POWER ELECTRONICS

Dr Roy Sebastian K M.Sc.,B.Ed.,M.Phil.,Ph.D.

Associated Professor

St. Joseph's College

Moolamattom

Dedicated to my daughter ASHLY ROY

CHAPTER 1

THYRISTORS

Introduction

A thyristor is a four layer PNPN device. It has three PN junctions. It has two stable switching states namely the ON or conducting state and the OFF or non-conducting state. There is no other state in between these two, as in bipolar and field-effect transistors. The thyristors are used specifically for high power switching applications such as control of a.c. power to the load, motor speed control, light dimmers etc. Thyristors are not designed to be used as linear amplifying devices.

A thyristor has characteristics similar to a thyratron tube. But from the construction view point, a thyristor (pnpn device) belongs to transistor family (npn or pnp device). The name thyristor is derived by a combination of the capital letters from THYRatron and transISTOR. This means that thyristor is a solid state device like a transistor and has characteristics similar to that of thyratron tube.

The definition of thyristor as per International Electro technical Commission (IEC) is

(1) It constitutes three or more p-n junctions.
(2) It has two stable states, an ON state and an OFF state and can change its state from one to another.

Types of Thyristors

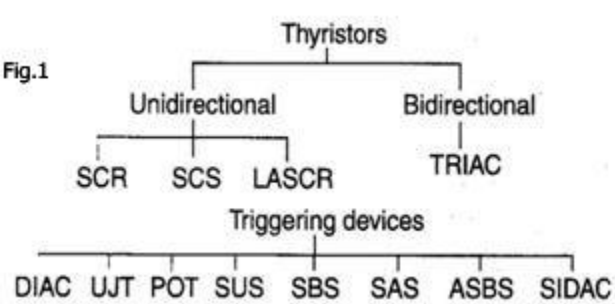
There are two main types of thyristors

1. **Unidirectional**: The thyristors which conduct in forward direction only are known as unidirectional thyristors.
   Eg: Silicon Controlled Rectifiers (SCR's), Light Activated Silicon Controlled Rectifiers (LASCR's) and Silicon Controlled Switch (SCS).

2 **Bidirectional**: The thyristors which can conduct in forward as well as in reverse direction are known as bidirectional thyristors.

Eg: Triode A.C. Switch (TRIAC)

Fig.1

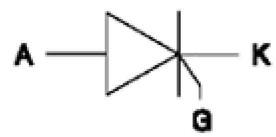


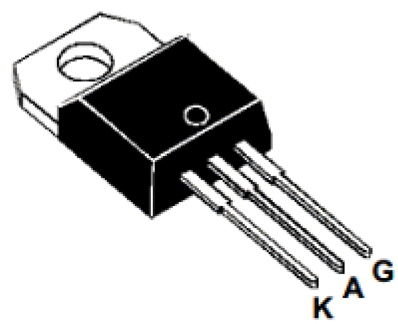
Triggering Devices

Thyristors require a control signal to switch from the non-conducting to the conducting state. The devices which generate such control signals are called triggering devices.

Eg: Diode A.C. Switch (DIAC), Unijunction Transistor (UJT), Silicon Unilateral Switch (SUS), Silicon Bilateral Switch (SBS), Silicon Asymmetrical Switch (SAS)

Silicon Controlled Rectifier (SCR)





TO220AB
(Plastic)

Silicon Controlled Rectifier (SCR) is an important semiconductor device used in industrial and power electronics field. SCR is used as a controlled switch to perform a variety of functions such as rectification, d.c. to a.c. inversion, phase control and power control. It is an important element in the control of electrical motor speed, electronic regulator of fan, electrical furnace heat, lighting etc.

An SCR is so called because silicon is used for its construction and its operation as a rectifier can be controlled. Like a diode, an SCR is a unidirectional device that blocks the current flow from cathode to anode. Unlike the diode, a thyristor also blocks the current flow from anode to cathode until it is triggered into conduction by a proper gate signal between gate and cathode terminals and the gate (G) terminal from the P2-layer.The symbol of SCR is shown in Fig.2(c).

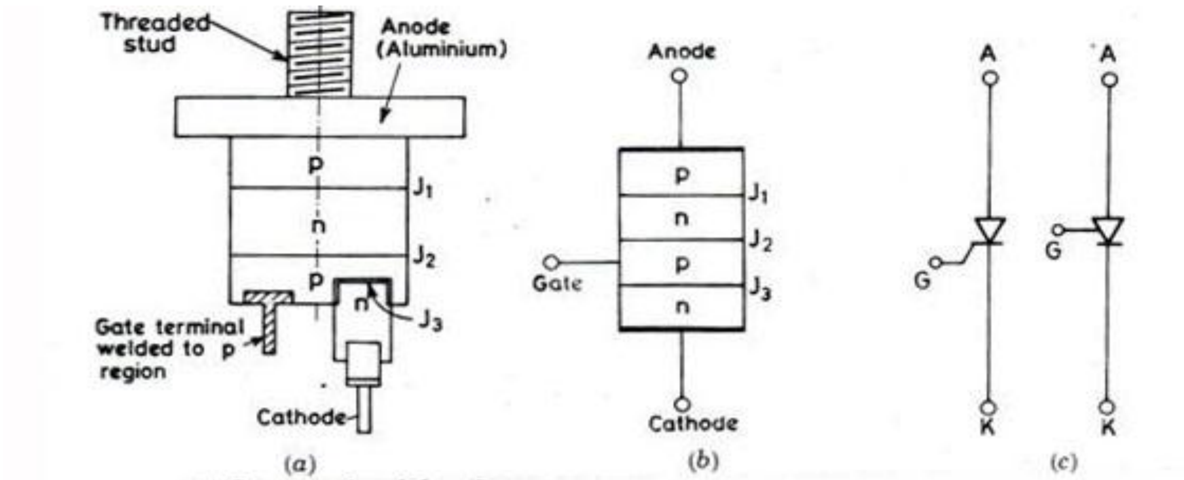


Fig.2 (*a*) Constructional details (*b*) Schematic diagram and (*c*) circuit symbol of a thyristor.

A Silicon Controlled Rectifier (SCR) consists of four semiconductor layers forming a PNPN structure as shown in Fig.2 (b). It has three PN junctions namely J1, J2 and J3. It has three terminals called anode (A), cathode (K) and the gate (G). The anode (A) terminal is taken out from the P1-layer; the cathode (K) terminal is taken out from the N2-layer

It may be noted that the SCR symbol is quite similar to that of a diode. SCR resembles the diode electrically because it conducts current in one direction only. The progression from Shockley diode to SCR is achieved with the addition of the gate (G) terminal. This gate is used to turn ON the device. If an SCR's gate is floating, it behaves exactly as a Shockley diode.

SCR Biasing

The SCR can be biased in two modes depending upon the polarity of the applied voltage across anode and cathode terminals. When the anode is positive, with respect to the cathode, the SCR is said to be forward biased as shown in Fig.3 (a).

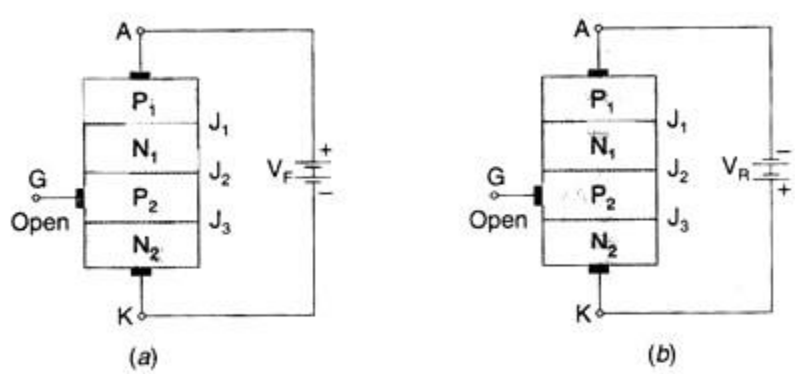


Fig.3 SCR biasing.

In this mode the junctions J1 and J3 are forward biased and the junction J2 is reverse biased. There is no current (except leakage current) through the SCR. Therefore the SCR is in 'OFF' (non-conducting) state. Under this condition the device offers a very high resistance. The value of this resistance is several megohms.

On the other hand, if the anode is negative, with respect to cathode, the SCR is said to be reverse biased as shown in Fig.3 (b). In this mode, the junctions J1 and J3 are reverse biased and the junction J2 is forward biased. Again there is no flow of current (except leakage current) through the SCR. Therefore the SCR is in 'OFF' (non-conducting) state.

SCR Operation

The SCR operation can be explained by using Fig.3 (a) and (b). When the SCR is forward biased with a small voltage it is in 'OFF' position and no current flows through the device. However, if the applied forward voltage is increased and it reaches the forward break over voltage (V_{BO}), the junction J2 breaks down. This causes the SCR to quickly switch to its 'ON' (conducting) position. Under this condition, the SCR offers very small resistance (of about 0.1 to 1.0Ω) and the voltage across it drops to a low value. The value of this voltage is about 1V. In the ON state the current through the SCR is very large and is controlled by the applied voltage and external resistance.

When the SCR is in the reverse biased condition (Fig.3b), the junctions J1 and J3 are reverse biased and junction J2 is forward biased. However, it has been found that most of the voltage will drop across junction J1 only. When the applied voltage is small, the SCR is OFF and therefore no current (except leakage current) flows through the device. If the reverse voltage is increased to reverse breakdown voltage, the junction J2 will breakdown due to avalanche effect. This causes a large current to flow through the SCR, due to which it may get damaged in the same way as the reverse biased PN-junction diode.

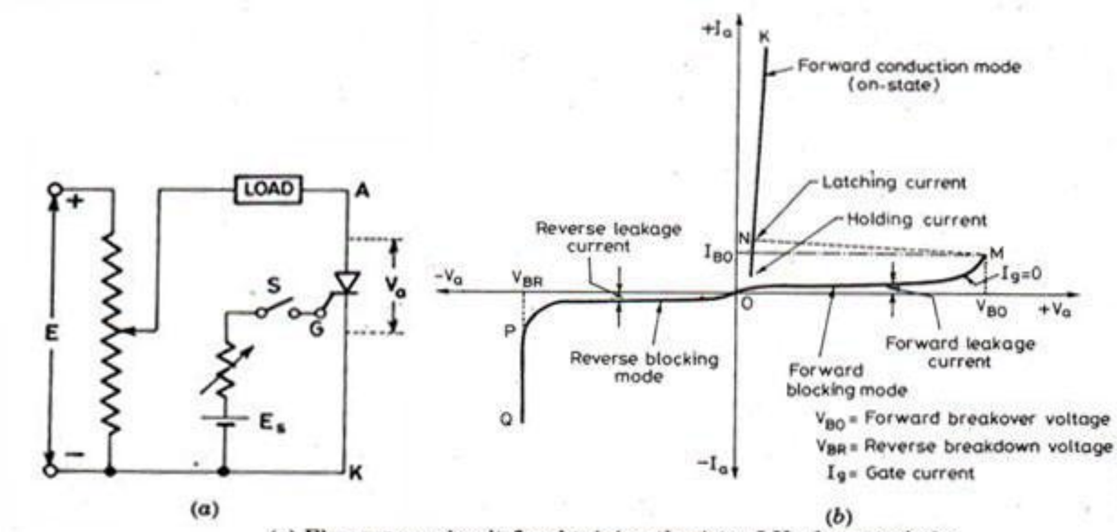
It is evident from the above discussion that SCR can be used to conduct in one forward direction only, like a rectifier diode. Therefore SCR is a unidirectional semiconductor device, which remains OFF so long as the applied anode voltage is below the break over voltage and turns ON when it exceeds the breakover voltage.

It will be interesting to know that SCR is never operated with the anode to cathode voltage equal to the forward breakover voltage. In fact, it is operated at a supply voltage much smaller than the forward breakover voltage. In that case SCR is turned ON by the gate voltage and gate current.

V-I Characteristics of SCR

It gives the relationship between the anode current and the anode-to-cathode voltage of SCR for different values of gate current. The SCR has two types of V-I characteristics namely forward characteristic and reverse characteristics.

1. Forward Characteristic



(a) Elementary circuit for obtaining thyristor I-V characteristics
(b) Static I-V characteristics of a thyristor.

Fig.4

The forward characteristic of SCR may be obtained by using the circuit shown in Fig. 4(a). Adjust the gate current to zero value by keeping the switch (S) open. Then increase the applied voltage across the SCR in small suitable steps. At each step, record the value of anode current. Plot a graph with anode-to-cathode voltage (+Va) along the X-axis and the anode current (+Ia) along the Y-axis.

This characteristic consists of the following regions

(a) **Forward Blocking Region (mode)**: (OM) The anode is positive but the anode voltage is less than break over voltage V_{BO}. In this condition the junctions J1 and J3 are forward biased and the junction J2 is reverse biased. A forward leakage current flows but the thyristor is not conducting and it offers a very high resistance. Therefore, a thyristor can be treated as an open switch even in the forward blocking mode.

(b) **Forward Conducting Region**: (NK) As the anode-to-cathode voltage exceeds the break over voltage V_{BO} the SCR turns ON and the anode-to-cathode voltage decrease quickly to a value marked by point N. At this stage, the current through the SCR increases rapidly to a large value, which is determined by the supply voltage and the value of load resistance in the circuit. The current must be more than the latching current I_L. If the current is reduced to less than holding current I_H, the thyristor switches back to forward blocking state. A thyristor can be brought from forward blocking mode to forward conduction mode by turning it on by applying (i) a positive gate pulse between gate and cathode or (ii) a forward break over voltage across anode to cathode.

Forward conduction mode NK shows that voltage drop across thyristor is of the order of 1 to 2 V depending upon the rating of SCR. It may be seen from NK that voltage drop across SCR 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 (VT) across the device is due to ohmic drop in the four layers. In forward conduction mode, thyristor is treated as a closed switch.

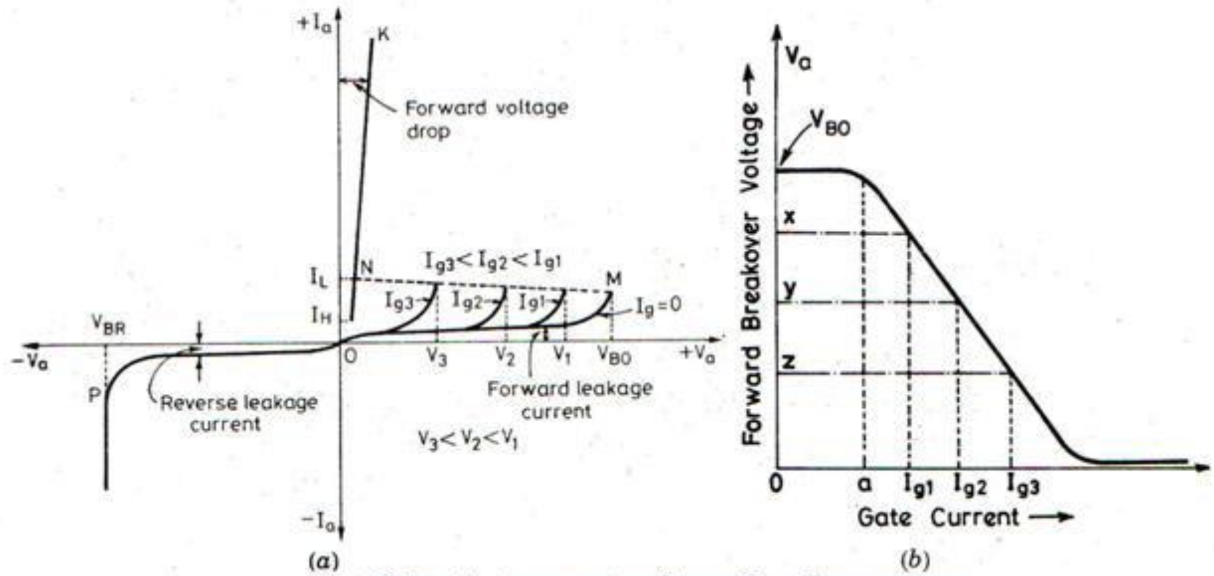


Fig.5 Effect of gate current on forward breakover voltage.

As the value of gate current (Ig) is increased above zero, the SCR turns ON at a lower break over voltages as shown in Fig. 5(a).

Reverse Characteristic of SCR

a. **Reverse Blocking Region**: (OP) Under this condition the cathode is positive with respect to anode. A small reverse current flows. The SCR is OFF and it offers a very high resistance.

b. **Reverse Avalanche Region**: (PQ) As the applied reverse voltage in increased, above the breakdown voltage, the reverse current increase more rapidly as shown by the curve PQ in Fig.4(b). This rapid increase is because of the avalanche breakdown of SCR and may damage the device if the current exceeds the rated value. The region PQ is called the reverse avalanche region.

VBR and VBO

The magnitude of forward breakdown and reverse breakdown voltages are nearly the same and both are temperature dependent. In practice, it is found that VBR is slightly more than VBO. Therefore, forward breakdown voltage is taken as the final voltage rating of the device during the design of SCR application.

Variation of Breakover voltage with gate current

When positive gate current is applied, gate P-layer is flooded with electrons from the cathode. This is because cathode N-layer is heavily doped as compared to gate P-layer. As the thyristor is forward biased, some of these electrons reach Junction J2. As a result, width of depletion layer near junction J2 is reduced. This causes the junction J2 to breakdown at an applied voltage lower than the forward breakover voltage VBO. If magnitude of gate current is increased, more electrons would reach junction J2, as a consequence thyristor would get turned ON at a much lower forward applied voltage. That is the breakover voltage decreases with increase in gate current.

Latching current and Holding current

Latching current (I_{L}) may be defined as the minimum value of anode current which it must attain during turn-ON process to maintain conduction when gate signal is removed.
Holding current (I_H) may be defined as the minimum value of anode current below which it must fall for turning OFF the thyristor.

Turning ON (or Triggering) SCR

There are different methods to turn ON an SCR. Turning ON is also known as triggering. The various triggering methods are: (a) voltage triggering (b) gate triggering (c) dv/dt triggering (d) high temperature triggering and (e) light triggering.

(a) **Voltage Triggering:** If the voltage across the SCR exceeds the rated forward break over voltage V_{BO}, the SCR will start conducting due to avalanche breakdown. A high forward voltage may destroy the thyristor. Therefore, this method is never used in actual practice.
(b) **Gate Triggering**: This is the most commonly used method to trigger the SCR. In this method, the SCR is operated with an anode voltage less than the rated forward break over voltage and is triggered into conduction by a low power gate pulse. It may be noted that once the SCR is switched ON, the gate has no further control on the device current. The gate pulse signals can be supplied either from a d.c. source or an a.c. source.

Because of gate current charges are injected into P_2 layer (Fig.3b). Higher the magnitude of gate current, greater is the number of charges injected and lower is the forward break over voltage. Fig 5(a) shows the variation of forward break over voltage with the magnitude of gate current.

Once the SCR is conducting a forward current, reverse biased junction J2 no longer exists. As such, no gate current is required for the device to remain in ON state. Therefore, if the gate current is removed, the conduction of current from anode to cathode remains unaffected. However, if gate current is reduced to zero before the rising anode current attains a value, called the latching current, the thyristor will turn OFF again. The gate pulse width should therefore be judiciously chosen to ensure that anode current rises above the latching current. Thus **latching current** (I_L) may be defined as the minimum value of anode current which it must attain during turn ON process to maintain conduction when gate signal is removed.

Once the thyristor is conducting, gate loses control. The thyristor can be turned OFF only if the forward current falls below a low-level current called the holding current. Thus **holding current** (I_H) may be defined as the minimum value of anode current below which it must fall for turning OFF the thyristor. The latching current is higher than the holding current. Note that latching current is associated with turn ON process and holding current with turn OFF process. It is usual to take latching current as two to three times the holding current. In industrial applications, holding current (typically 10mA) is almost taken as zero.

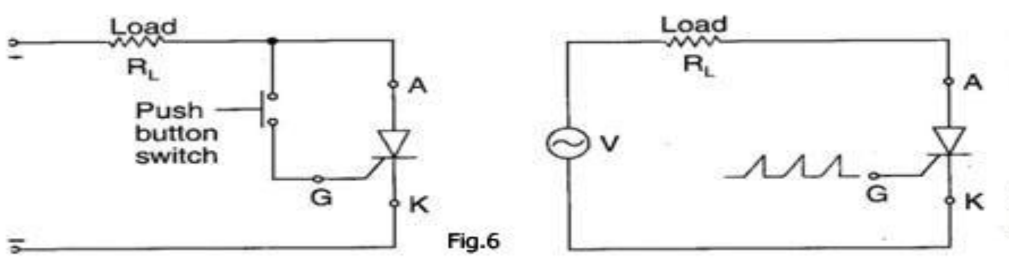


Fig. 6 (a) Triggering SCR from d.c. source (b) Triggering SCR from pulses

Figure 6(a) shows an SCR connected to the d.c. source through a load. In this case, the gate signal is generated by a push button switch. When the switch is pressed, momentarily, a positive voltage is applied at the gate. As a result of this, the SCR is turned ON, and the current flows through the load. The SCR will remain in its ON position, until the supply voltage is removed or reversed.

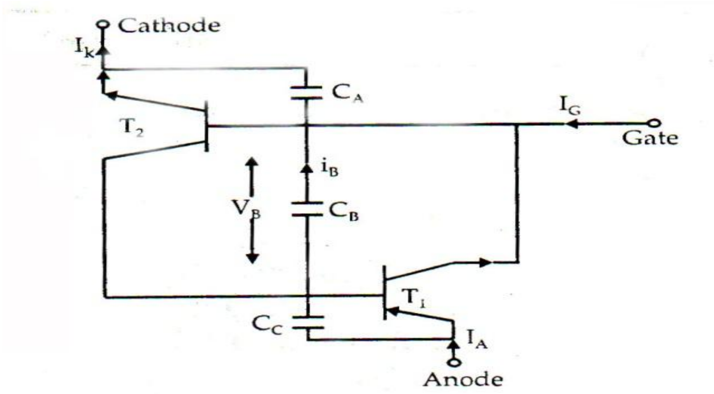
Figure 6(b) shows an SCR connected to the a.c. source through a load. In this circuit, the gate signal is provided by the timing pulses. Such pulses can be generated by a number of devices called triggering devices. Such devices are UJT, DIAC, and SUS etc.

(c) **Rate-effect or dV/dt triggering**: The reverse biased junction in the thyristor behaves like a capacitor. If a rapidly changing forward voltage is applied, a charging current flows. This charging current i_B can be written as

$$\mathbf{i_B = C_B(dV_B/dt)}$$

If dV_B/dt is high, the charging current i_B would be large. This means that the forward leakage current of collector-base junction would be high and may turn on the thyristor. This is known as dv/dt triggering. This method of triggering is not desirable because a high charging current i_B may damage the thyristor.

Junction capacitance in a thyristor



Junction capacitances in a thyristor.

The junction capacitances affect the thyristor characteristics under transient conditions. Let the thyristor be in forward blocking state. The current i_B is

$$i_B = V_B\frac{dCB}{dt} + C_B\frac{dVB}{dt}$$

If dv/dt is high, current i_B would be high. This would result in an increase in leakage current I_{CBO1} and I_{CBO2} and cause the thyristor to turn ON.

(d) **High Temperature triggering**: As the temperature of a p-n junction increases, the width of depletion layer decreases. This is due to the reason that the number of electron-hole pairs is increased and the leakage current increases. At a certain temperature the reverse biased junction may breakdown and the thyristor starts conducting. High temperature triggering may cause thermal run away and is generally avoided.

(e) **Light triggering**: In this method the SCR is triggered by irradiating it with light. When the light falls on the middle junction (J2) of the SCR, the device turns ON due to increase in the number of electron hole pairs. This method of triggering is used in Light-Activated Silicon Controlled Rectifier (LASCR) and light activated silicon controlled switch (LASCS).

Example 1: A thyristor can be triggered if dv/dt is 190 V/µs. If the capacitive current flowing through the junction is 8mA, find the equivalent capacitance of depletion layer.

Solution: $I_C = C\ dv/dt$ or $8 \times 10^{-3} = C \times 190 \times 10^6$

Or $C = 42.1 \times 10^{-12}F$

Turning OFF SCR

Once the SCR turns ON it continues to conduct even when the gate is removed. This ability of the SCR to remain conducting, even when the gate signal is removed, is known as latching. It means that SCR cannot be turned OFF simply by removing the gate signal. The following are the methods to turn OFF the SCR

1. Reversing polarity of anode-to-cathode voltage.
2. Interrupting anode current by means of momentarily series or parallel switching arrangement. This method is known as anode current interruption.
3. Reducing the current through SCR below the holding current. This method is known as forced commutation.

Two Transistor model of SCR

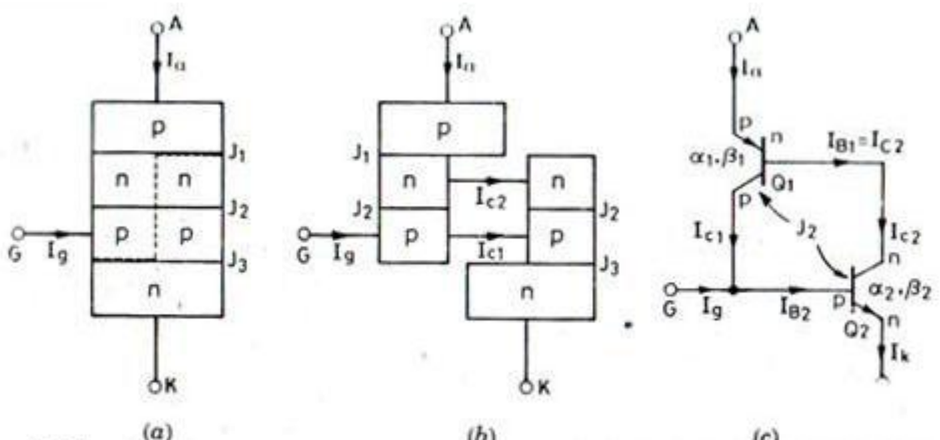


Fig.7 Thyristor (a) its schematic diagram, (b) and (c) its two-transistor model.

If IE1 and IB1 are the emitter current and base currents respectively of the PNP transistor; IA and IK are the respective anode current and cathode current of the SCR. IC1 and IC2 are the collector currents of PNP and NPN transistors respectively. IG is the gate current of the SCR. Let α1 and α2 are the fraction of holes and electrons injected from anode and cathode on junction J2 respectively. Neglect leakage currents we have

$IB_1 = IA - IC_1 = IA - \alpha 1 IA = (1-\alpha 1)IA$ (1)

Also $IC_2 = \alpha 2 IK$

And $IB_1 = IC_2$

Or $(1-\alpha 1)IA = \alpha 2 IK$ (2)

Or $\frac{(1-\alpha 1)IA}{\alpha 2}$ = IA + IG since IK = IA + IG

Or (1-α1)IA = α2(IA + IG)

Or IA = $\frac{\alpha 2 IG}{1-(\alpha 1+\alpha 2)}$ (3)

From equation (3) it is clear that if α1 + α2 become equal to unity, then anode current IA attains infinite value. In other words, the device suddenly latches into conduction state from the original non-conducting state. If the gate current IG is of such a magnitude that α1 + α2 = 1, the SCR will be triggered.

When (α1 + α2) becomes appreciably less than unity, the anode current IA, according to equation (3) becomes extremely small and the device is said to be OFF or non-conducting state. On the other hand with (α1 + α2) =1, the current is extremely large and the device is said to be in the ON or conducting state. In conducting state, the voltage drop across the device drops to a low value and large current flows through it, limited only by the resistor R in the external circuit. Thus the existence of the device either in the ON state or in the OFF state depends on the applied voltage and the gate current.

Example 2: The following data is available for an SCR:

Gain of NPN transistor of two transistor model = 0.4

Gain of PNP transistor of two transistor model = 0.35

Gate current = 40mA, neglect leakage current. Find anode current.

Solution: Given α1 = 0.35 and α2 = 0.4, IG = 40mA = .04A

$$I_A = \frac{\alpha 2 IG}{1-(\alpha 1+\alpha 2)} = \frac{0.4\times .04}{1-(0.4+0.35)} = 64 \times 10^{-3} A$$

Trigger Current and Trigger Voltage

To trigger an SCR, a proper voltage has to be applied to the gate. For most SCR's the gate voltage required for triggering is about 0.7V. A certain minimum current must also flow in the gate circuit for triggering to take place. The values of trigger voltage and current are given in manufacturer's data sheets.

The actual source voltage needed for triggering depends on the gate circuit. In Fig. 8 the gate current I_G flows through a resistance R_G. It is seen that

$V_S = V_G + I_G R_G$

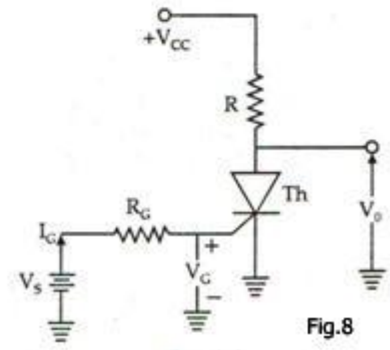


Fig.8

In some circuits the resistance R_G is not used. In that case R_G is the Thevenin resistance of the circuit driving the gate. Thyristor turns ON when V_G is more than the trigger voltage. Once the thyristor has turned ON it cannot turn OFF even if the gate voltage is reduced to zero. The only way to turn it OFF is to reduce its current to less than the holding current. This can be done by increasing the resistance R or by reducing V_{CC} to a very low value.

Example 3: In the circuit of Fig .8 the thyristor has a trigger voltage of 0.75V and a trigger current of 7mA. The holding current is 5mA. Find (a) The output voltage when thyristor is in OFF state, (b) the voltage V_S necessary to turn ON the thyristor, (c) To what value should V_{CC} be reduced to turn OFF the thyristor if thyristor is ideal, (d) To what value should V_{CC} be reduced to turn OFF the thyristor if a voltage of 0.7V exists across it when it is conducting. Assume RG = 2000Ω, V_{CC} = 20V and R = 200Ω.

Solution: (a) When thyristor is not conducting there is no current through it. Vo = 20V.

(b) $Vs = 0.75 + (7 \times 10^{-3}) \times 2000 = 14.75V$

(c) To turn off the thyristor, its current should be reduced to less than holding current when current is 5mA, voltage drop across R is $5 \times 10^{-3} \times 200 = 1V$. Hence Vcc should be reduced to less than 1V.

(d) Vcc should be reduced to less than (1 + 0.7) or 1.7V

Example 4: The gate voltage current relation for a thyristor is

$V_G = 1 + 9I_G$

The gate signal is a rectangular pulse of amplitude 25V and duration π radians during each cycle. It is desired that average gate power loss be limited to 0.6 W. Find V_G, I_G and the resistance RG to be connected in series with the gate circuit to limit the gate power loss to this value.

Solution: The voltage-current equation for the gate circuit is

$Vs = V_G + I_G R_G$

i.e. $25 = R_G I_G + 1 + 9I_G$

or $9I_G + R_G I_G = 24$

Average power loss = 0.6W

Power loss during conduction = $\frac{0.6\times 2\pi}{\pi}$ = 1.2W

1.2 = $V_G I_G = (1+9I_G)I_G$

Or $9I_G^2 + I_G - 1.2 = 0$

Or I_G = 0.314A

V_G = 1+9x0.314 = 3.826V

$R_G = \frac{24-9IG}{IG}$ = 67.43 ohms

Example 5: A dc supply of 100 V feeds an inductance of 10H through a thyristor. Find the minimum width of the gate pulse so that the thyristor is triggered. The latching current of thyristor is 80mA.

Solution: The circuit is shown in Fig. 9.

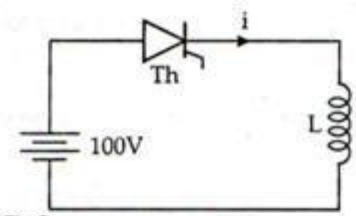


Fig.9

100 = L $\frac{di}{dt}$

Or i = $\frac{100}{10}$ t = 10t

Thyristor will trigger when I = 80mA

Therefore $t = \frac{80\times 10^{-3}}{10} = 8 \times 10^{-3}$s

Therefore width of pulse should be more than 8 milli-seconds.

Example 6: A dc supply of 100V feeds a load having a resistance of 10 ohms and an inductance of 5H through a thyristor. The latching current of thyristor is 50mA. Find the minimum width of the gate pulse.

Solution: The circuit is shown in Fig. 10. The current at any time is

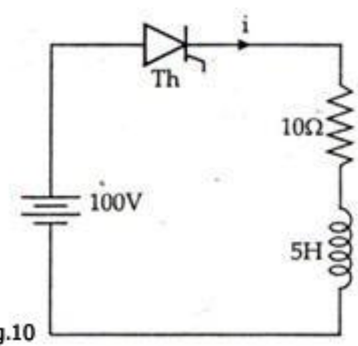


Fig.10

$i = \frac{100}{10}(1-e^{-Rt/L}) = 10(1-e^{-2t})$

Thyristor will trigger when i = 50mA

$50 \times 10^{-3} = 10\,(1-e^{-2t})$

Or e^{-2t} = 0.995

Or t = 0.0025 seconds = 2.5 milli-seconds

Hence minimum width of gate pulse is 2.5 milli-seconds.

Example 7: The latching current of the given thyristor circuit is 50mA. The duration of the firing pulse is 50µs. The values of resistor and inductor in Fig.10 are 20Ω and 0.5H respectively. Will the thyristor get fired?

Solution: As the SCR is triggered, the current will rise exponentially in the inductive circuit

$$i = \frac{V}{R}(1-e^{-Rt/L})$$

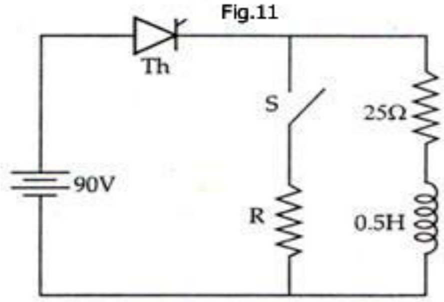
V = 100volts, R = 20Ω, L = 0.5H and t =50µs

$$i = \frac{100}{20}(1-e^{-20 \times 50\mu s/0.5}) = 9.99mA$$

Since the calculated circuit current value is less than the given latching current value of the SCR, it will not get fired.

Example 8: Figure(11) shows a thyristor circuit. Assume that switch S is open. The thyristor has a latching current of 40mA and is fired by a pulse of width 40µs.(a) Find if the thyristor will turn on (b) The switch is closed. Find the maximum value of R so that thyristor may turn on.

Fig.11



Solution: (a) switch is open. Resistance R is not in circuit.

The circuit current is

$$i = \frac{90}{25}(1-e^{-25t/0.5}) = \frac{90}{25}(1-e^{-50t})$$

At the end of gate pulse, i.e. at $t = 40 \times 10^{-6}$s

$$i = \frac{90}{25}(1-e^{-50x40\mu s}) = 0.0072A$$

Since the current is less than latching current, the thyristor will not turn on.

(b) $R = \dfrac{90}{40\times10^{-3} \;\; -0.0072} = 2744\Omega$

R should be less than 2744 ohm.

Example 9: The thyristor in figure below has a holding current of 50mA and is fired by a pulse of length 50µs. Show that without resistance R the thyristor will fail to remain ON when the firing pulse ends. Find the maximum value of R to ensure firing. Neglect voltage drop across thyristor.

Solution: Let R be infinite. The current is

$$\mathbf{i = \frac{100}{20}(1\text{-}}e^{-20t/0.5}) \quad \text{or } I = 5(1-e^{-40t})$$

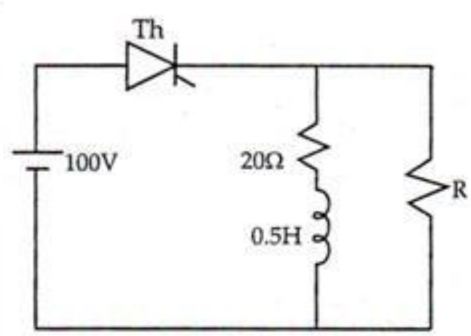


Fig.12

When firing pulse ends $t = 50 \times 10^{-6}$s

$i = 5(1-e^{-40 \times 50 \times .000001}) = 0.00999A = 9.99mA$

Since this current is less than holding current, the thyristor will not remain on and return to OFF state. To ensure that thyristor remains ON, the current through thyristor at t = 50µs should at least equal to holding current.

Current through R = 50 – 9.99 = 40.01mA = .04001A

Maximum value of R = $\frac{100}{0.04001}$ = 2499.375ohm

Example 10: Latching current for an SCR, inserted in between a dc voltage source of 200V and the load, is 100mA. Compute the minimum width of gate-pulse current required to turn ON this SCR in case the load consists of (a) L = 0.2H, (b) R = 20Ω in series with L = 0.2H and (c) R = = 20Ω in series with L = 2H.

Solution: (a) When load consists of pure inductance L, the voltage equation is

$V = L\frac{di}{dt}$ or $di = \frac{V}{L}t$ or $i = \frac{V}{L}t$

Therefore $0.100 = \frac{200}{0.2}t$ or $t = \frac{0.1 \times 0.2}{200}$ = 100µsec

Thus minimum gate pulse is 100µsec

(b) The voltage equation for R-L load is

$$V = Ri + L\frac{di}{dt}$$

Or $i = \frac{V}{R}(1-e^{-Rt/L})$ or $0.100 = \frac{200}{20}(1-e^{-100t})$

Or t = 100.503 µsec

Therefore minimum gate pulse width is 100.503µsec

(c) $i = \frac{V}{R}(1-e^{-Rt/L})$

or $0.1 = \frac{200}{20}(1-e^{-10t})$ or t = 1005.03µsec

Example 11: For an SCR the gate-cathode characteristic has a straight line slope of 130. For trigger source voltage of 15V and allowable gate power dissipation of 0.5watts, compute the gate-source resistance.

Solution: Here $V_G I_G = 0.5W$ and $\frac{VG}{IG} = 130$

Therefore $130I_G^2 = 0.5$

This gives $I_G = [0.5/130]^{1/2} = 0.062A = 62mA$

Therefore gate voltage, $V_G = 130 \times 62 \times 10^{-3} = 8.06V$

For the gate circuit, $Vs = I_G R_G + V_G = 0.062Rs + 8.06 = 15$

Or $Rs = \frac{15-8.06}{0.062} = 111.94\Omega$

Example 12: The trigger circuit of a thyristor has a source voltage of 15V and the load line has a slope of 120V per ampere. The minimum gate current to turn ON the SCR is 25mA. Compute

(a) Source resistance required in the gate circuit and
(b) The trigger voltage and trigger current for an average gate power dissipation of 0.4watts.

Solution: (a) The slope of load line gives the required gate source resistance. From the load line, series resistance required in the gate circuit is 120Ω.

(b) Here $V_G I_G = 0.4W$
For the gate circuit, $Es = RsI_G + V_G$
Therefore $15 = 120I_G + 0.4/I_G$
Or $120I_G^2 - 15I_G + 0.4 = 0$
Its solution gives $I_G = 38.56mA$ or $86.44mA$
Therefore $V_G = 0.4\times10^3/38.56 = 10.37V$
Or $V_G = 0.4\times10^3/86.44 = 4.627V$
Choose $V_G = 4.627V$ and $I_G = 86.44mA$ for minimum gate current of 25mA.

Example 13: For an SCR the gate –cathode characteristic is given by a straight line with a gradient of 20volts per ampere passing through origin. The maximum turn ON time is 4 µs and the minimum gate current required to quick turn ON is 400mA. If the gate source voltage is 15V, calculate the resistance to be connected n series.

Solution: $Es = I_G Rs + V_G$
$V_G/I_G = 20V/A$, $I_G = 400mA$
Therefore $V_G = 20 \times I_G = 20 \times 0.4 = 8V$
Therefore $Rs = \frac{Es-VG}{IG} = \frac{15-8}{0.4} = 17.5\Omega$

Thyristor Specifications and Ratings

Thyristor ratings indicate voltage, current, power and temperature limits within which a thyristor can be used without damage or malfunction. Ratings and specifications serve as a link between the designer and the user of SCR systems.

For reliable operation of a thyristor, it should be ensured that its current and voltage ratings are not exceeded during its working. One of the major disadvantages of thyristors is that they have low thermal time constant. If a thyristor handles voltage, current and power greater than its specified ratings, the junction temperature may rise above the safe limit and as a result, thyristor may get damaged. Therefore, when SCRs are selected, some safety margin must keep in the form of choosing device ratings somewhat higher than their normal working values. The manufacturers of thyristors make a comprehensive list of the voltage, current, power and temperature ratings after carefully testing the device. If SCRs are operated under these specified conditions, no damage will be done to SCRs.

A) **Anode Voltage Ratings**: A thyristor is made up of four layers and three junctions. The middle junction J2 blocks the forward voltage whereas the two end junctions J1 and J3 block the reverse voltage. The anode voltage ratings indicate the values of maximum voltages that a thyristor can withstand without a breakdown of the junction area with gate circuit open.

B) **Forward dv/dt Rating**: It is the maximum rate of rise of anode voltage which will not trigger the thyristor if the gate signal is not applied. It is evident that if actual dv/dt is more than the rated value, the thyristor may be turned ON. If rate of rise of forward anode-to-cathode voltage is high, thyristor may turn ON even when (i) there is no gate signal and (ii) anode-to-cathode voltage is less than forward break over voltage.

C) **Current Ratings**: The current carrying capacity of a thyristor is determined by the allowable junction temperature. A current higher than rated may cause a high junction temperature which may lead to damage to the thyristor. The current ratings are specified in terms of repetitive and non-repetitive values.

(i) **Average on state (forward) current (I_{TAV})**: Since the voltage drop across a conducting thyristor is low, current I_{TAV} determines the power loss in the thyristor. For the same average current but different conducting periods, the peak currents are different and therefore, the junction temperatures are different. Therefore, the permissible average current should decrease with increase in period of conduction.

(ii) **RMS on state current (I_{RMS})**: Even if the actual average value of forward current is less than the specified value, the heating may be excessive. This is because of the reason that heating depends on effective (RMS) current and not average current. Therefore, an rms value of forward current is also specified for the maximum junction temperature.

(iii) **Impulse (surge) current rating ((I_{TSM}):** In addition to rated steady state current, a thyristor is also subjected to surge current under abnormal conditions. This current is the maximum surge current (non-repetitive) which the thyristor can withstand.

The surge current, which a device can withstand, is inversely proportional to the duration of the surge. The duration of surge is specified in terms of the number of cycles of the mains frequency of 50 or 60Hz. The one cycle surge current is the peak value of allowable non-repetitive half sine wave (i.e. duration 10 ms for 50Hz frequency). For durations of less than half cycle, a sub-cycle surge current is also specified. This rating can be computed by equating the energies involved in the one cycle surge and sub-cycle surge. i.e.,

$$I_{sub}^2 t = I^2 T$$

$$\text{Or} \quad I_{sub} = I(T/t)^{1/2}$$

Where I = one cycle surge current rating, A

Isub = sub cycle surge current rating, A

T = time duration of half-cycle, Secs

t = time duration of sub cycle surge, secs

For 50Hz mains frequency we have $T = 10 \times 10^{-3}$s

$Isub = I\,(10 \times 10^{-3}/t)^{1/2} = 0.1I/\sqrt{t}$

(iv) **I^2t rating**: It is the maximum non-repetitive value of square of instantaneous current integrated over the time. Thus it indicates the energy that the device can absorb without getting damaged. It is usually specified for overloads lasting less than one half cycle. This rating is necessary to coordinate the working of the thyristor with the operation of a fast acting fuse used to protect the thyristor against overloads.

(v) **di/dt rating**: This rating indicates the maximum allowable rate of increase of anode current. When a thyristor is triggered, the conduction initially starts near the cathode and then spreads to the whole junction. If di/dt is very high, the conductivity may not be able to spread as fast and local hot spots may occur. This may raise the temperature beyond the permissible limit. The safe value of di/dt lies in the range of 50 to 800A/μ seconds.

D. **Power ratings**: Power losses within the thyristor are converted into heat and tend to increase the temperature of the junctions. The rate of dissipation of heat should be such that the junction temperature does not increase beyond the permissible value. The rate of heat dissipation depends on the surface areas and the ambient temperature. The maximum power ratings have to be specified so that abnormal temperature rise may not occur. Heat is generated due to the following losses: (a) forward conduction loss, (b) turn ON loss, (c) turn OFF loss, (d) forward blocking and reverse blocking loss and (e) gate loss.

E. **Temperature Ratings: (a) Junction temperature (Tj**): The junction temperature determines the ability of a thyristor to operate successfully. If the junction temperature goes beyond the specified value, the thyristor may start conducting even if the gate signal is not applied. The forward breakover voltage, turn OFF time and thermal stability depend on junction temperature.

(b) **Thermal resistance**: The heat dissipation from the cooling surfaces depends on the thermal resistance. It is expressed in the units of temperature difference (°C) per watt of power dissipated.

F. **Turn-ON and turn-OFF time specifications**: The selection of these quantities depends on the circuit for the particular application. Fast switching devices have very small turn on and turn off times. Such devices have higher leakage current.

Example 14: An SCR has half cycle surge current rating of 2000A for 50Hz ac. Find one cycle surge current rating and corresponding I^2t rating.

Solution: $I_{sub}^2 t = I^2T$

I_{sub} = 2000A, T = duration of half cycle = 10×10^{-3}s, t = 5×10^{-3}s

$I = \{[(2000)^2 \times 5 \times 10^{-3}]/(10 \times 10^{-3})\}^{0.5} = 2000/\sqrt{2} = 1414.2A$

I^2T rating = $(1414.2)^2 \times 10 \times 10^{-3} = 2 \times 10^4\ A^2sec$

Example 15: An SCR is subjected to 40A surge that lasts for 15ms. Determine whether or not this surge will destroy the device. The circuit fusing rating of the device is $93A^2$s.

Solution: Given I =40A and t = 15ms = 15×10^{-3}sec.

We know that $I_{sub}^2 t$ value for the SCR = $40^2 \times 15 \times 10^{-3} = 24\ A^2s$

Since this value is well below the maximum rating of 93 A^2s, therefore the device will not be destroyed.

Example 16: An SCR has a circuit fusing rating of $75A^2$s. Determine the maximum allowable duration of a 100A surge that passes through the SCR.

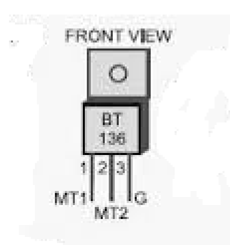
Solution: Given $I^2T = 75A^2s$ and I_{sub} = 100A

We know that maximum allowable duration, $t = I^2T/I_{sub}^2 = \frac{75}{100^2} = 7.5 \times 10^{-3}s = 7.5ms$

Applications of SCR

motor speed control, light-dimming control, heater control, phase control, battery charges, inverters, static switches, rectifier power supplies, relay control etc.

TRIAC



An SCR is a unidirectional device as it can conduct from anode to cathode only and not from cathode to anode. A TRIAC can, however, conduct in both the directions. A TRIAC is thus a bidirectional thyristor with three terminals. It is used extensively for the control of power in ac circuits. TRIAC is the word derived by combining the capital letters from the words TRIode and AC. When in operation, a triac is equivalent to two SCRs connected in antiparallel. The anode and gate voltage applied in either direction will trigger the triac. It is due to the fact that the applied voltage will trigger at least one of the

SCR's connected in opposite direction. The triacs are available with current ratings up to 300A(rms) and voltage ratings up to 1200volts.

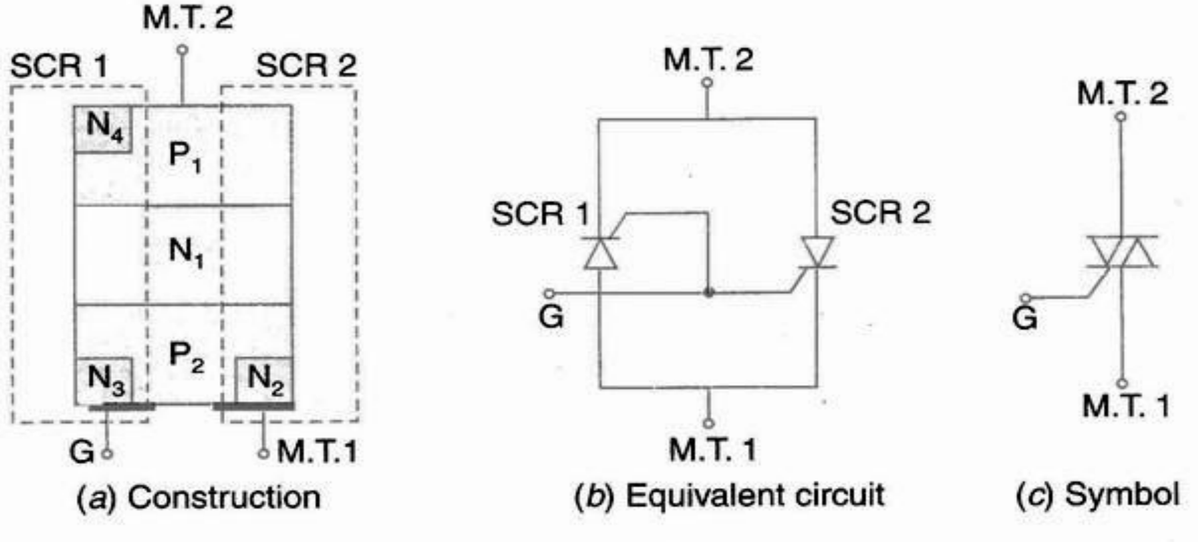


Fig.13 Triac.

The basic construction of a triac is shown in Fig.13 (a). It may be noted from this figure that the triac consists of two four layer switches in parallel. These switches are $P_1N_1P_2N_2$ and $P_2N_1P_1N_4$ as shown by the broken lines in the figure 13(a). As the triac can conduct in both directions, the terms anode and cathode are not applicable to triac. Its three terminals are usually designated as MT1 (main terminal 1), MT2 and the gate by G as in a thyristor. Figure 13(b) shows the equivalent circuit of a triac, which consists of two SCR's connected in parallel but in opposite directions with a common gate terminal. Figure13(c) shows the schematic symbol of a triac.

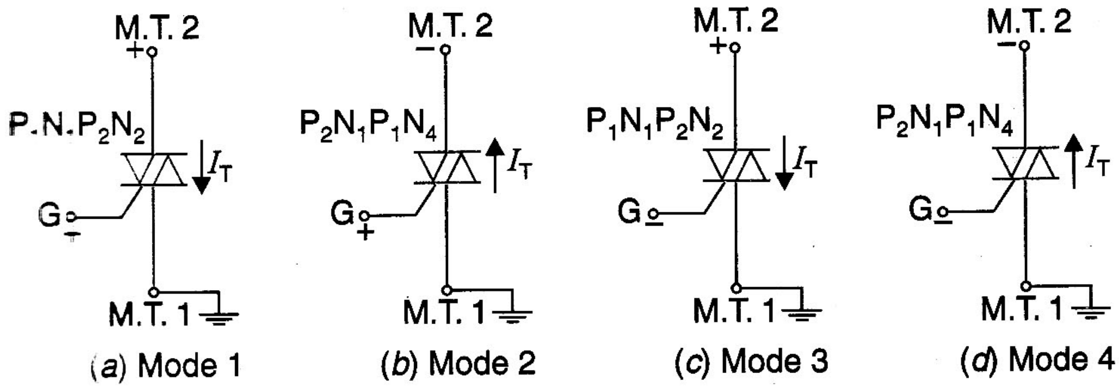
Triac Operation

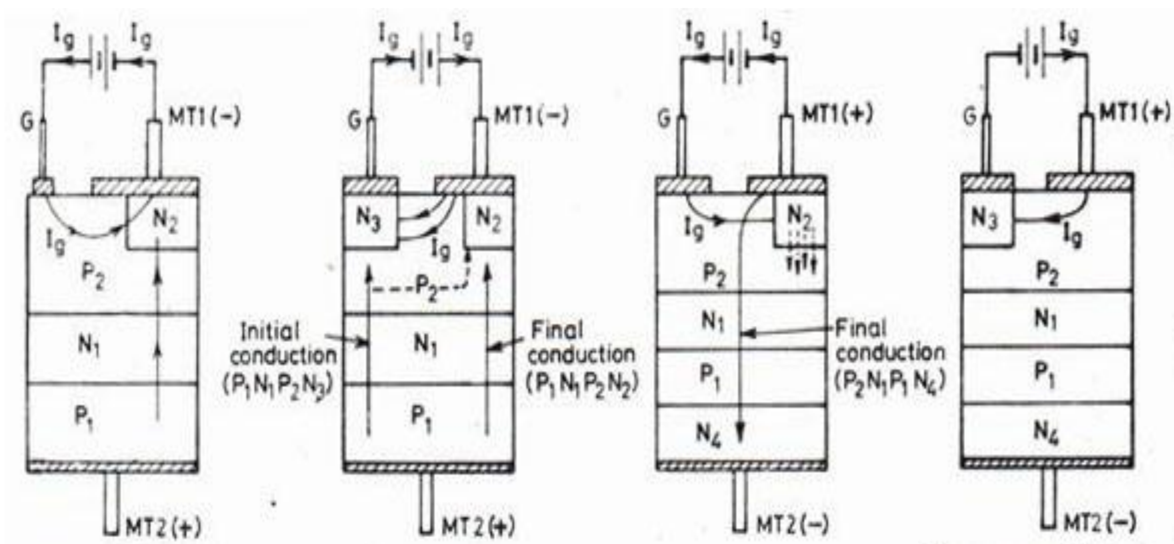
There are four modes of triac operation, depending upon the polarity of voltage across its main terminals and gate terminal. These modes are described as below:

(i) **MT_2 is positive and gate current is also positive**: When MT_2 is positive with respect of MT_1, junction P_1N_1, P_2N_2 are forward biased but junction N_1P_2 is reverse biased. When gate terminal is positive with respect to MT_1, gate current flows mainly through P_2N_2 junction like an ordinary SCR (as in Fig 14(a)). When gate current has injected sufficient charge into P_2 layer, reverse biased junction N_1P_2 breaks down just as in a normal SCR. As a result, triac starts conducting through $P_1N_1P_2N_2$ layers. This shows that when MT_2 and gate terminals are positive with respect to MT_1, triac turns ON like a conventional thyristor. The device is more sensitive in this mode.

(ii) **MT_2 is positive but gate current is negative**: When gate terminal is negative with respect to MT1, gate current flows through P_2N_3 junction, Fig.14(b) and reverse biased junction N_1P_2 is forward biased as in a normal thyristor. As a result, triac starts conducting through $P_1N_1P_2N_3$

layers initially. With the conduction of $P_1N_1P_2N_3$, the voltage drop across this path falls but potential of layer between P_2N_3 rises towards the anode potential of MT2. As the right hand portion of P_2 is clamped at the cathode potential of MT1, a potential gradient exists across layer P_2, its left hand region being at higher potential than its right hand region. A current shown dotted is thus established in layer P_2 from left to right. This current is similar to conventional gate current of an SCR. As a consequence, right-hand part of triac consisting of main structure $P_1N_1P_2N_2$ begins to conduct. The device structure $P_1N_1P_2N_3$ may be regarded as pilot SCR and the structure $P_1N_1P_2N_2$ as the main SCR. It can then be stated that anode current of pilot SCR serves as the gate current for the main SCR. This mode is less sensitive.





(a) more sensitive (b) (c) (d) more sensitive

Turning-on process in a triac. Final conduction is through $P_1 N_1 P_2 N_2$ in

Fig.14 (a) and (b) and through $P_2 N_1 P_1 N_4$ in (c) and (d).

(iii) MT2 is negative but gate current is positive: The gate current Ig forward biases P_2N_2 junction (Fig. 14 c). Layer N_2 injects electrons into P_2 layer as shown by dotted arrows. As a result, reverse biased junction N_1P_1 breaks down as in a conventional thyristor. Eventually the structure $P_2N_1P_1N_4$ is completely turned on. As usual, the current after turn-ON is limited by the external load. As the triac is turned on by remote gate N_2, the device is less sensitive.

(iv) Both MT2 and gate current are negative: In this mode, N_3 acts as a remote gate (Fig 14 d). The gate current Ig flows from P_2 to N_3 as in a normal thyristor. Reverse-biased junction N_1P_1 is broken and finally, the structure $P_2N_1P_1N_4$ is turned ON completely. Though the triac is turned ON by remote gate N_3, yet the device is more sensitive under this condition.

V-I Characteristics of a Triac

It gives the relationship between the Triac current and voltage applied across its two main terminals. The triac is operated usually in two ways (i) when MT2 and gate both are positive with respect to MT1 and (ii) when MT2 and gate both are negative with respect to MT1. In the first case, the triac current flows from the MT 2 to MT 1. And in the second case, the triac current flows from the MT 1 to MT 2.

When the triac is operated, with its MT 2 and gate both positive with respect to MT 1, the V-I characteristic obtained is as shown in the first quadrant of Fig. 15(b).

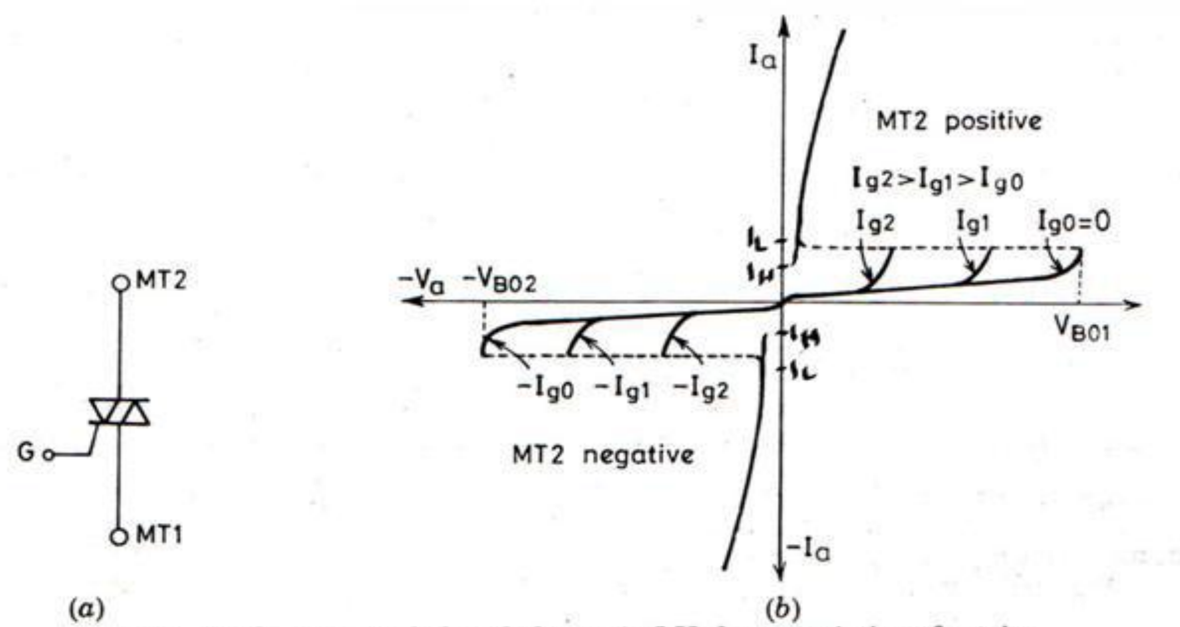


Fig.15 (*a*) Circuit symbol and (*b*) static *I-V* characteristics of a triac.

Similarly, when the Triac is operated with its main terminal 2 and gate both negative with respect to main terminal 1, the V-I characteristic obtained is shown in the third quadrant of Fig.15(b).

The V-I characteristic of a triac gives us the information about the following important points.

1. The curves shown in the first and third quadrants are symmetrical and identical to the forward characteristic of silicon controlled rectifier (SCR).
2. The triac is OFF until the applied voltage of either polarity exceeds the breakover voltage.
3. As the applied voltage of either polarity exceed the breakover voltage, the traic turns ON and the voltage drop across the triac decreases to a low value (0.7V). The triac current increases to a value determined by the supply voltage and load resistance.
4. As the value of gate current (Ig) is increased above zero, the breakover voltage is lowered. Like SCR, the triac is never operated with the zero gate current. When the gate current of a suitable value is applied, the triac turns ON at much lower breakover voltage.

Applications of Triac

The triac has an important property that it can conduct current in either forward or reverse direction, depending upon the polarity of the voltage across its terminals. This property makes the triac very useful in a large number of industrial applications. Some of the triac applications are:

1. Phase control 2. Speed control of small single-phase series induction motors 3. Heater control 4. Residential lamp dimmers 5. Static switch to turn ac power ON and OFF.

DIAC

The diac is a two terminal device, which can pass current in either direction when the breakover voltage is reached in either polarity across the two terminals. The basic construction of a diac is similar to a triac, but without a gate terminal as shown in Fig.16.

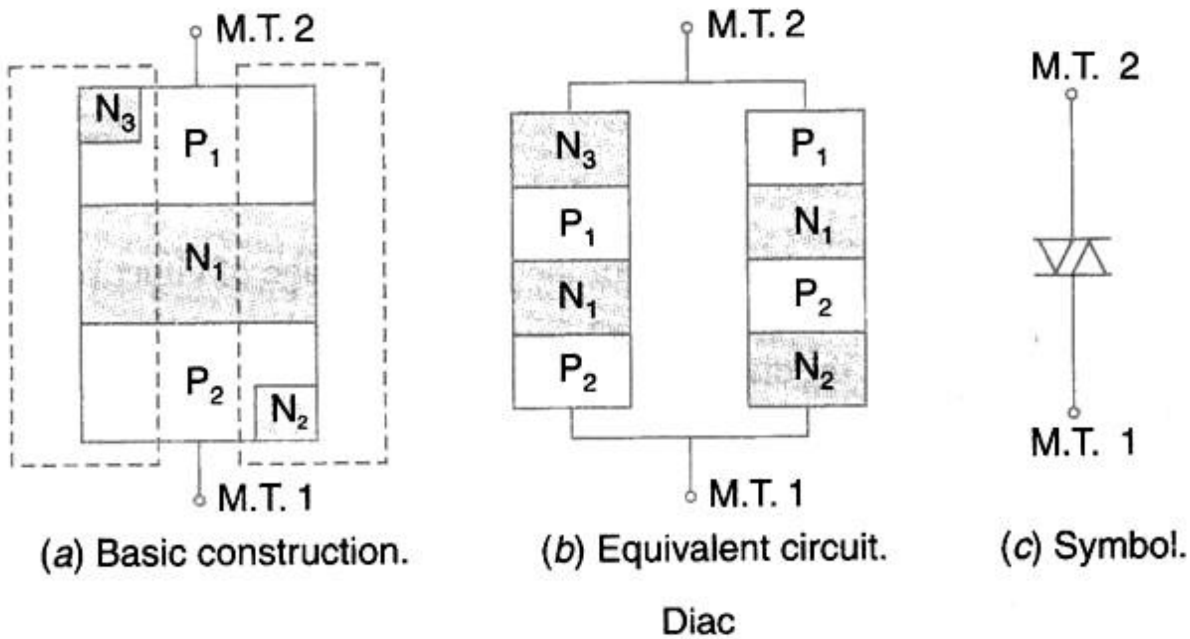


Fig.16

It may be noted from the figure that a diac consists of two 4-layer diodes connected in parallel but in opposite directions. The four layer diodes are $P_1N_1P_2N_2$ and $P_2N_1P_1N_3$ as shown by the broken lines in the figure 16(a). Since the diac conducts in both directions, therefore the terminals are designated by numbers instead of anode and cathode. The diac has two main terminals namely MT1 and MT2. Figure 16 (b) shows the equivalent circuit of a diac, which consists of two four-layer diodes connected in parallel but in opposite directions. Figure 16(c) shows the schematic symbol of the diac.

The diac can pass current in either direction depending upon the polarity of voltage across its main terminals. It can be turned ON only when the applied voltage across its main terminals reaches the breakover voltage. When the applied voltage makes the MT2 positive with respect to MT1, the diac passes current through the diode $P_1N_1P_2N_2$ from MT2 to MT1 as shown in Fig.17 (a).

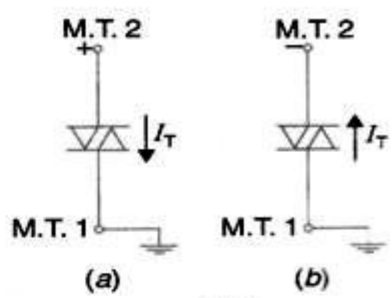


Fig.17

However if the applied voltage makes MT2 negative with respect to the MT1, the diac passes current through the diode $P_2N_1P_1N_3$ from MT1 to MT2 as shown in Fig.17 (b). The diac turns OFF when the current drops below the holding value

V-I Characteristic of a Diac

The diac can conduct in either direction, depending upon the polarity of the applied voltage across its main terminals. When a diac is operated with MT2 positive with respect to MT1, the V-I characteristic obtained is as shown in Fig.18 by the curve marked OAB. Similarly, when the diac is operated with its MT2 negative with respect to MT1, the V-I characteristic obtained is as shown by the curve marked OCD

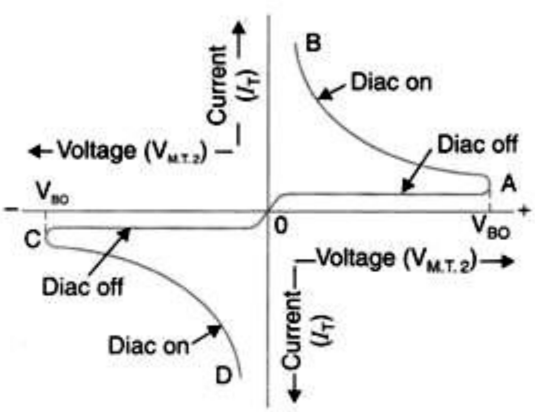


Fig.18 V-I characteristic of a disc.

The V-I characteristic of a diac gives us important information about the following points:

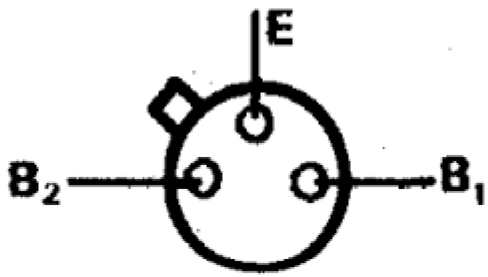
1. The curves OAB and OCD are symmetrical and identical. It is true because the operation of a diac is identical in both directions of conduction.
2. The diac does not pass any current, until the applied voltage of either polarity reaches the breakover voltage.
3. At the breakover voltage, the diac turns ON and the current through the diac increases rapidly as shown in the figure 18.
4. The operating voltage and currents are the same in either direction. Therefore the diac is a symmetrical bilateral diode.

The diacs are available with a breakdown voltage ranging from 28 to 36V and maximum pulse current 2A. Its leads are interchangeable. When not conducting, it acts like an open switch. A diac is sometimes called a gateless triac.

Applications of Diac

A diac is used as a triggering device for triac in phase control circuits such as light dimming, heat control and motor speed controls etc.

Unijunction Transistor (UJT)



A unijunction transistor (UJT) is a three terminal silicon semiconductor device. The UJT has only one PN junction like an ordinary diode. However, it is different from the ordinary diode in the sense that it has three terminals. The behavior of unijunction transistor is quite different from the other transistors like bipolar junction transistor (BJT) and the field effect transistor (FET).

Basic Construction of UJT

The basic construction of a unijunction transistor (UJT) is as shown in Fig 19(a). It consists of an N-type silicon semiconductor bar and a P-type silicon region. The N-type bar is called a base and the P-type region as the emitter. Thus a PN junction is formed between the emitter and base regions. The emitter region is heavily doped, while the base region is lightly doped. Due to this reason, the resistivity of the base material is very high. Three terminals are taken out of the whole structure one from the emitter region and two from the ends of the base region. These terminals are labeled as emitter (E), base 1 (B1) and base 2 (B2). It may be noted that the emitter region is shown closer to base 2 terminal than base 1. Figure (b) shows the schematic symbol of UJT.

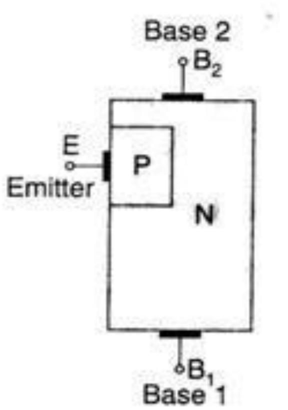


Fig.19 Construction

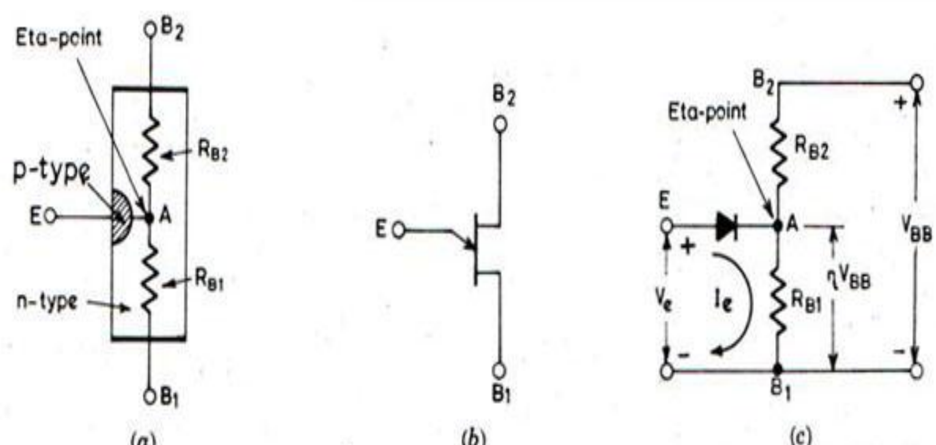


Fig.20 (a) Basic structure of UJT (b) symbolic representation and (c) its equivalent circuit.

It may be noted that the schematic symbol of UJT is different from that of JFET. The difference is that the arrow is at some angle in the schematic symbol of UJT.

Equivalent Circuit of UJT

Figure 20(c) shows the equivalent circuit of a unijunction transistor (UJT). It consists of a diode and a resistance (RBB). The diode represents the PN junction, while the resistance RBB is the internal bulk resistance of the silicon bar from one end to the other. In other words, the resistance RBB represents the total resistance between the base terminals and is called the interbase resistance. The resistance RBB is represented by the sum of two separate resistances RB1 and RB2 in the equivalent circuit of UJT. The resistances RB1 represents the bulk resistance between the emitter (E) and base 1 (B1), whereas resistance RB2 is the bulk resistance between the emitter (E) and base 2 (B2). Mathematically, the resistance

RBB = RB1 + RB2

When there is no voltage applied to the UJT, the value of resistance, RBB is typically 5 to 10KΩ. The resistance RB1 is shown as a variable resistance in the UJT equivalent circuit. It is because of the fact that the value of resistance RB1 varies inversely with the emitter current (IE). Depending upon the value of emitter current, the value of resistance RB1 can vary typically from 4KΩ to 40Ω.

Intrinsic Stand-off Ratio

Consider the equivalent circuit of a unijunction transistor (UJT) with a battery voltage VBB applied across its base terminals B1 and B2 as shown in Fig. 20(c). As the emitter is open, the applied voltage VBB, divides itself across resistance RB1 and RB2. The voltage across the resistance RB1 is

$$V1 = \frac{RB1}{RB1+RB2} \text{x } VBB = \frac{RB1}{RBB} \text{x } VBB = \eta \ VBB$$

The resistance ratio $\frac{RB1}{RBB}$ is known as **intrinsic stand-off ratio** and is denoted by η.

That is intrinsic stand-off ratio, $\eta = \frac{RB1}{RBB} = \frac{RB1}{RB1+RB2}$

The value of intrinsic stand-off ratio is between 0.5 and 0.8. The voltage drop across the resistance RB1 is called intrinsic standoff voltage. It reverse biases the emitter diode.

UJT Operation

Consider the equivalent circuit of a UJT with the voltage source VEE and VBB as shown in Fig.21 . Hence, the emitter diode is reverse biased by a voltage drop across the resistance RB1 (equal to η.VBB) and its own barrier potential (VD). Thus the total reverse bias voltage across a diode is equal to the sum of η.VBB and VD.

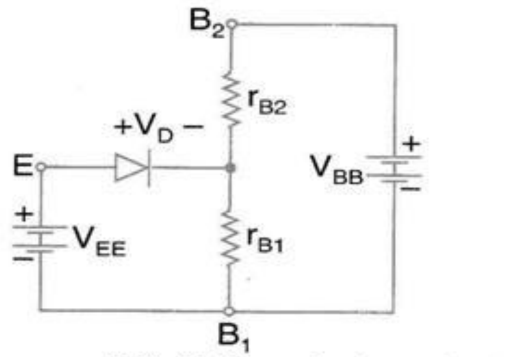


Fig.21 UJT equivalent circuit with V_{EE} and V_{BB} supplies.

As long as the applied emitter voltage is below the total reverse bias voltage (i.e. η.VBB + VD) across the diode, it remains reverse biased. And there is no emitter current. However, as the applied emitter voltage become equal to or exceeds η.VBB + VD, the diode conducts and the emitter current flows. The value of emitter voltage, which causes the diode to conduct, is called peak-point voltage. The peak-point voltage

Vp = η.VBB + VD

It is evident from the above discussion that as the emitter voltage reaches the peak-point voltage, the diode conducts (it becomes forward biased) and the emitter begins to flow. Under this condition, the UJT is said to be fired, triggered or turned ON. At this instant, the holes from the P-type emitter region are injected into the base region and are swept by the electric field towards the base terminals B1. The presence of excess holes, slightly reduce the resistance RB1 which in turn reduces the intrinsic stand-off voltage (η.VBB). This action is called conductivity modulation because the conductivity of the material between the emitter and base of terminals increases as the holes are injected into it. It is a regenerative process because a smaller value of intrinsic stand-off voltage results in a stronger forward bias across the diode. Due to this, more holes are injected and the intrinsic stand-off voltage (η.VBB) is further reduced. As a result of this, the emitter current increases, while the voltage at the emitter (VE = η.VBB + VD) decreases. It produces a negative resistance region in the V-I characteristic of UJT, and the UJT switches from its OFF position to ON position.

V-I Characteristic of UJT

Figure (23) shows the V-I characteristic of UJT. There are two important points on the characteristic curve namely the peak- point and the valley- point. These points divide the curve into three important regions namely, cut-off region, negative resistance region and saturation region.

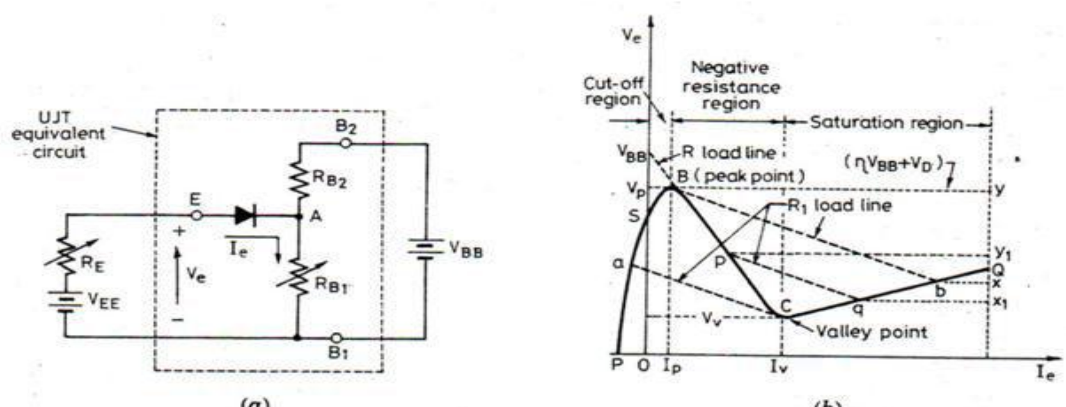


Fig.22 UJT (*a*) equivalent circuit with V_{BB} and V_{EE}, and (*b*) typical static $V-I$ characteristics.

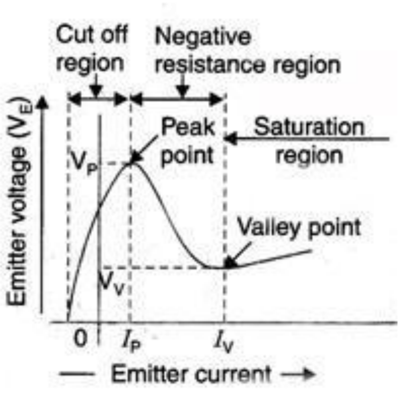


Fig.23 V-I characteristics of UJT.

1. **Cut-off region**: In this region the emitter voltage is below the peak-point voltage (Vp) and the emitter current is approximately zero. The UJT is in its OFF position in this region.

2. **Negative resistance region**: The region between peak-point and valley-point is called negative resistance region. In this region the emitter voltage decreases from Vp to Vv and the emitter current increases from Ip to Iv. The increase in emitter current is due to the decrease in resistance RB1. It is because of this fact that this region is called negative-resistance region. It is the most important region from the application point of view. For example, when the UJT is operated as an oscillator, it works in the negative-resistance region.

3. **Saturation region**: The region beyond the valley point is called saturation region. In this region the device is in its ON position. The emitter voltage (VE) remains almost constant with the increasing emitter current.

Application of UJT

The important applications of UJT are (1) Trigger device for SCR's and TRIAC's (2)Non-sinusoidal oscillators (3) Saw-tooth generators (4) Timing circuits

UJT Relaxation Oscillator

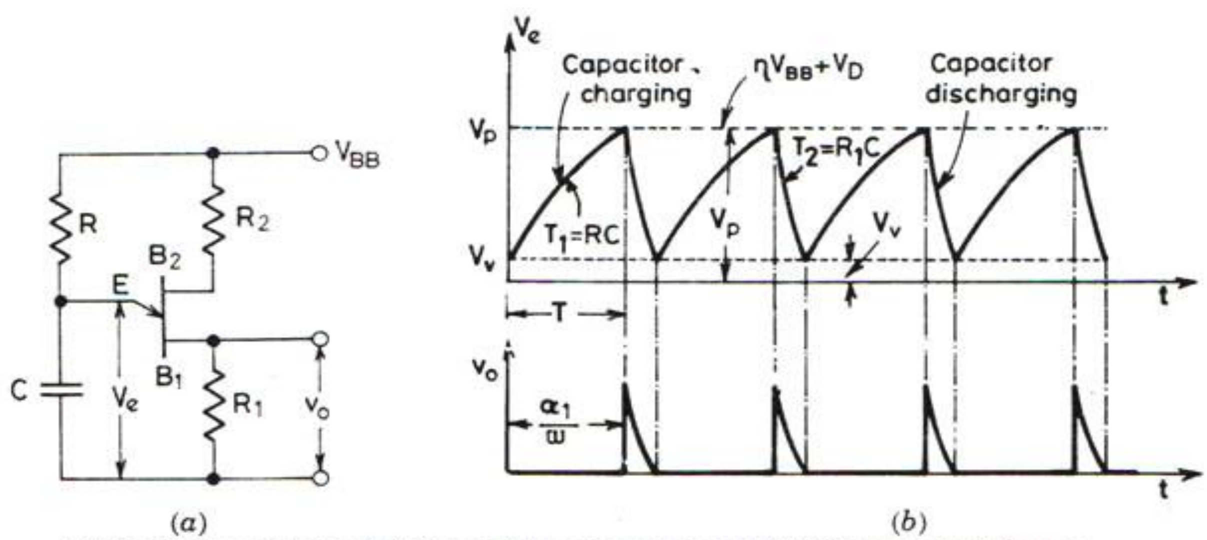


Fig.24 UJT oscillator (*a*) Connection diagram and (*b*) Voltage waveforms.

One of the major applications of the UJT is its use in the construction of an oscillator circuit called the relaxation oscillator. The UJT relaxation oscillator consists of a capacitor C and a resistor R connected to the emitter of UJT. Base B2 is connected to the +ve power supply through resistor R2 and base B1 is connected to the ground through resistor R1. Usually R1 and R2 are low value resistors

(100Ω). These are used to limit the current through the UJT and protect it. We can take three outputs from the UJT relaxation oscillator. These are from emitter (E), base B1 and base B2.

Initially, the UJT is in the OFF state, and the capacitor C is uncharged. C now gets charged through R towards VBB. When the voltage across the capacitor,

$$V_c = V_p = \eta V_{BB} + V_D$$

the UJT get fired and C gets discharged through the UJT (which is now on). The capacitor C discharges to the valley point Vv, at which the UJT turns OFF and C stops discharging. Once the UJT stops conducting and C discharges to Vv, the capacitor C again starts charging and the whole operation repeats. It can be seen that the charging and the discharging of the capacitor produces a type of sweep or saw tooth wave form across C as shown in Fig. 24(b).

Figure 24(b) shows the capacitor C charging towards Vp in time T1 and discharging towards Vv in time T2, producing a sawtooth waveform, with a period T = T1 + T2. Usually the UJT discharges with a very low ON resistance so that T2 << T1 and hence can be neglected. Thus the period of oscillation is determined mainly by T =T1. For producing oscillations, UJT operates between the peak point and the valley point. Since they are the stable operating points of the UJT, we say that the UJT operates in its relaxed modes of operation. So, we call the UJT oscillator as a relaxation oscillator.

Figure 24(b) shows the waveforms at E and B1 respectively. The waveform at B1 shows sharp trigger pulses. This is due to the fact that the circuit, under the firing condition, represents a differentiating circuit consisting of the UJT (ON), C and R.

The voltage across C at the time of firing of the UJT is Vp, and this is the voltage with which the UJT just turns ON. So, at the time of turning ON, the voltage across R1 is Vp itself, and this appears across C as shown in Fig.24(b). Therefore C discharges very fast producing a sharp trigger pulse across R1. This pulse is used for triggering SCR's.

The waveform at B2 is the complementary of the waveform at B1.

The equation governing the charging of a capacitor is given by

$$V_c = V_v + V_{BB}(1-e^{-t/RC}) \qquad (1)$$

Where Vc = voltage across C

VBB = the final voltage

Vv = initial voltage

$$\text{But } V_c = V_p = \eta V_{BB} + V_D \qquad (2)$$

Equating Equs. (1) and (2)

$$\eta V_{BB} + V_D = V_v + V_{BB}(1-e^{-t/RC})$$

$$\text{or} \quad t = RC \ln\left(\frac{Vv-VBB}{VBB(1-\eta)+VD}\right)$$

since Vv and VD are negligible compared to VBB

$$t = T = RC \ln\left(\frac{1}{1-\eta}\right) = 2.303\ RC \log\left(\frac{1}{1-\eta}\right)$$

Therefore the frequency of oscillation

$$\mathbf{f} = \frac{1}{RC \ln\left[\frac{1}{1-\eta}\right]} = \frac{1}{2.303 RC \log\left[\frac{1}{1-\eta}\right]}$$

Example 17: A silicon UJT has an interbase resistance of 8KΩ and RB1 of 5KΩ with IE = 0. Determine

(i) RB2 and (ii) intrinsic standoff ratio. Determine the UJT current, standoff voltage and peak point voltage when voltage of 15V is applied between the bases. Take VD = 0.7V.

Solution: Given RBB = 8KΩ and RB1 = 5KΩ

(i) RB2 = RBB – RB1 = 8-5 = 3KΩ

(ii) Intrinsic stand of ratio η = $\frac{RB1}{RBB}$ = $\frac{5}{8}$ = 0.625

Assuming VE less than peak-point voltage, UJT current, IB1 = IB2 = $\frac{VBB}{RBB}$ = $\frac{15}{8000}$ = 1.875mA

Standoff voltage = ηVBB = 0.625 x 15 = 9.375V

Peak point voltage, Vp = ηVBB + VD = 9.375 + 0.7 = 10.075

Example 18: The intrinsic stand- off ratio for an UJT is 0.65. Its interbase resistance is 10KΩ. Calculate the values of the interbase resistances.

Solution: Given η = 0.65 and RBB = 10KΩ

η = $\frac{RB1}{RBB}$ or RB1 = η x RBB

i.e RB1 = 0.65 x 10 = 6.5KΩ

we have RBB = RB1 + RB2

Therefore RB2 = RBB – RB1 = 10-6.5 = 3.5KΩ

Example 19: The internal resistance for a UJT are as follows RB1 = 6KΩ, RB2 = 3KΩ. Calculate the intrinsic stand- off ratio.

Solution: η = $\frac{RB1}{RB1+RB2}$ = $\frac{6}{6+3}$ = 0.66

Example 20: A silicon UJT has a stand- off ratio of 0.7 and an externally applied voltage VBB of 30V. Calculate the stand- off voltage.

Solution: stand-off voltage, Vp = ηVBB = 0.7x30 **= 21V**

Example 21: A UJT relaxation oscillator has R = 60KΩ and C= 0.25µF. Determine the pulse repetition frequency. Take intrinsic stand- off ratio to be 0.65.

Solution: Pulse repetition frequency

$$f = \frac{\mathbf{1}}{\mathbf{2.303}\boldsymbol{RC}\ \boldsymbol{log}[\frac{\mathbf{1}}{\mathbf{1-\eta}}]}\ \mathbf{= 63.5Hz}$$

Example 22: In UJT relaxation oscillator C = 0.2μF. Determine the frequency of the output voltage spikes for 5KΩ and 10KΩ settings.

Solution: $$f = \frac{1}{2.303RC\,log[\frac{1}{1-\eta}]}$$

(i) R = 5KΩ, f = 980Hz

(ii) R =10KΩ, f = 490Hz

Example 23: Determine the free running frequency of a UJT relaxation oscillator if RB1 = 4KΩ, RB2 = 2KΩ, R = 8.2KΩ and C = 0.01μF.

Solution: $$f = \frac{1}{2.303RC\,log[\frac{1}{1-\eta}]}$$

Example 24: Estimate the minimum and maximum values of charging resistor in the UJT oscillator circuit for manual trigger angle control of α between 20° and 160° for 50Hz supply. Assume C = 0.47μF and η = 0.6.

Solution: Firing angle $\alpha = \omega T = \omega RC\, ln(\frac{1}{1-\eta}) = 2\pi fRC \times 2.303\, log(\frac{1}{1-\eta})$

(i) For α1 =20, R = R1

$$\alpha 1 = 2\pi \times 50 \times R1 \times 0.47 \times 10^{-6} \times 2.303 \times log\, (\frac{1}{1-0.6}) = 20$$

Therefore R1 = 147.87KΩ

(ii) For α2 = 160, R = R2

$$\alpha 2 = 2\pi \times 50 \times R2 \times 0.47 \times 10^{-6} \times 2.303 \times log(\frac{1}{1-0.6}) = 160$$

Therefore R2 = 1182.99KΩ

Silicon Controlled Switch (SCS)

A silicon controlled switch (SCS) is similar in construction to a silicon controlled rectifier as shown in Fig.25(a). It has four terminals namely anode, cathode and two gate terminals called anode gate and cathode gate. Figure 25(b) shows the schematic symbol of silicon controlled switch.

The silicon controlled switch has an advantage that it can be turned ON and OFF using either gate terminal. On the other hand an SCR can be turned ON only using its gate terminal. But SCR cannot be turned OFF using the same gate terminal.

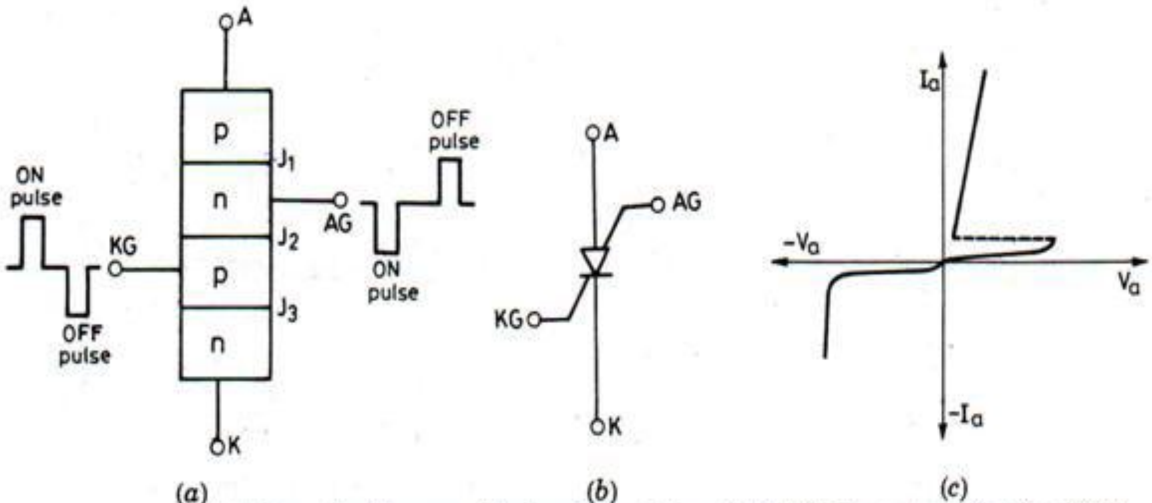


Fig.25 (*a*) Schematic diagram (*b*) circuit symbol and (*c*) *I-V* characteristic of an SCS.

Operation of SCS

The operation of silicon controlled switch may be understood by referring to its transistor equivalent circuit as shown in Fig.26.

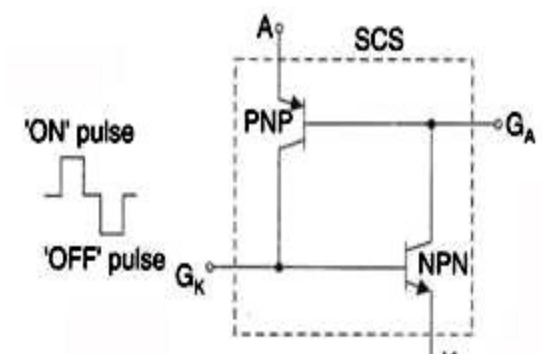


Fig.26

In the beginning let us assume that the transistors Q1(PNP) and Q2(NPN) are OFF. Therefore the SCS is also OFF. If a positive pulse is applied on the cathode gate, the transistor Q2 will be driven into conduction and thus provides a path for the base current of transistor Q1. When the transistor Q1 turns ON, its collector current provides the base drive to the transistor Q2. This action drives both the transistors Q1 and Q2 into saturation and hence the silicon controlled switch turns ON. The silicon controlled switch can also be turned ON by applying a negative pulse at the anode gate terminal as shown in the figure.

The SCS can be turned OFF by applying a positive pulse at the anode gate or a negative pulse at the cathode gate. The applied anode gate voltage pulse reverse biases the base-emitter junction of the transistor Q1 and turns it OFF. This in turn cuts-off the transistor Q2 due to which the silicon controlled switch is also turned OFF. It will be interesting to know that the SCS can also be turned OFF by reducing the anode current below the holding current value.

SCS has a low turn OFF time about 1 to 10µs. It is a low power device, anode current is about 200mA and power dissipation up to 500mW.

Advantages and disadvantages of SCS

The SCS has two major **advantages** over SCR

1. SCS has a fast turn OFF
2. It can be turned ON and OFF with pulses on either gate terminal.

The SCS has one **disadvantage**

1. It is available only in lower power ratings.

Applications of SCS

1. In timing, logic and triggering circuits
2. In pulse generators
3. In voltage sensors
4. In oscillators

Silicon Unilateral Switch (SUS)

Silicon unilateral switch (SUS) is a programmable unijunction transistor (PUT) and an avalanche diode connected between gate and cathode. The avalanche diode is inbuilt into the device. Fig.(27) shows its equivalent circuit, symbol and V-I characteristics.

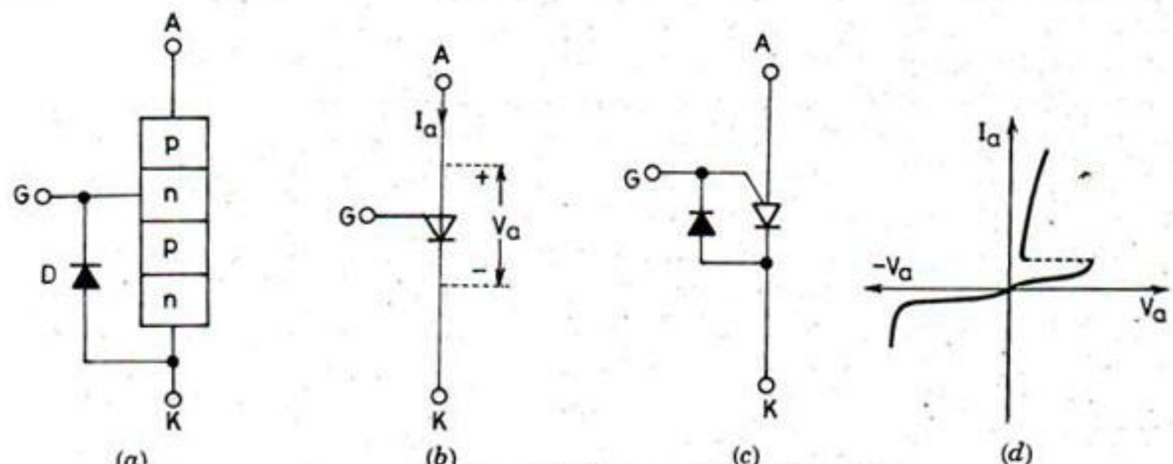


Fig.27 (*a*) Schematic diagram (*b*) circuit symbol (*c*) equivalent circuit and (*d*) *I-V* characteristics of an SUS.

The main feature of SUS is that it switches at a fixed voltage (Vs) determined by its avalanche diode (the trigger voltage of SCR vary widely with changes in ambient temperature). When the anode to cathode applied voltage is less than forward switching voltage, the current is nearly zero. When anode to cathode voltage exceeds Vs (6 to 10 V) the device switches ON. The voltage drop across a SUS when it is ON is about 1.5V. It is a unilateral device as it can conduct only in one direction from anode to cathode. When applied voltage is less than Vs the application of a gate signal can turn ON the device.

For turning OFF it requires special commutation circuits as in a thyristor. The reverse breakdown voltage is about 30V. SUS is used mainly in timing, logic and trigger circuits.

Silicon Bilateral Switch (SBS)

The silicon bilateral switch (SBS) is used for triggering SCR's and triacs. SBS consist of two silicon unilateral switches connected in parallel but in opposite directions. As the name suggests it can conduct in both directions when anode to cathode voltage is more than switching voltage Vs (about 6 to 10 volts). Figure 28(a) shows the equivalent circuit, symbol and V-I characteristic of SBS. The operation of SBS is similar to that of a triac. When the SBS is ON the voltage drop across it is about 1.7 volts.

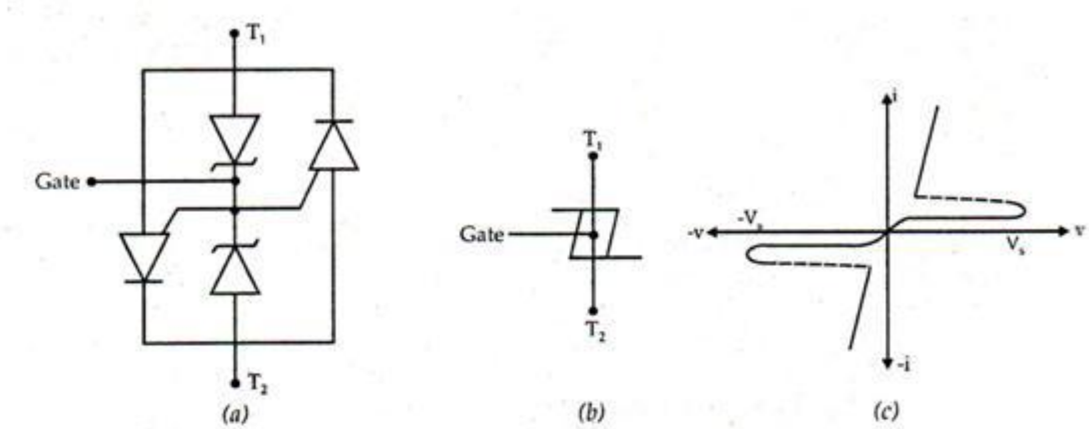


Fig. 28 . . SBS (a) equivalent circuit (b) symbol (c) i-v characteristics.

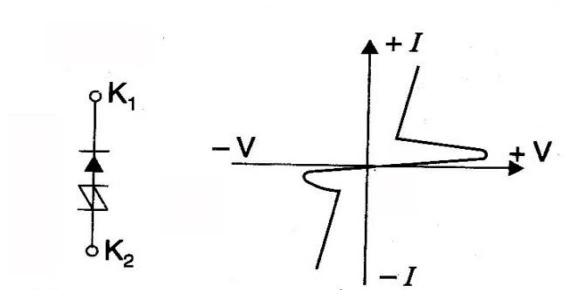
Since the silicon bilateral switch conducts in either direction, therefore it does not have any reverse voltage rating like SUS.

Applications

SUS and SBS are used in high speed switching circuits, digital circuits, dc power supply circuits, pulse generators etc.

Silicon Asymmetrical Switch (SAS)

Silicon Asymmetrical switch (SAS) is similar to silicon bilateral switch (SBS). The advantage of SAS over SBS is that the SAS has different firing voltage in the positive quadrant than it does in the negative quadrant. This feature is useful in those circuits that are affected by hysteresis. Example: circuits with large inductors, motor circuits and transformers.



(*a*) Symbol (*b*) V-I characteristic

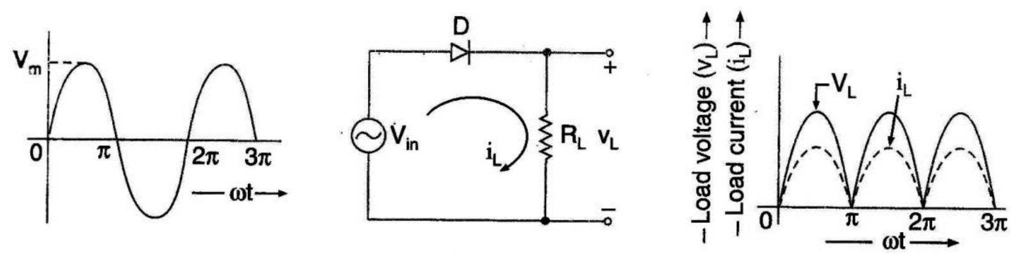
Fig 29

We know that when an inductor charges with current, it will become magnetized at a specific rate. When the current flow is stopped or reversed the rate at which the original magnetic field collapses and the reverse magnetic field builds will not be the same rate as the original signal. This effect is called hysteresis and it may carry over to the electronic components used to provide the firing pulse to the thyristors that are controlling the current flow. When hysteresis occurs the electronic device will heat up more than the normal. The asymmetrical characteristic of the SAS will help limit the effects of hysteresis.

CHAPTER 2

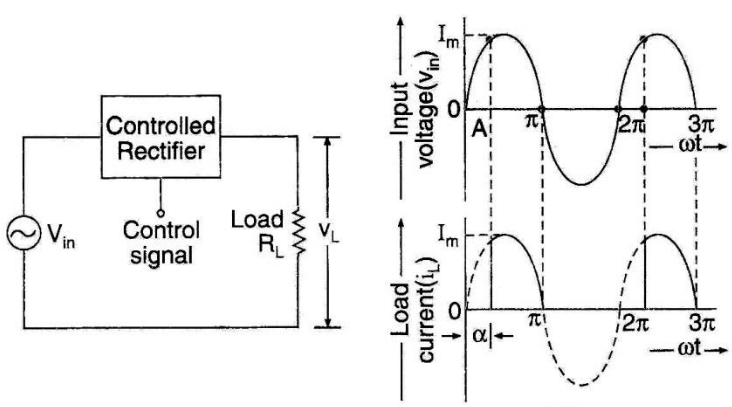
CONTROLLED RECTIFIERS (CONVERTERS)

In ordinary half wave diode rectifier the load current flows during the positive half cycle of the input signal. Where as in the case of controlled rectifier load current flows only when a control signal is applied at the gate terminal to turn 'ON' the rectifier. In controlled rectifier SCR or TRIAC is used instead of diode.



Diode half-wave rectifier.

Figure below (a) shows a half wave controlled rectifier circuit and (b) shows the input voltage waveform and load current waveform. It may be noted that the control signal is applied to turn on the rectifier in such a way that the conduction starts at a specific point marked A in Fig. (b). The point A (called firing point) corresponds to the angle α, so that the conduction is delayed by this much period. It is because



(a) (b)

Half-wave controlled rectifier.

of this delay that the amount of load current has reduced in a controlled rectifier as compared to an ordinary rectifier.

It will be noted that once the rectifier is turned 'ON' it remains in conduction for the rest of the positive half-cycle i.e. up to 180° (or π radians). Thus the point A (at which the conduction starts) is determined by the angle of delay in applying control signal to the rectifier circuit. As the angle α increases, conduction is further delayed and the load current is also reduced.

The load current in a controlled rectifier may be controlled easily by selecting the firing point. This feature (i.e. control over the load current) is of great advantage in controlled rectifiers.

Let the equation of the input voltage be,

Vi = Vm. sinωt = Vm. sinθ

For a half-wave rectifier, the average value is found by taking the average over the whole cycle (0 to 2π) even though the conduction takes place only from 0 to π in the entire cycle.

Therefore $VL = \frac{1}{2\pi}\int_0^{\pi} Vin.d\theta = \frac{1}{2\pi}\int_0^{\pi} Vmsin\theta.d\theta = \frac{Vm}{2\pi}\int_0^{\pi} sin\theta.d\theta$

$= \frac{Vm}{2\pi}|-cos\theta|_{\alpha}^{\pi}$

$= \frac{Vm}{2\pi}|(-cos\pi) - (-cos\alpha)| = \frac{Vm}{2\pi}(1+cos\alpha)$

And dc output voltage (or average load voltage), $Vdc = VL = \frac{Vm}{2\pi}(1+cos\alpha)$

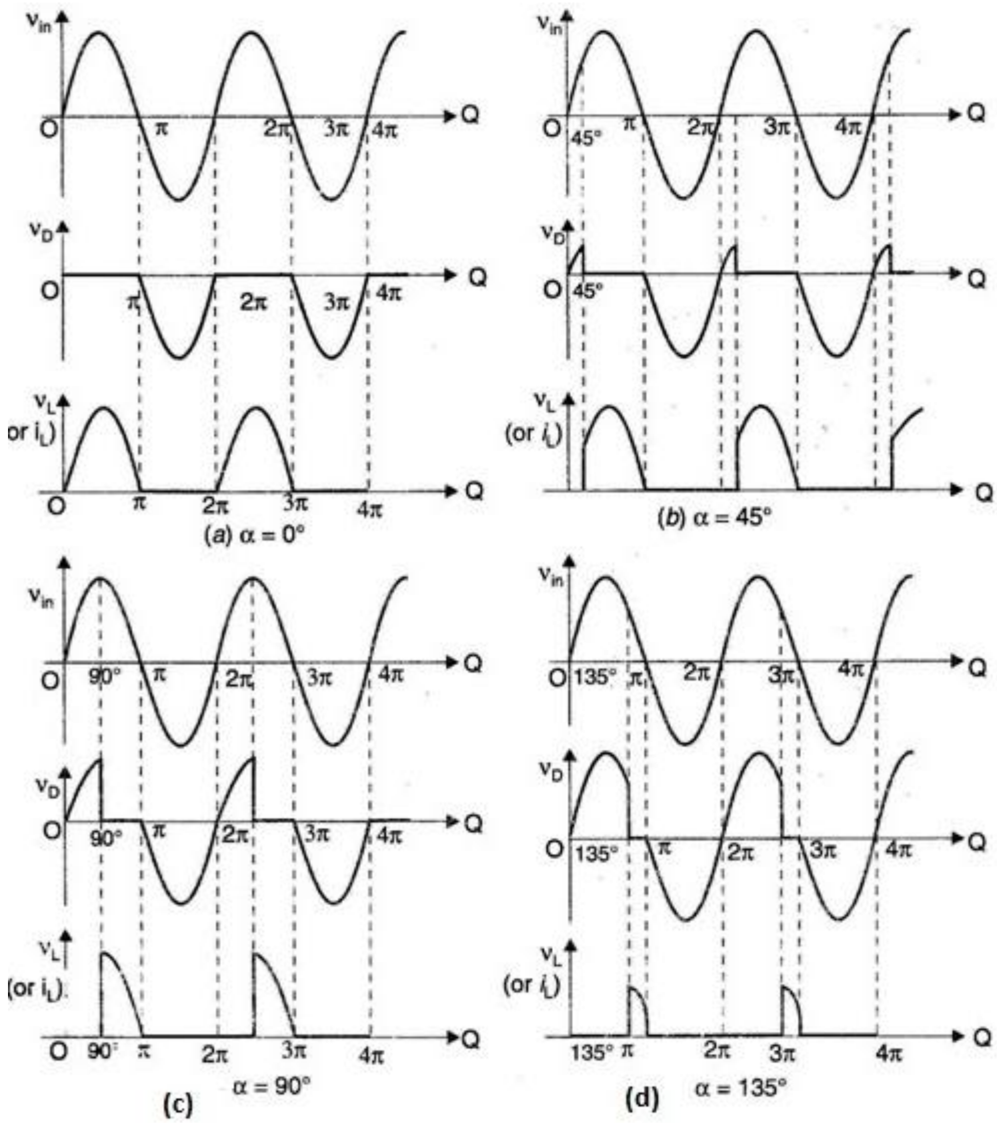
For a resistive load, average load current, $Idc = IL = \frac{Vm}{2\pi RL}(1+cos\alpha)$

If α = 0, then $Vdc = \frac{Vm}{\pi}$ and $Idc = \frac{Vm}{\pi RL}$

(The above values are the same as that of diode half wave rectifier)

Output waveforms for different Firing Angles

Fig. (a), (b), (c) and (d) shows the output waveforms for different firing angles (0°, 45°, 90° and 135°) along with the waveforms for input voltage and voltage drop across the controlled rectifier. For all these waveforms the ac supply voltage is sinusoidal ($V_{in} = V_m sin\theta$). Also a resistive load is assumed. Further, when the SCR conduct the voltage drop across it is zero. When it does not conduct, it is open circuit. It is evident from the waveforms that the firing angle 'α' is increased from 0 through 135°, the output voltage keeps decreasing till α = 180°, the output is zero.

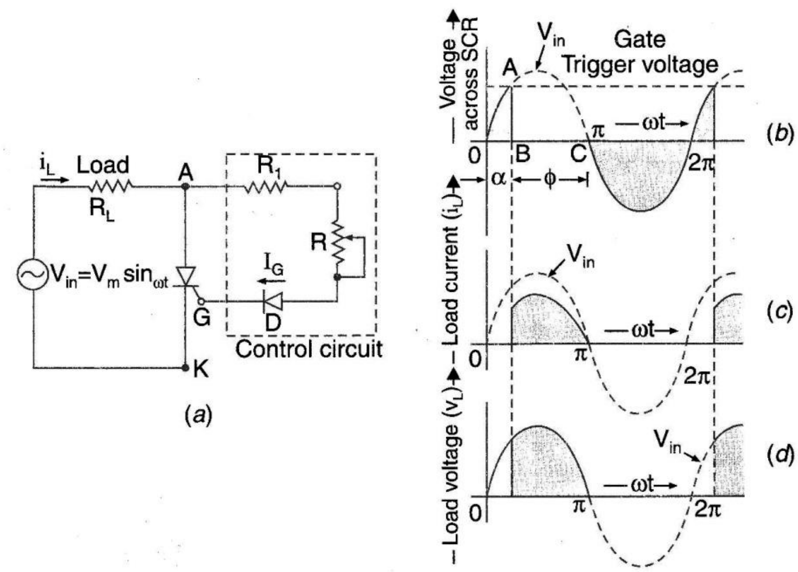


Power Control using SCR

We know that a simple way to vary theload current is either to control the transformer secondary voltage or insert a resistor in the load circuit. But in actual practice, neither of these two methods is desirable. The control of transformer secondary voltage requires an expensive equipment, whereas the insertion of resistor in the load circuit result in a loss of power. Therefore, the use of silicon controlled rectifier is an efficient way of controlling the power. When an ac voltage is applied across an SCR, it will turn ON during each positive half cycle and OFF during each negative half cycle. The average load current can be varied over a wide limit by controlling the point in each positive half cycle at which the SCR is turned ON. The point, at which the SCR turns ON, may be controlled either by amplitude triggering or pulse triggering.

SCR Half wave Rectifier

Figure(a) shows the circuit of a SCR half-wave rectifier. In this circuit, the ac supply is connected to the SCR through a load resistance RL. The gate current is obtained from the ac supply through the resistances R and R1 and diode D connected in series. The diode D is connected in such a way, so that it blocks the reverse voltage on the gate during the negative half-cycle.



SCR half-wave rectifier and its waveforms.

Figure (b), (c) and (d) shows the waveforms of the voltage across SCR (V_{SCR}), the load current (I_L) and voltage across the load (V_L) respectively. The various curves in the waveforms may be expained as follows: During the positive half-cycle, the SCR remains 'OFF' till the input voltage reaches the gate trigger voltage i.e. point A in Fig. (b). As a result, there is no current through RL. Hence load currrent (IL) and load voltage (V_L) are zero. At point A, SCR is fired into conduction. It acts like a short and voltage across it drops to zero i.e., curve AB in Fig. (b). Under this condition, whole of the applied voltage drops across the load resistance. During the negative input half cycle, the SCR is reverse biased and hence does not conduct. As a result, all the applied voltage appears across SCR and none across the load resistance (RL).

The horizontal distance between the points O and A in Fig. (b) represents the time in the positive half-cycle, when SCR is not conducting. This distance in degrees is called the firing angle, phase angle or delay angle (α). This angle gives us an idea about the position at which the SCR starts conduction with respect to the origin. It may may be noted from the figure that the SCR is coducting between the points B and C. This angle is called conduction angle (ϕ) and its value is equal to (π – α).

Average Values of Load Voltage and Current

Average load voltage

The equation of a.c. supply voltage is

$V_{in} = V_m.\sin\omega t = V_m.\sin\theta$

We also know that for a half wave rectifier, the average value of a load voltage is determined by the relation,

$$Vdc = \frac{Area\ under\ the\ curve\ over\ a\ complete\ cycle}{Base}$$

$$= \frac{\int_0^{2\pi} Vin.d\theta}{2\pi} = \frac{1}{2\pi}\int_0^{2\pi} Vm.\sin\theta d\theta \quad \text{-----(1)}$$

Now the load voltage is developed only during the period SCR conducts. This period lies between the angles α and π. Therefore, we must take the average over the limits α to π instead of 0 to 2π in equation (1)

$$Vdc = \frac{1}{2\pi}\int_\alpha^{\pi} Vm.\sin\theta d\theta = \frac{Vm}{2\pi}\int_\alpha^{\pi} \sin\theta.d\theta$$

$$= \frac{Vm}{2\pi}\left|-\cos\theta\right|_\alpha^\pi$$

$$= \frac{Vm}{2\pi}\left|(-\cos\pi) - (-\cos\alpha)\right|$$

$$= \frac{Vm}{2\pi}(1+\cos\alpha) \quad \text{-------(2)}$$

Average load current

We know that load current, iL = vL/RL, therefore, the average value of the load current,

$$Idc = \frac{Vdc}{RL} = \frac{Vm}{2\pi RL}(1 + \cos\alpha) = \frac{Im}{2\pi}(1 + \cos\alpha) \quad \text{------(3)}$$

Where Im is equal to Vm/RL and is the maximum value of the load current. It may be noted that if the firing angle (α) is equal to zero, then the average values of load voltage and current is obtained from equations (2) and (3)

Therefore $Vdc = \frac{Vm}{\pi}$ and

$$Idc = \frac{Im}{\pi} = \frac{Vm}{\pi.RL} = \frac{Vdc}{RL}$$

It may be noted that the above results are the same as obtained for an ordinary diode half-wave rectifier.

RMS load voltage

The rms voltage across the load is

$$Vrms = [\frac{1}{2\pi}\int_{\alpha}^{\pi}(Vmsin\omega t)^2 d(\omega t)]^{0.5} = Vm[\frac{1}{2\pi}\int_{\alpha}^{\pi} sin^2\omega t d(\omega t)]^{0.5}$$

$$= Vm[\frac{1}{2\pi}\int_{\alpha}^{\pi}\frac{(1-cos2\omega t)}{2} d(\omega t)]^{0.5} = Vm[\frac{1}{4\pi}\{(\omega t\ \frac{sin2\omega t}{2})\}]^{0.5}$$

$$\text{Or } Vrms = Vm[\frac{\pi-\alpha}{4\pi} + \frac{sin2\alpha}{8\pi}]^{0.5}$$

RMS load current

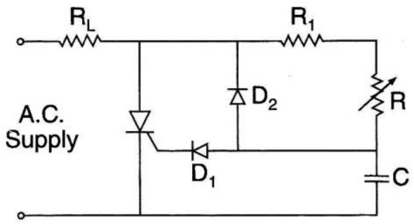
And the rms load current is $Irms = \frac{Vrms}{RL}$

90° Variable Half-wave Rectifier (Converter)

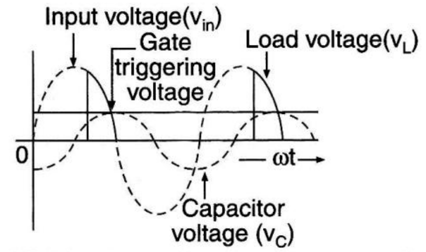
The SCR half-wave rectifier circuit shown in the half-wave rectifier is known as 90° variable half-wave rectifier (or 90° variable phase control circuit). The term 90° variable implies that we can make SCR to conduct anywhere from the origin to the maximum value of the positive half-cycle i.e. the firing angle can be varied from 0° to 90°. The firing angle depends upon the value of variable resistance (R). If the resistance R is set at a low value, the SCR will start conducting near the origin. On the other hand, if R is set at a large value, the SCR may not conduct until the maximum value of positive half-cycle.

180° Variable Half-wave Rectifier

Figure (a) shown below is a 180° variable half-wave rectifier. It is also called 180° variable phase control circuit. In 180° variable half-wave rectifier, a capacitor (C) has been added between the variable resistance (R) and the cathode of SCR. The combination of resistance (R) and capacitor (C) forms a phase shift network. This network delays the point at which SCR will trigger on the positive half of the applied voltage. The delay is provided by charging of the capacitor through the resistance R. This allows the firing angle to be controlled from 0° up to a maximum of 180°.



(*a*) 180° Variable half-wave rectifier.



(*b*) Waveform of input voltage, capacitor voltage and load voltage.

Figure (b) shows the waveforms of input voltage (Vin), capacitor voltage (Vc) and load voltage (VL). It may be noted that capacitor voltage lags behind the input voltage. Their phase relationship is given by the relation,

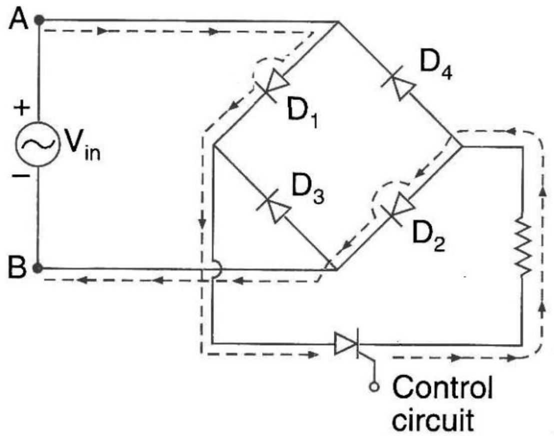
$$Vc = \frac{Vin}{1+ \omega.C.R}$$

It may be noted that the above expression that if the value of ω.C.R is much smaller than unity, then the capacitor voltage (Vc) and the input voltage (Vin) are in phase with each other. As a result of this, the firing will occur almost immediately after the input voltage is positive (i.e. α = 0°, ϕ = 180°). On the other hand, if the value of ω.C.R is much larger than unity, then capacitor voltage is delayed by practically 90° from the input voltage and is much reduced in amplitude. This allows the firing to be delayed to almost the end of half a cycle (i.e. α = 180°, ϕ = 0°)

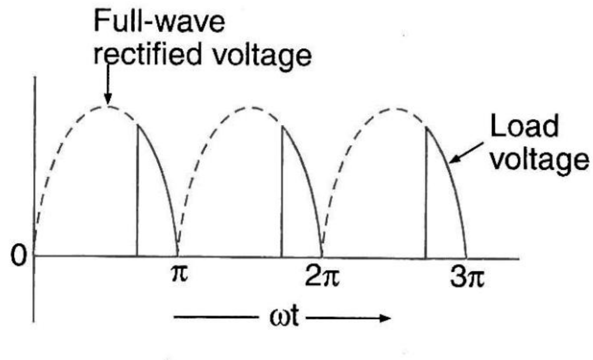
The diode D2 has been added to reset capacitor (C) by discharging it during it during the negative half cycle. This allows the firing to occur at the same point in each cycle.

SCR Full-wave Rectifier

Figure below shows the circuit used for SCR full-wave rectifier. It consists of a diode bridge in series with SCR. The gate control input is left open, because a number of different firing circuits can be used.



(*a*) SCR full-wave rectifier.



(*b*) The full-wave rectified and load voltage waveforms.

When the terminal A is positive, the current will flow through the diode D1, SCR, load resistance and D2 to the terminal B. However, if the terminal B is positive, the current will flow through diode D3, SCR, load resistance and D4 to the terminal A. Thus the four diodes forming a bridge provide full-wave rectification, while the SCR controls the amount of voltage applied to the load.

Figure (b) shows the full-wave rectified and load voltage waveforms. The amount of voltage applied to the load may be controlled by adjusting the firing angle of the SCR. This can be achieved by adjusting the gate current supplied by the control circuit.

The average value of load voltage and load current may be obtained from the equation of the applied voltage, i.e.,

Vin = Vm sinωt = Vm sinθ

Then average value of load voltage,

$$Vdc = \frac{1}{\pi}\int_{\alpha}^{\pi} Vm.sin\theta.d\theta = \frac{Vm}{\pi}\int_{\alpha}^{\pi} sin\theta.d\theta$$

$$= \frac{Vm}{\pi}\left|-cos\theta\right|_{\alpha}^{\pi} = \frac{Vm}{\pi}[(-\cos\pi) - (-\cos\alpha)]$$

$$= \frac{Vm}{\pi}(1+\cos\alpha) \quad \text{-----(1)}$$

And the average value of load current,

$$Idc = \frac{Vdc}{RL} = \frac{Vm}{\pi RL}(1+\cos\alpha) \quad \text{--------(2)}$$

It may be noted that if α = 0 in equation (1) and (2) then average value of voltage and current, Vdc = $\frac{2Vm}{\pi}$ and Idc = $\frac{2Vm}{\pi RL}$

These values are the same as in an ordinary diode full-wave rectifier.

Problems:

1. A 100Ω load is connected to a peak supply of 300V through a controlled half-wave rectifier. The load power is to be varied from 25W to 80W. What is the angular firing control required?

Solution: RL = 100Ω and Vm= 300V

We know that load power, P = Vdc.Idc

$= [\frac{Vm}{2\pi}(1+\cos\alpha)] \times [\frac{Vm}{2\pi RL}(1+\cos\alpha)]$

$= 22.8\ (1+\cos\alpha)^2$

(a) Angular firing control when load power , P = 25W

$25 = 22.8\ (1+\cos\alpha)^2$

Or cosα = 0.096 or α = **89.4°**

(b) Angular firing control when load power P = 80W

$80 = 22.8\ (1+\cos\alpha)^2$

Or cosα = 0.873 or α = **29.2°**

This shows that when the load power is varied from 25W to 80W, the firing angle is reduced from 89.4° to 29.2°.

2. In a controlled half-wave rectifier, peak supply voltage is 200V and the value of load resistor is 1KΩ. Calculate the power delivered to the load circuit for firing angles of (i) 0°, (ii) 45°, (iii) 90° and (iv) 135°.

Given Vm = 200V, and RL = 1KΩ

(i) α = 0°, Vdc = $\frac{Vm}{2\pi}(1+\cos\alpha)$ = 63.6V

Idc = $\frac{Vdc}{RL} = \frac{63.6}{1000}$ = 63.6mA

Therefore load power, P = Vdc .Idc = 63.6V x 63.6mA = 4045mW= **4.045W**

(ii) α = 45°, dc output voltage, Vdc = $\frac{Vm}{2\pi}(1+\cos\alpha)$ = 54V

Idc = $\frac{Vdc}{RL} = \frac{54}{1000}$ = 54mA

Therefore load power, P = Vdc.Idc = 54V x 54mA = 2916mW = **2.916W**

(iii) α = 90°, dc output voltage, Vdc = $\frac{Vm}{2\pi}(1+\cos\alpha)$ = 31.8V

Idc = $\frac{Vdc}{RL} = \frac{54}{1000}$ = 31.8mA

Therefore load power, P = Vdc.Idc = 31.8V x 31.8mA = 1011mW = **1.011W**

(iv) α = 135°, dc output voltage, Vdc = $\frac{Vm}{2\pi}(1+\cos\alpha)$ = 9.3V

Idc = $\frac{Vdc}{RL} = \frac{54}{1000}$ = 9.3mA

Therefore load power, P = Vdc.Idc = 9.3V x 9.3mA = **86.49mW**

3. An SCR is used for converting a.c. to d.c. The anode supply is 220V, 50Hz and the firing angle is adjusted at 60°. Find out the d.c. output voltage.

Sol: Vrms = 220Vand α = 60°

The maximum value of the applied voltage, i.e. anode supply

Vm = √2 x Vrms = √2 x 220 = 311V

The d.c. output voltage Vdc = $\frac{Vm}{2\pi}$(1+cosα) = $\frac{311}{2\pi}$(1+cos60°) = **74.2V**

4. Find the value of resistance to limit the average current to 0.5A, when 100V r.m.s. is applied to an SCR with a firing angle of 45°.

Sol: Idc = 0.5A, Vrms = 100V and α= 45°

Let RL is the value of resistance which limits the anode current to 0.5A

We know that maximum value of applied voltage, Vm= √2 x Vrms = √2 x 100= 141.4V

The average current, Idc = $\frac{Vm}{2\pi RL}$(1+cosα) = $\frac{141.4}{2\pi}$(1+cos45°) = 38.42/RL = 0.5

Therefore RL = 38.42/0.5 = **76.84Ω**

5. A single phase half-wave rectifier circuit using a thyristor is fed by a transformer whose secondary voltage is 400sinωt. Find the average load voltage, rms load voltage, average load current and rms load current if the thyristor is fired at 30° in each positive half cycle. The load resistance is 50Ω.

Sol: Vm = 400V, α = 30° and RL = 50Ω

Average dc voltage Vdc = $\frac{Vm}{2\pi}$(1+cosα) = $\frac{400}{2\pi}$(1+cos30°) = **118.8V**

Average load current, Idc = $\frac{Vdc}{RL}$ = $\frac{118.8}{50}$ = **2.376A**

RMS voltage,Vrms = Vm[$\frac{\pi-\alpha}{4\pi}$ + $\frac{sin2\alpha}{8\pi}$]$^{0.5}$ = 400[$\frac{\pi-30°}{4\pi}$ + $\frac{sin60}{8\pi}$]$^{0.5}$ = **197.1V**

RMS current, Irms = $\frac{Vrms}{RL}$ = $\frac{197.1}{50}$ = **3.942A**

6. A single phase ac supply 100sinωt is used to charge a 50V battery through a thyristor and a 10Ω resistor. The thyristor is continuously fired by a dc signal. Find the average current in the circuit.

Sol: The thyristor will conduct when the instantaneous value of ac voltage is more than 50V or

100sinωt = 50

Or ωt = π/6 and 5π/6

i = $\frac{100sin\omega t-50}{10}$ = 10sinωt -5

Average current = $\frac{1}{2\pi}\int_{\pi/6}^{5\pi/6}(10sin\omega t - 5)d(\omega t)$ =$\frac{1}{2\pi}$|-10cosωt -5ωt|$_{\pi/6}^{5\pi/6}$

= $\frac{1}{2\pi}$(-10cos$\frac{5\pi}{6}$ + 10cos$\frac{\pi}{6}$ - 5x$\frac{5\pi}{6}$ + 5x$\frac{\pi}{6}$) = **1.09A**

7. If a half-wave controlled rectifier has a purely resistive load of R and the delay angle is α = π/3. Determine (a) Rectification efficiency, (b) Form factor, (c) Ripple factor, (d) Transformer utilization factor and (e) Peak inverse voltage for SCR

Solution:

(a) Rectification efficiency, η = $\frac{Pdc}{Pac}$ where, Pdc = dc load power = V^2dc/R and Pac = rms load power = V^2rms/R.

Vdc = $\frac{Vm}{2\pi}$(1+cosα) , since,α=π/3 therefore Vdc = 0.239Vm

Also Vrms = Vm[$\frac{\pi-\alpha}{4\pi}$ + $\frac{sin2\alpha}{8\pi}$]$^{0.5}$

For firing angle α=π/3 , Vrms = 0.485Vm

Therefore rectification efficiency η = $(0.239Vm)^2/(0.485Vm)^2$ =**0 .2428 = 24.28%**

(b) Form factor, (ff) = Vrms/Vdc = 0.485Vm/0.239Vm = **2.033 = 203.3%**

(c) Ripple factor (Rf) = √(ff^2 – 1) = 1.77 = 177%

(d) Trasformer utilization factor (TUF) = $\frac{Pdc}{Vs.Is}$ where Vs and Is are the rms secondary voltage and current respectively.

Now Vs = Vm/√2 = 0.707Vm and Is = rms load current = Vrms/R = 0.485Vm/R

Therefore TUF =(V^2dc/R)/Vs.Is = $(0.239Vm)^2$/R/(0.707Vm x 0.485Vm/R)

= **0.166 or 16.6%**

(e) Peak inverse voltage = **Vm**

8. An SCR is used to control the power of 1kW, 230V, 50Hz heater. Determine the heater power for firing angles of 45° and 90°.

Solution: The heater resistance = R, and the rms current is the heat producing component of load current.

Vrms = Vm[$\frac{\pi-\alpha}{4\pi}$ + $\frac{sin2\alpha}{8\pi}$]$^{0.5}$

(i) At α=π/4, Vrms = 155V, Therefore heat power W = V^2rms/R

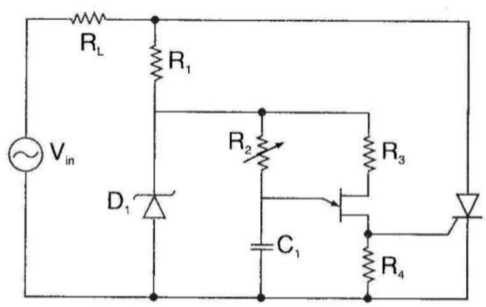
R = 230^2/1kW = 52.90Ω

Therefore W = $(155)^2$/52.90 = **454.15 watts**

(ii) At α=π/2, Vrms = 115V, Therefore W = $(115)^2$/52.90 = **250watts**

UJT Triggered SCR Phase Control

In SCR power control circuit a control circuit is needed to vary the firing or the phase angle at which the SCR is triggered. The value of phase angle controls the power delivered to the load. If we want to deliver the maximum power to the load, then the SCR must be triggered as soon as the a.c. voltage across it goes positive i.e., the firing angle must be zero. Therefore, the SCR will conduct for 180°after triggering. If the power requirement is below the maximum value, the firing angle must be between 0° and 180°. In order to adjust the firing angle between 0° and 180°, we need a control circuit. We have already seen that a 180° half-wave rectifier circuit can be used to accomplish the control. But this circuit is affected by loading and supply voltage variation. Therefore, this circuit does not give a better phase control. However, a better control cab be achieved by using a unijunction transistor (UJT) relaxation oscillator circuit.



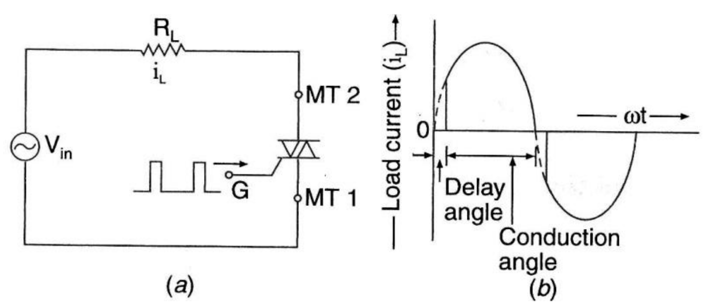
UJT triggered SCR phase control.

This circuit shows a UJT oscillator controlling a SCR circuit. The SCR is in it 'OFF' state until the UJT fires. When the UJT fires, the capacitor will discharge quickly through the resistor R4. This positive pulse will turn 'ON' the SCR. The SCR will remain 'ON' until the SCR line voltage approaches zero. At this point, the SCR will turn 'OFF' throughout the entire negative circle. A similar circuit can also be made for triac phase control.

TRIAC Power Control

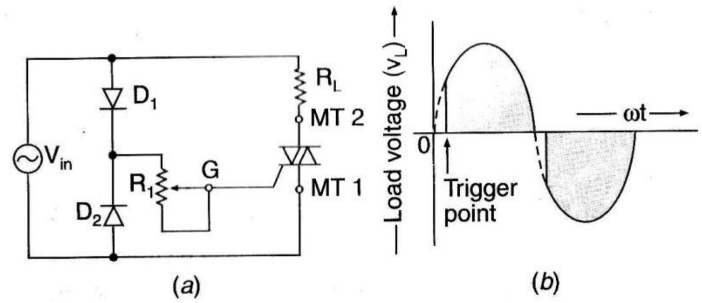
The triacs, like SCR's are also used to control average power delivered to the load by the method of phase control. The triac can be triggered such that the a.c. power is supplied to the load for a controlled position of each half-cycle.

The triac is in its 'OFF' position during each positive half-cycle of the a.c. for a certain interval called the delay angle or firing angle. Then triac is turned 'ON' and passes current through the load for the remaining portion of the positive half-cycle, except that the current passes in the opposite direction through the load. The action during both half-cycles is illustrated in the figure (a). The resulting waveform of load current is shown in figure (b).



Basic triac phase control.

A simple example of phase control using a triac is shown in the figure (a) shown below. The diodes are used to provide trigger pulses to the gate of the triac. The diode D1 conducts during the positive half-cycle. The value of resistance R1 sets the point on the positive half-cycle at which the triac triggers. It may be noted that during this portion of the a.c. cycle, M.T.2 and G are positive with respect to M.T.1.

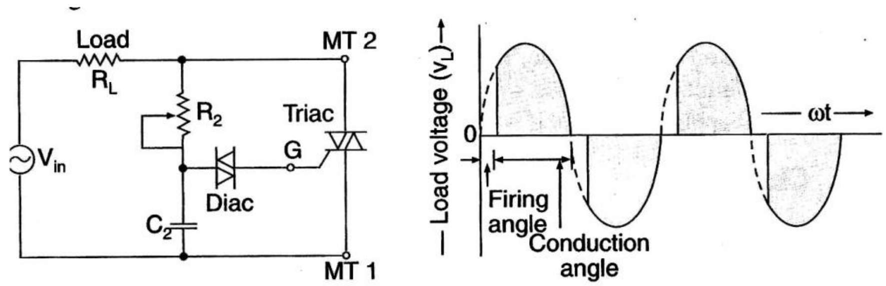


Triac phase control circuit.

The diode D2 conducts during the negative half-cycle and the resistance R1 sets the trigger point. It may be noted that during this portion of the a.c. cycle, M.T.2 and G are negative with respect to M.T.1. The resulting waveform of the voltage across the load resistor is shown in Fig. (b). In the control circuit applications, it is necessary that the triac turn 'OFF' occurs at the end of each positive and negative alteration of the input voltage. But the triac turn 'OFF' occurs, usually, before the alteration of (positive or negative), when the load current falls below the holding current value.

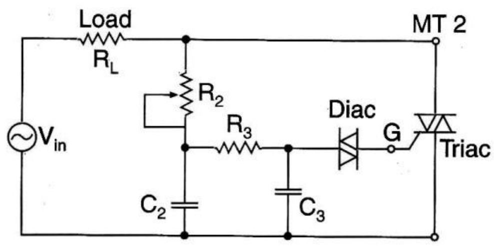
Diac-Traic Phase Control Circuit

Figure (a) below shows a basic diac-traic phase control circuit. When the input voltage increases, either positively or negatively, the capacitor C2 charges at the rate determined by setting of resistance R2. When the voltage across capacitor C2 exceeds the break over voltage of diac, it turns 'ON'. As a result of this, the capacitor C2 discharges through the conducting diac into the gate of triac. Hence the triac turns ON and it conducts current through the load. The waveform of voltage across the load is as shown in Fig. (b).



(a) Diac-triac phase control circuit. (b) Load voltage waveform.

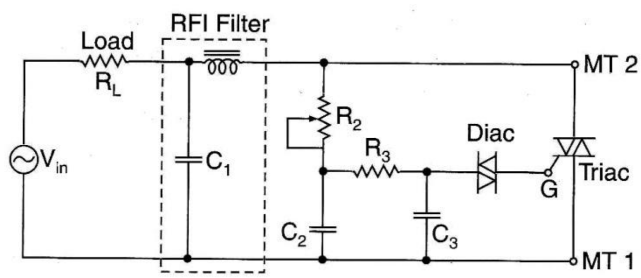
The circuit of Fig. (a) has a drawback that it can cause triac to trigger before the desired turn-ON time. Such early turn-ON gives a prior control at low conduction angles. This drawback can be minimized by including another time constant (R3.C3) as shown in Figure below.



Phase control circuit using double time constant.

This circuit can be adjusted to trigger triac over a wide range i.e., practically zero to full ON. The waveform of load voltage shown in Fig. (b) above indicates that the current rises quickly (in about 1 or 2 msec.) each time the triac conducts. This rapid rise produces noise or radio frequency interference (RFI), which may be radiated and can cause direct interference equipment. The following methods may be used to reduce radio frequency interference, depending upon the application.

1. In light dimming and speed controls, a RFI filter may be used as shown in figure below



Phase control circuit using RFI filter.

2. In heat controls, the current through an electrical heater may be turned ON for a few cycles and then turned OFF for a few cycles to maintain a desired temperature. If the turn ON is only allowed to take place when the voltage is zero, no rapid increase in current takes place as it does if the switching takes place during the cycle.

Applications: Diac-Traic phase control circuit can be used for light dimming, heat control or universal motor control.

Inverters

Classification of Inverters

Inverters can be classified on the basis of a number of factors:

(a) Classification According to the Nature of Input Source

Based on the nature of input power source, inverters are classified as

(i) Voltage source inverters (VSI)

(ii) Current source inverters(CSI)

In case of VSI, the input to the inverter is provided by a ripple free dc voltage source whereas in CSI, the voltage source is first converted into a current source and then used to supply the power to the inverter.

(b) Classification According to the Wave shape of the output voltage

The inverters can be classified according to the nature of output voltage waveform as:

(i) Square wave inverter
(ii) Quasi square wave inverter
(iii) Pulse-width modulated (PWM) inverters

A square wave inverter produces a square-wave ac voltage of a constant magnitude. The output voltage of this type of inverter can only be varied by controlling the input dc voltage. Square-wave ac output voltage of an inverter is adequate for low and medium power applications. However, the sine-wave output voltage is the ideal waveform for many high power applications. Two methods can be used to make the output closer to a sinusoid. One is to use a filter circuit on the output side of the inverter. This filter must be capable of handling the large power output of the inverter, so it must be large and will therefore add to the cost and weight of the inverter. Moreover, the efficiency will be reduced due to the additional power losses in the filter.

The second method, pulse-width modulation (PWM) uses a switching scheme within the inverter to modify the shape of the output voltage waveform.

Thyristor Inverter Classification

The thyristor invertors can be classified in the following categories:

1. According to the method of commutation
2. According to the connections

(a) Classification According to the Method of Commutation

According to the method of commutation, the SCR inverters can mainly be categorized in two types, viz

1. Line commutated inverters
2. Forced commutated inverters

1. Line Commutated inverters: In case of ac circuits, ac line voltage is available across the device. When the current in the SCR goes through a natural zero, the device is turned-off. This process is known as natural commutation process and the inverters based on this principle are known as line commutated inverters.
2. Forced Commutated Inverters: In case of dc circuits, since the supply voltage does not go through the zero point, some external source is required to commutate the device. This process is known as the forced commutation process and the inverters based on this principle are called as forced commutated inverters. As the device is to be

commutated forcefully, these types of inverters require complicated commutation circuitries. These inverters are further classified as: (i) Auxiliary commutated inverters and (ii) Complementary commutated inverters.

(b) Classification According to Connections

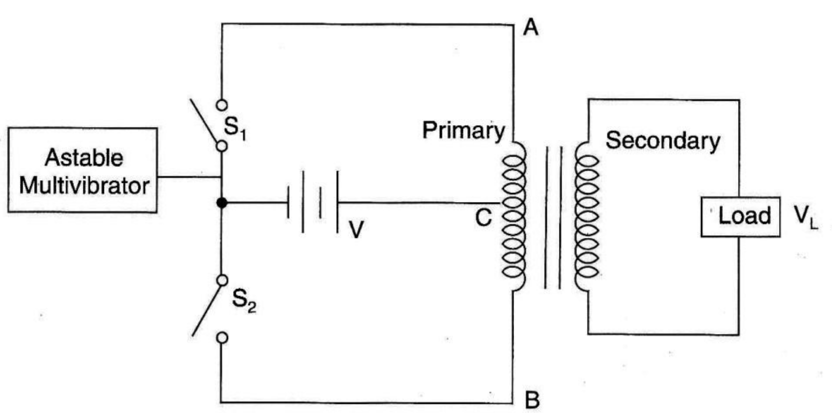
According to the connections of the thyristors and commutating components, the inverters can be classified mainly in three groups. These are:

1. Series inverters
2. Parallel inverters
3. Bridge inverters: Bridge inverters are further classified as: (i) Half-bridge and (ii) Full-Bridge.

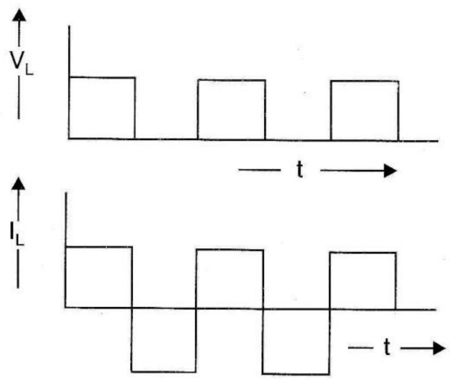
An inverter is a device that changes dc power into ac power. The inversion process can be achieved with the help of transistors, SCRs and tunnel diodes etc. For low and medium outputs, transistorized inverters are suitable but for high power outputs, SCR inverters are essential. For very low voltage and high current requirements, tunnel diode inverters are used.

For inverter applications, transistors have definite advantages over SCRs regarding the switching speed, simplicity of control circuitry, high efficiency and greater reliability. It is mainly due to this fact that SCR inverters require complicated circuitry for triggering and commutation.

The basic working principle of an inverter may be explained with the help of circuit shown in the following figure. It is called voltage-driven inverter because a dc voltage source is connected through



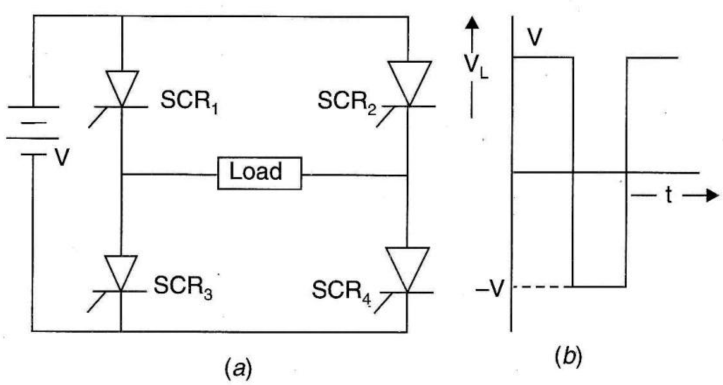
semiconductor switches directly to the primary of a transformer. In the figure S1 and S2 are switching devices which open and close alternately at regular intervals of time. The two switching devices are generally driven by an astable multi-vibrator operating at the desired frequency. When S1 is closed, the entire dc source voltage V is applied across points A and B of the transformer primary. S1 remains closed for a certain period of time after which it is cut off and S2 closes. It also remains closed for the same period of time during which the source voltage V is impressed across points B and C of the primary. S2 then opens out and S1 closes. In this way, an alternating voltage is applied across the primary which induces an ac voltage in the secondary. Since dc supply voltage is connected directly across the primary, the output waveform of the secondary voltage is a square wave (shown in figure below) irrespective of the type of load and load power factor. However, the waveforms of both the



primary and secondary currents depend on the type of load whether resistive, inductive or capacitive.

Single-Phase Inverter

Figure shows a single phase inverter with a load resistor using 4 SCRs working in pairs. The triggering and commutating circuitry of the SCRs has not been shown in the figure. The two thyristors SCR1 and SCR4 are triggered simultaneously so that load current passes through RL from left to right.



Exactly when these two SCRs are switched off by the commutating circuitry, thyristors SCR2 and SCR3 are triggered into conduction thereby sending current through RL from right to left. Hence, an ac voltage is developed across the load whose waveform is as shown in figure.

Push Pull Inverter

Figure shows an inverter which employs two SCRs and one transformer. These two SCRs are triggered into conduction alternately for the same period of time. As a result, current through the primary becomes alternating which induces an ac voltage across the secondary and hence the load. The secondary ac voltage has a square waveform. The capacitor C is connected across the anodes of the two SCRs and provides commutation i.e. switching off of the SCRs. The capacitor charges to double the supply voltage as a result of transformer action between the two halves of the primary winding. This large voltage is sufficient to reverse-bias the SCRs and drive the holding current below its rated value.