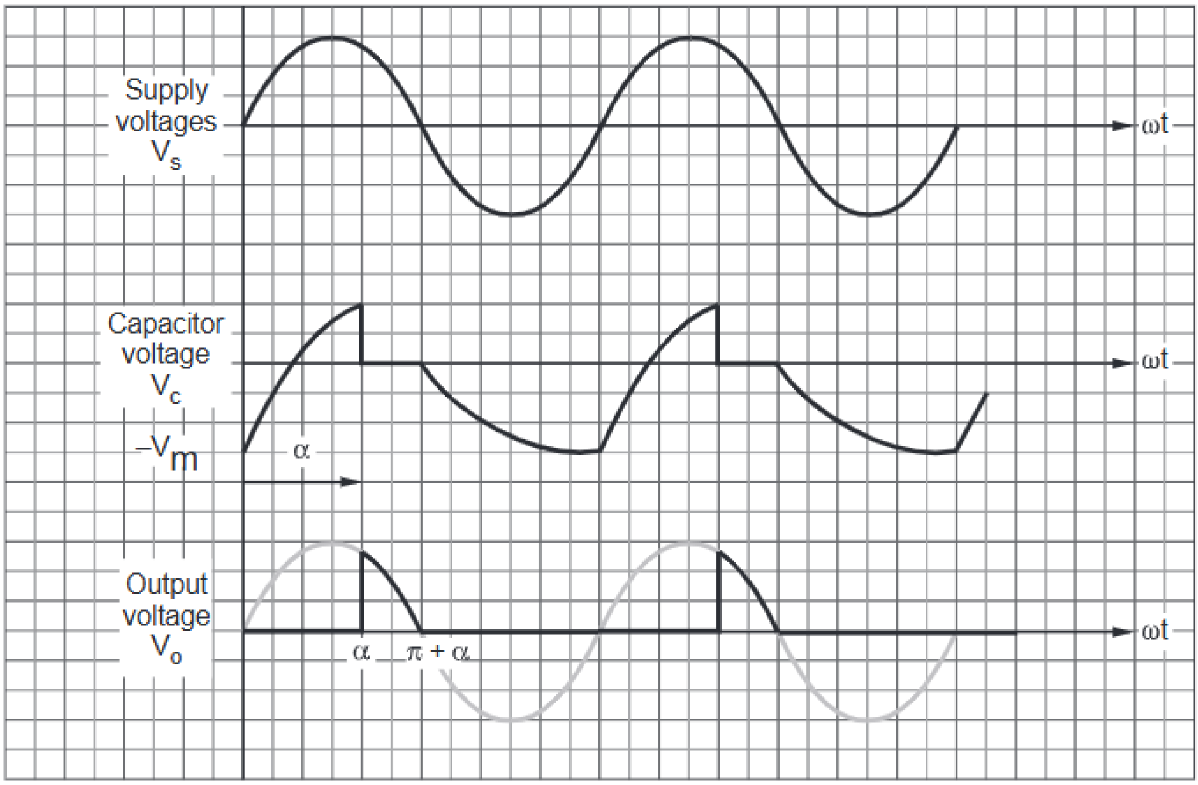


Fig. 2 Waveforms of half wave RC firing circuit

voltage appearing to gate of the thyristor. The triggering angle can be controlled from 0 to 180°. For zero output (i.e. maximum firing angle), the following relation holds :

$$RC \geq \frac{1.3}{2f} \quad ....(1)$$

Here f is the supply frequency. Since triggering is controlled only in one half cycle of the supply, this circuit is also called *half wave RC firing circuit.*

Full Wave RC-Firing Circuit:

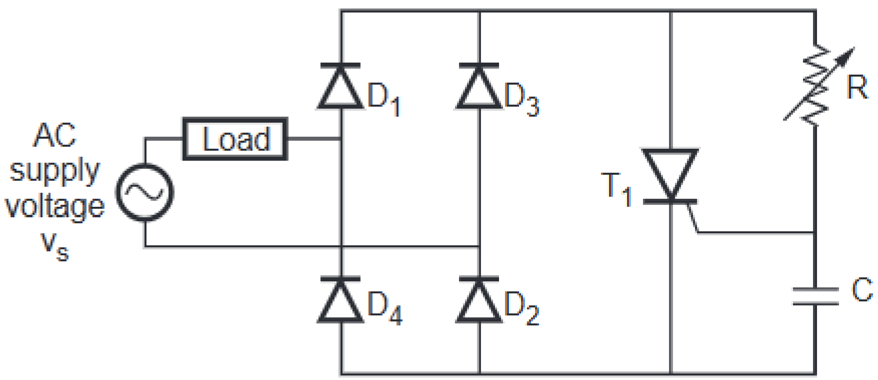


Fig. 1 Full wave RC firing circuit

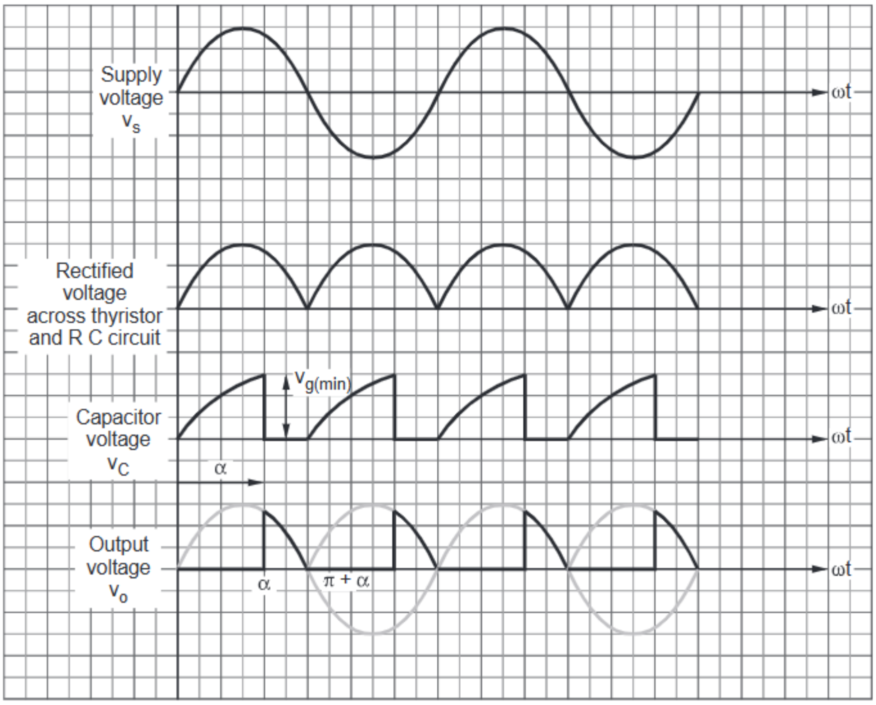


Fig.2 Waveforms of full wave RC firing circuit

Fig. 1 shows the full wave RC firing circuit. The supply to the thyristor is given through the uncontrolled rectifier. Hence both the half cycles are positive half cycles to the thyristor. The capacitor starts charging in every half cycle at the begining. Whenever the capacitor voltage reaches to the value greater than $v_{g(min)}$, the thyristor turns-on. Fig. 2 shows the waveforms of this circuit. Once the thyristor turns-on, the capacitor voltage is clamped to zero, till next half cycle. The capacitor again starts charging from zero. The firing angle can be varied from 0 to 180°. The triggering is controlled in both the cycles. The following relation holds for maximum firing angle,

$$RC \geq \frac{0.157}{2\pi f} \quad ....(1)$$

Here f is the frequency of the supply.

UJT Triggering Circuit:

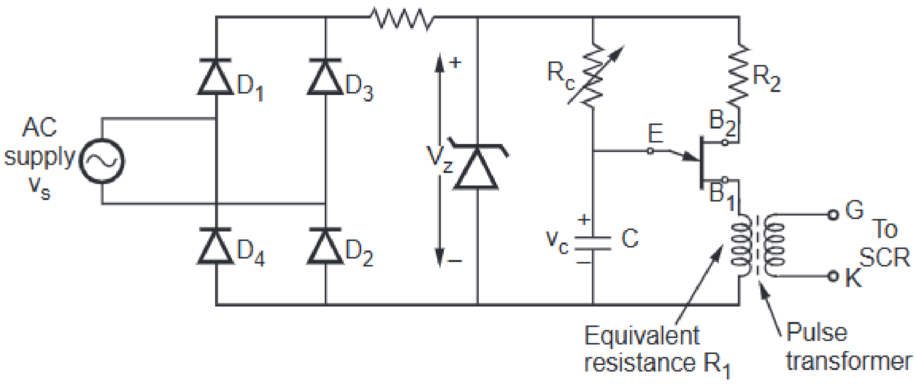


Fig. 1 UJT triggering circuit

Fig. 1 shows the circuit diagram of UJT triggering circuit. The supply voltage is rectified and given to the Zener regulator. The voltage of zener diode is V_Z. The zener diode clamps the rectified voltage to V_Z as shown in the waveforms of Fig. 2. Hence voltage Vz is applied to the UJT circuit.

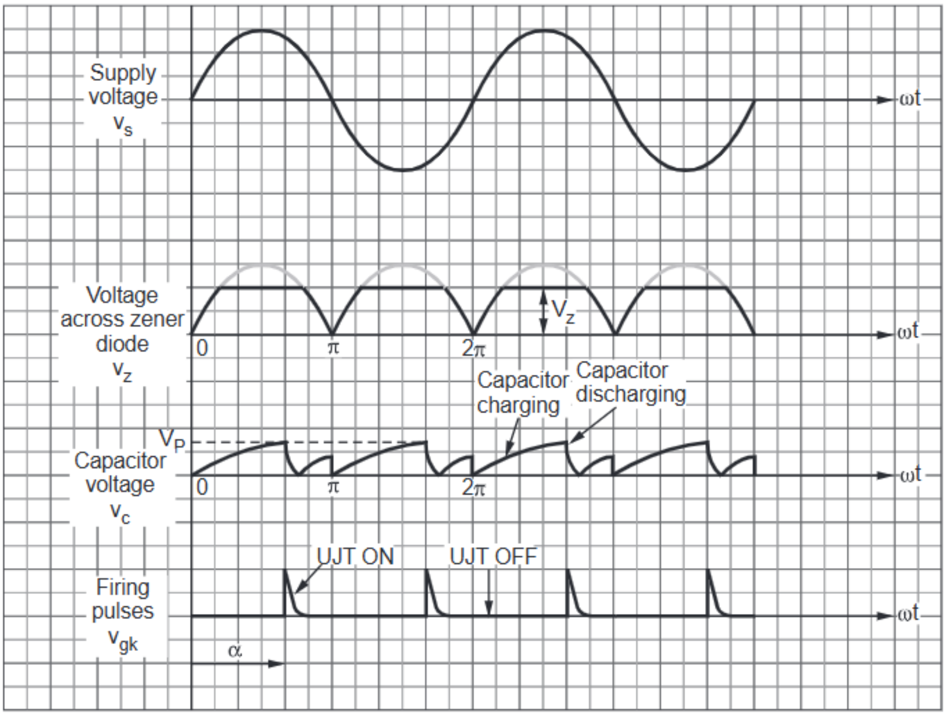


Fig. 2 Waveforms of UJT triggering circuit

The capacitor charges through resistance Rc. When the capacitor voltage becomes equal to Vp, the peak voltage of the UJT, it turns-on. The capacitor discharges through emitter (E), base (B_l) and primary of pulse transformer. The UJT is turned-on when the capacitor discharges. Since current flows through the primary of pulse transformer, a pulse is generated. This pulse as shown in Fig.1 is the gate triggering pulse. When the capacitor discharges to a voltage called valley voltage (Vv), the UJT turns-off and capacitor again starts charging. This mode of working of UJT is called relaxation oscillator. The delay angle 'α' is the angle when first triggering pulse is generated in the half cycle. The charging of the capacitor can be varied by resistance Rc. Hence delay angle can also be varied. The UJT trigger circuit has the firing angle range from 0 to 180^0.

The zener voltage acts as a supply voltage for UJT relaxation oscillator. This voltage becomes zero at 0, π, 2π, 3π,....etc. The capacitor voltage also becomes zero at these instants. Thus synchronization with zero crossings is achieved. The UJT trigger circuit can be used to trigger SCRs in 1Ø converters, 1Ø AC regulators etc.

Mathematical analysis:

The peak voltage at which UJT turns on is given as,

$$V_p = \eta V_{BB} + V_D \qquad \cdots 1$$

Here V_p is the peak voltage

V_{BB} is the supply voltage of UJT circuit

V_D is forward drop of UJT

η is intrinsic standoff ratio.

The intrinsic standoff ratio (η) depends upon the UJT. The period of oscillation of the UJT relaxation oscillator is given as

$$T = R_c C \ln\left(\frac{1}{1-\eta}\right) \qquad \cdots (2)$$

Fig. 3 shows the waveforms of free running UJT relaxation oscillator. The capacitor voltage waveform and UJT output are shown in the above figure. From Fig. 2, it is clear that triggering angle will be,

$$\alpha = \omega T$$

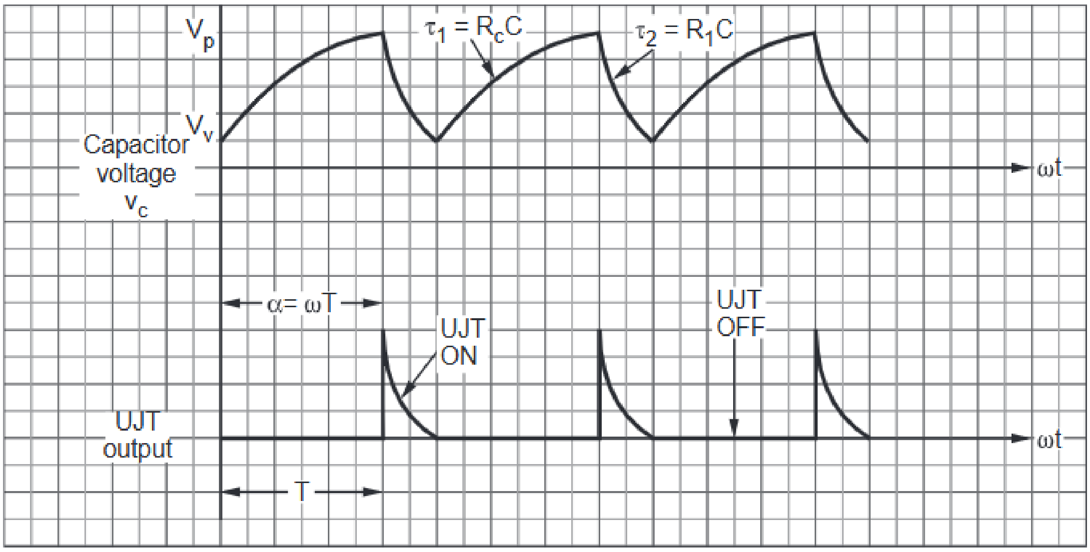


Fig. 3. Waveforms of free running UJT relaxation oscillator

Hence from equation (2) we can write,

$$\alpha = \omega R_c C \ln\left(\frac{1}{1-\eta}\right) \quad \cdots (3)$$

This equation gives firing angle of UJT triggering circuit. Here $\omega = 2\pi f$ and f is the frequency of UJT oscillator. The resistance R_2 should be selected as follows :

$$R_2 = \frac{0.7\left(R_{B2} + R_{B1}\right)}{\eta V_{BB}} \quad \cdots (4)$$

Here R_{B2} and R_{B1} are interbase resistance of the UJT. R_2 can also be calculated approximately as,

$$R_2 = \frac{10^4}{\eta V_{BB}} \quad \ldots.(5)$$

Note that this expression does not require R_{B1} and R_{B2}. Normally pulse transformer is connected at the base B_1 of UJT. Pulses are passed through pulse transformer. This provides isolation between SCR circuit and UJT triggering circuit.

The resistance of pulse transformer primary can be denoted by R_1. This resistance controls width of the triggering pulse. From Fig. 3, this width is given as,

$$\text{Width of triggering pulse, } \tau_2 = R_1 C \quad \cdots (6)$$

More accurately this pulse width will be,

$$\tau_2 = (R_1 + R_{B1})C \quad \cdots (7)$$

Here we have considered the interbase resistance R_{B1} also. If leakage current of UJT is given, then R_1 can be calculated using following equation,

$$V_{BB} = I_{leakage}(R_1 + R_2 + R_{B1} + R_{B2}) \quad \cdots (8)$$

Here $I_{leakage}$ is the leakage current of UJT.

The maximum value of R_c is given as,

$$R_{c(max)} = \frac{V_{BB} - V_p}{I_p} \quad \cdots (9)$$

and the minimum value of R_c is given as,

$$R_{c(min)} = \frac{V_{BB} - V_v}{I_v} \quad \cdots (10)$$

Here V_p is peak voltage

I_p is peak current

V_v is valley voltage

I_v is valley current