Subject Name: **Industrial Electronics**

Subject Code: **EC-5005**

Semester: **5th**

Unit II

Silicon controlled rectifier (SCR), constructional features, principle of operation, SCR terminology, turn-on methods, turn-off methods, triggering methods of SCR circuits, types of commutation, comparison of thyristor and transistors, thermal characteristics of SCR, causes of damage to SCR, SCR overvoltage protection circuit, series and parallel operation of SCRs, Line commutated converters (half wave rectifier with inductive and resistive load, single phase and three phase full wave rectifiers).

Silicon Controlled Rectifier (SCR):

SCR is a unidirectional semiconductor device which has three junctions and four P-N-P-N layers. Figure1 (i) shows P-N-P-N layer structure. Three terminals are taken; one from the outer P-type material called Anode (A), second from the outer N-type material called Cathode (K) and the third from the base of transistor called as Gate (G). In normal operating condition of SCR, Anode is kept on positive potential w. r. t. Cathode and small positive voltage applied between the Gate and Cathode terminal. Figure 1 (ii) Shows the symbol of SCR.

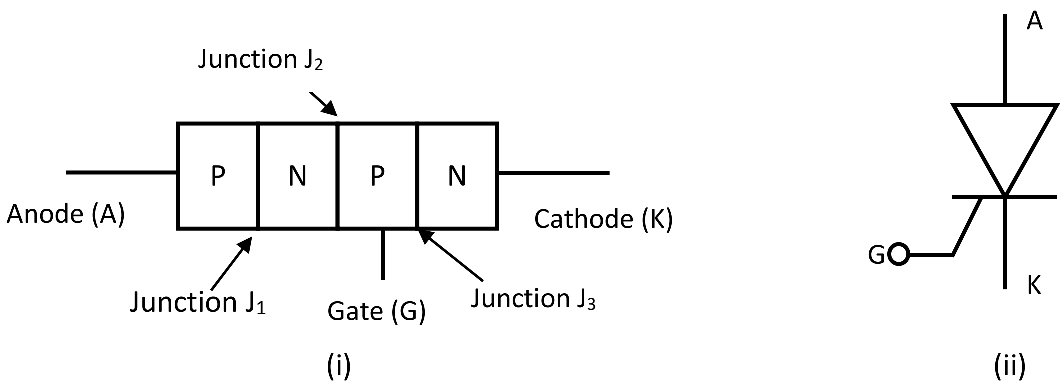
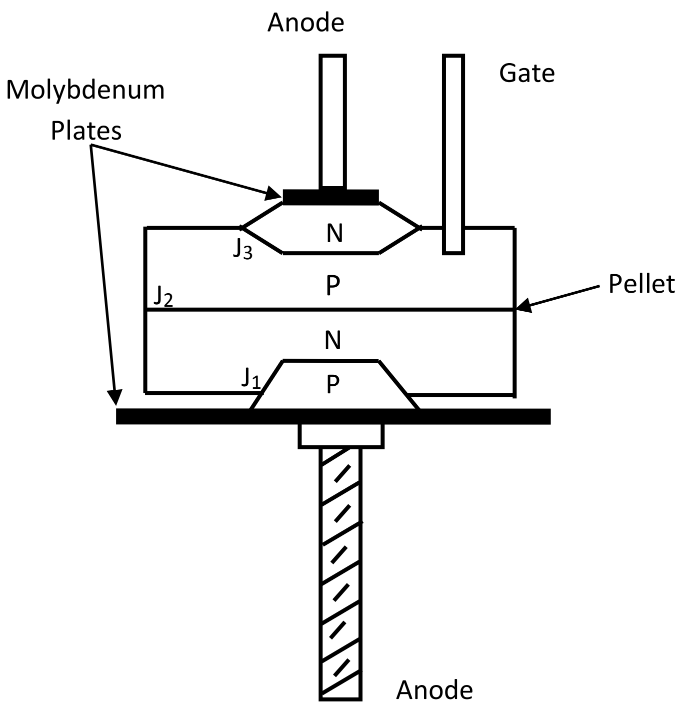


Figure 1 (i) Layer structure, (ii) Symbolic Representation

Constructional details:



It consists of four layer pellet of P and N type semiconductor materials. The junctions are diffused. The contact with anode can be made with an aluminum foil and through cathode and gate by metal sheet. The mesa type construction is shown in figure 2. In this technique, the inner junction J_2 is obtained by diffusion, and then the outer two layers are alloyed to it. The PNPN pellet is properly braced molybdenum plates to provide greater mechanical strength and make it capable of handling large current and voltages. These plates are soldered to an aluminum stud, which is threaded for attachment to a heat sink. The heat sink provides an efficient thermal path for conducting the internal losses to the environment.

Figure 2 Mesa type constructions

Principle of operation

(i) Forward Blocking Mode:

In this mode, the SCR is forward biased by connecting its Anode to positive terminal and Cathode to negative terminal of the battery with gate open as shown in Figure 3. Under this condition, junction J_2 is reverse biased while junctions J_1 and J_3 are forward biased due to junction J_2 is reverse biased no current flows and the SCR do not act as closed switch. If the applied input voltage V is gradually increased, a stage is reached when reverse biased junction J_2 breaks down and current start flowing abruptly and that state is called as forward conduction ON state. The maximum voltage at which SCR conducts without applying gate voltage is called Break over voltage.

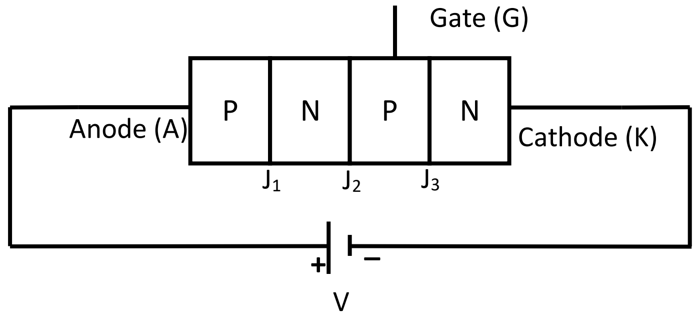


Figure 3 SCR with open Gate

(ii) Forward Conduction Mode:

In this mode, the SCR is forward biased by connecting its Anode to positive terminal and Cathode to negative terminal of the battery with applying positive voltage to gate terminal as shown in figure 4. Under this condition the electrons from N-type material start moving across junction J_3 whereas holes from p-type towards the negative potential of the battery. The electrons from junction J_3 are attracted across junction J_2 and gate current starts flowing. As soon as the gate current flows, anode current increases. The increased anode current in turn makes more electrons available at junction J_2 and in this state the device is in ON state.

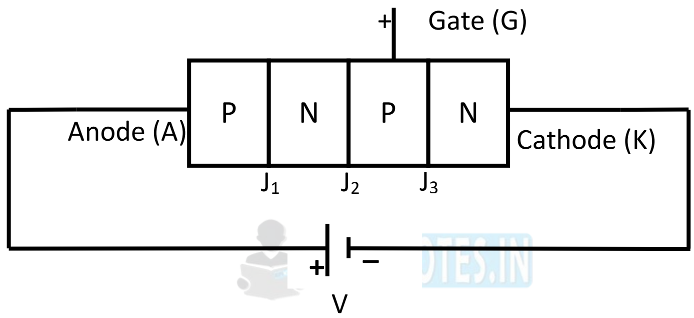


Figure 4 Positive Gate Voltage applied w. r. t. Cathode

(iii)Reverse Blocking Mode:

In this mode, the SCR is reverse biased by connecting its Anode to negative terminal and Cathode to positive terminal of the battery with gate terminal open as shown in figure 5. Due to this the junctions J_1 and J_3 are reversed biased, which do not allow the current to flow through the device, though the junction J_2 is forward biased. Hence the device remains in reverse blocking state.

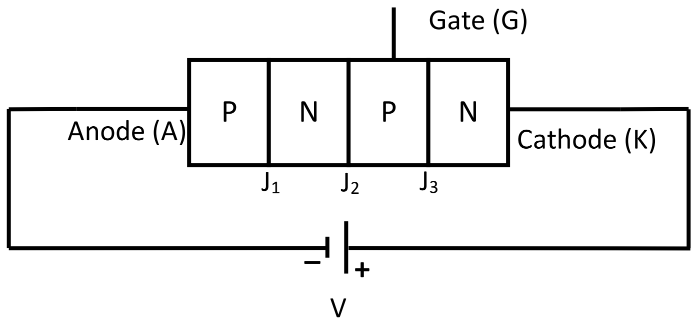


Figure 5 Reverse biasing of SCR

V-I characteristics of SCR

Figure 6 shows the V-I characteristics of a SCR.

(i) Forward characteristics:

When Anode of SCR is connected to positive terminal of the battery w. r. t. Cathode under this condition SCR is forward biased. The figure 6 shows the graph between forward Voltage and forward current is called the forward characteristics of SCR. In Figure 6 OABC is the forward characteristics of SCR at I_G=0.

If the input voltage is increased from zero, a point is reached (point A) when the SCR starts conducting. Under this condition, the voltage across SCR suddenly drops as shown by dotted curve AB and is called as negative resistance region. If proper current is applied on Gate terminal then SCR can be turned ON earlier than forward break over voltage. The line between BC is called forward conduction ON state.

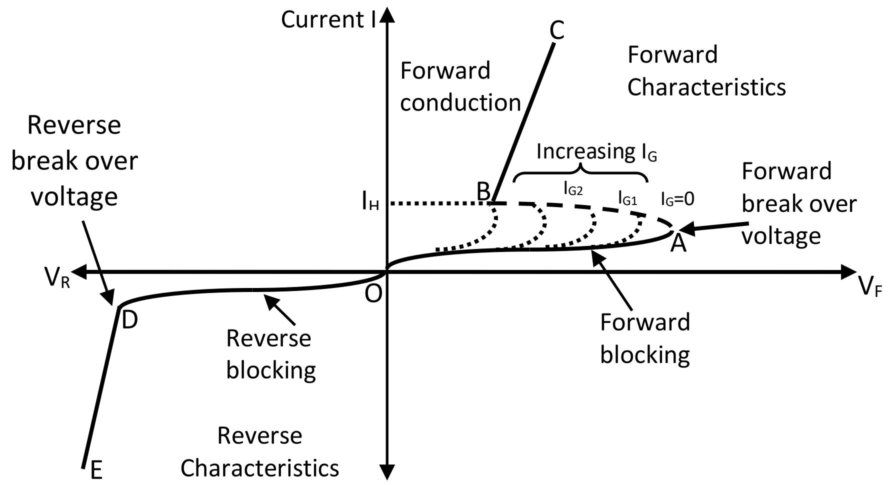


Figure 6 V-I characteristics of SCR

(ii) Reverse characteristics:

When Anode SCR is connected to negative terminal of the battery w. r. t. Cathode under this condition SCR is reversed biased. The figure 6 shows the graph between reverse voltage and reverse current is called the reverse characteristics of SCR.

If the reverse voltage is gradually increased then flows through the SCR and at some reverse voltage, avalanche breakdown occurs and large reverse current flows through the SCR as shown in figure 6 as DE and called as reverse breakdown voltage.

Important Terms

(i) Break over voltage
(ii) Peak reverse voltage
(iii) Holding current
(iv) Latching Current

(i) Break over voltage:

When the gate is open and a minimum positive anode to cathode voltage is applied the SCR starts conducting that stage is called break over voltage.

(ii) Peak reverse voltage (PRV):

It is the maximum value of reverse voltage that can be applied across the SCR without conducting in reverse direction.

(iii) Holding current:

It is the minimum value of anode current required to keep the SCR in conduction mode. If the anode current of SCR is reduced below the holding current value then it cannot maintain to remain in ON state and revert to OFF state.

(iv) Latching Current:

The minimum value of current required to maintain conduction immediately after the SCR is switched from Off state to ON state with Gate terminal open. When the latching current is reached the SCR remains in ON state until anode current is reduced below the holding current.

Two transistor analogy of SCR:

Operating principle of SCR can be easily understood by the **two transistor model**, where two types of transistor is used one in NPN and other is PNP transistor as shown in figure7.

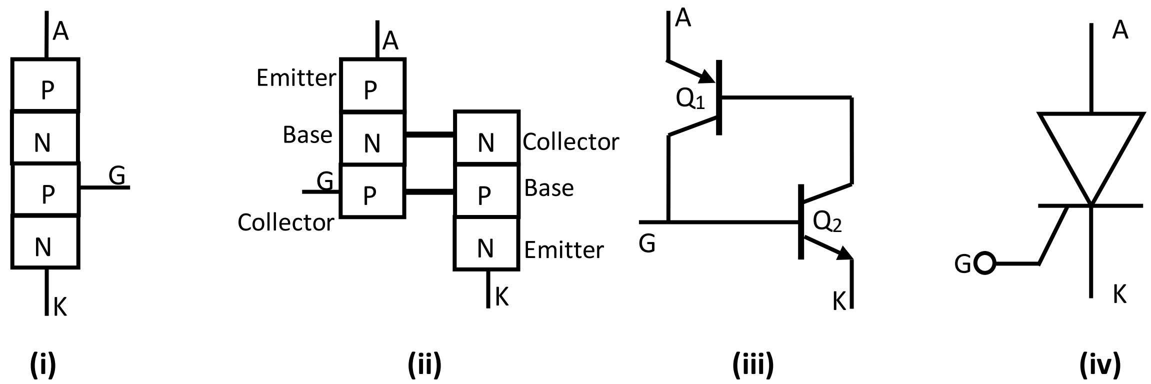


Figure 7 (i) Layer structure,(ii) Two transistor model,(iii)Symbolic model,(iv) Symbolic Representation

The layer structure of SCR is shown in Figure7 (i). Two transistor layers are shown in Figure 7 (ii). Thus, the equivalent circuit of SCR is composed of PNP transistor and NPN transistor connected as shown in Figure 7 (iii). In the diagram base of one transistor is connected to collector terminal of another transistor and making a device to work in positive feedback loop. The working of SCR can be easily explained from its equivalent circuit.

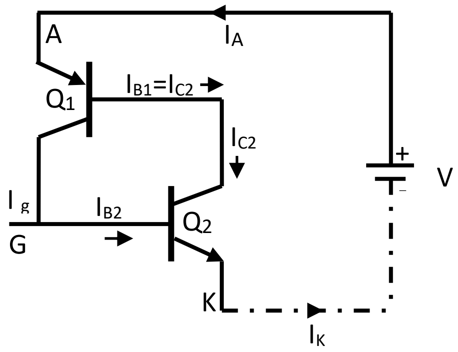


Figure 8 Equivalent circuit of SCR with supply voltage V

Figure 8 shows the equivalent circuit of SCR with supply voltage V. Initially the supply voltage V is less than break over voltage. With gate open there is no base current flows through the transistor Q_2 and in this condition no current flows through the collector of Q_2 and hence no current flows through the base of transistor Q_1 and SCR does not conduct. When a small gate current I_G flows through the base of transistor Q_2 , the transistor Q_2 conducts and collector current I_{C2} flows through the base of Q_1 ,therefore the collector of transistor Q1 increases. But the collector current of Q_2 is the base current of Q_1 which combines with the gate current I_G .It thus results in the enhancement of the base current of Q_2. This phenomenon is cumulative since an increase in current of one transistor causes an increase in current of the other transistor. As a result ,both the transistor are driven into saturation causing a large value of current I_A to flows through both the transistors and in such condition SCR is said to be turned ON.

Let's for transistor Q_1

$I_{c1} = \alpha_1 I_A + I_{CBO1}$ ----------------- (i)

And that for transistor Q_2

$I_{c2} = \alpha_2 I_K + I_{CBO2}$ ----------------- (ii)

Again $I_{c2} = \beta_2 I_{B2}$

Now, by the analysis of two transistors model we can get anode current,

$I_A = I_{c1} + I_{c2}$

Substituting the value of I_{c1} and I_{c2} results

$I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_K + I_{CBO2}$-----(iii)

Cathode current is given by

$I_K = I_A + I_g$

By substituting this value of I_k in equation (iii) we get

$I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2 (I_A + I_g) + I_{CBO2}$

$I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_A + \alpha_2 I_g + I_{CBO2}$

$I_A = \alpha_1 I_A + \alpha_2 I_A + \alpha_2 I_g + I_{CBO1} + I_{CBO2}$

$I_A = I_A(\alpha_1 + \alpha_2) + \alpha_2 I_g + I_{CBO1} + I_{CBO2}$

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

$I_A[1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$

Or

$I_A[1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$

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

From the above relation it is clear that with increasing the value of $(\alpha_1 + \alpha_2)$ towards unity, corresponding anode current will increase.

Turn-ON methods

A Thyristor can be switched from a non conducting state to a conducting state in several methods:

(i) Forward voltage triggering:

In this method when anode is kept positive w. r. t. Cathode the device is in forward biased condition with gate open, the reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward break over voltage. At this voltage SCR changes the state from OFF to ON state.

(ii) Thermal Triggering (Temperature Triggering):

In forward biased condition of SCR junction J_2 is reversed biased under such condition reverse current flows through the SCR. This reverse current is highly sensitive to variation in temperature. If the temperature of SCR increases, then there is increase in the number of electron and hole pairs across the junction J_2 which results in increase of reverse leakage current. This increases the current gain of both the transistors .due to the regenerative action the summation of current approaches to unity and the SCR is turned ON.

(iii) Radiation Triggering (Light Triggering):

When junction J_2 is reversed biased in forward biased condition then width of the depletion layer is increased. When the beam of light with adequate energy falls on gate cathode junction can produce sufficient energy to break electron-hole pairs, resulting in an increase in reverse leakage current and thus SCR is turned ON.

(iv) $\frac{dv}{dt}$ Triggering:

A rapid rate of increase in forward anode to cathode voltage produces a sufficient gate current to turn ON the SCR. This gate current is caused by anode-gate and gate-cathode junction capacitances. When SCR is forward biased, junction j_1 and j_3 is forward bias and junction j_2 is reverse bias. This reverse biased junction j_2 will breakdown if the forward voltage is suddenly applied to turn ON the SCR.

(iv) Gate Triggering:

When SCR is forward biased, junction j_1 and j_3 is forward bias and junction j_2 is reverse bias, under such condition when the minority carriers are injected into the gate region the forward blocking voltage of the SCR is decreased and SCR is turned ON.

Turn-off methods of SCR:

Once the SCR is in forward conduction ON state, it remains in ON state even Gate current is removed.

(a) Natural Commutation

This type of commutation takes place when AC supply voltage is applied across the SCR. In positive half cycle, SCR is forward biased and current flows through the SCR, For negative half cycle, SCR is reverse biased and a reverse voltage appears across the SCR and it turns off by itself. Hence no special circuits are required to turn off the SCR.

(b) Reverse-bias Turn-OFF

This type of commutation takes place when DC supply voltage is applied across the SCR. In this case natural commutation is not possible because the polarity of the DC supply remains unchanged. Hence special methods must be used to reduce the SCR current below the holding value or to apply a reverse voltage across the SCR for a time interval greater than the turn off time of the SCR. This technique is called FORCED COMMUTATION and is applied in all circuits where the supply voltage is DC.

Comparison between Natural and Forced communication:

S.N.	Natural commutation	Forced Commutation
1	Requires AC voltage at input	Requires DC voltage at input
2	External components are not required	External components are required
3	Used in controlled rectifiers, AC voltage controller	Used in choppers and inverter
4	SCR turns OFF due to negative supply voltage	SCR turns OFF due to current and voltage both
5	No power loss takes place during commutation	Power loss takes place during commutation
6	Less cost	Expensive

Triggering methods of SCR circuits

There are two methods of AC voltage triggering namely (i) R Triggering (ii) RC triggering

(i) Resistance triggering:

The figure 9 shows the resistance triggering.

- When the positive half cycle is applied across the SCR the variable resistor provides the sufficient current to diode to provide gate pulse to turn ON the SCR from OFF state.
- Value of variable resistor is selected such that it can turn on the SCR to conduct.
- The diode D is provides the gate current for positive half cycle and remain reverse biased in negative half cycle.
- The maximum firing angle of 90° can be achieved by this method.

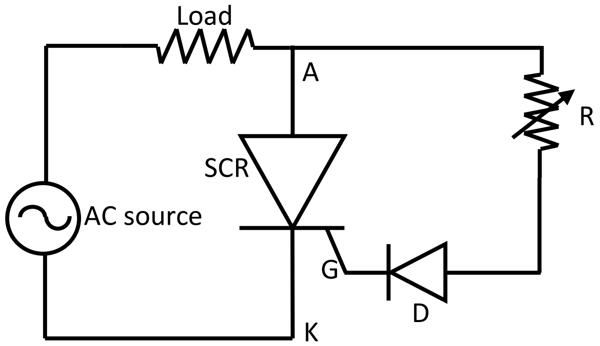


Figure 9 Resistance triggering circuit diagram

(ii) RC Triggering

The limitation of resistance triggering circuit can be neglected by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees.

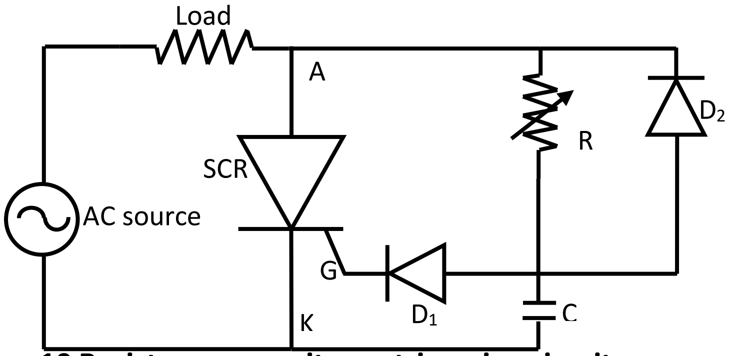


Figure 10 Resistance-capacitance triggering circuit

The above figure 10 shows the resistance-capacitance triggering.

- For the positive half cycle of the applied AC supply the capacitor is charged to the peak voltage using variable resistance R which controls the charging time of the capacitor.
- As the capacitor is fully charged then it discharges through the diode and gate current flows through the SCR to turn on.
- When the negative half cycle appears across the diode, it is reverse biased and do not allow current to flow through gate terminal hence it does not conduct.

(iii) Pulse Gate Triggering:-

For providing the isolation between Gate terminal and load pulse triggering method is employed. The Gate firing circuit requires low voltage to turn ON the SCR, whereas Load is connected across higher AC supply voltage. The figure 11 shows the Pulse gate triggering circuit.

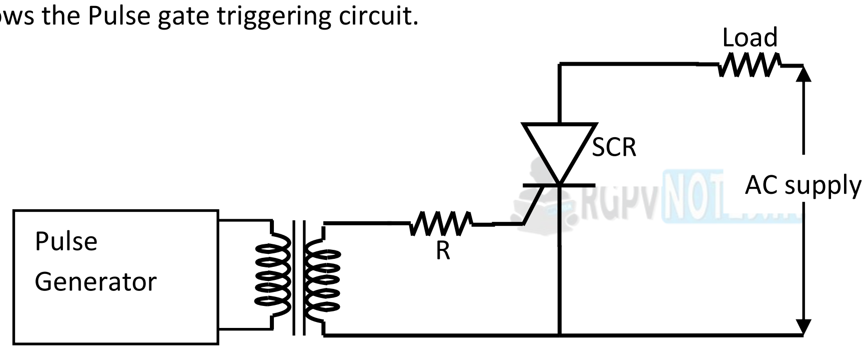


Figure 11 Pulse gate triggering circuit

- The sequence of pulses is applied periodically to the gate of the SCR to turn ON.

Thyristor Commutation Techniques

Class A: Self Commutated by a Resonating Load

Figure 12 shows the Class 'A' Commutation.

When the SCR is forward biased and applied voltage is more than break over voltage then the current flows through the capacitor and inductor. Inductor store the energy in form of magnetic field and when the reverse bias is applied the inductor changes its polarity and reverse biases the SCR to turn off. The capacitor discharges through the resistance R.

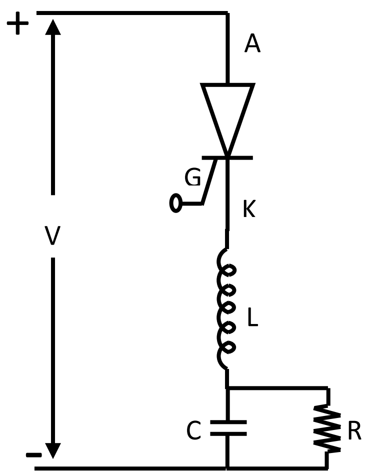


Figure 12 Class 'A' Commutation

Class B: Self Commutated by an L-C Circuit

Figure 13 shows Class 'B' commutation.

When the positive half cycle appears across the SCR, capacitor C charges to applied forward voltage before a gate pulse is applied. When the SCR is triggered the current flows through the load and reach to ground terminal. When the capacitor is fully charged then inductor changes its polarity and SCR is turned off.

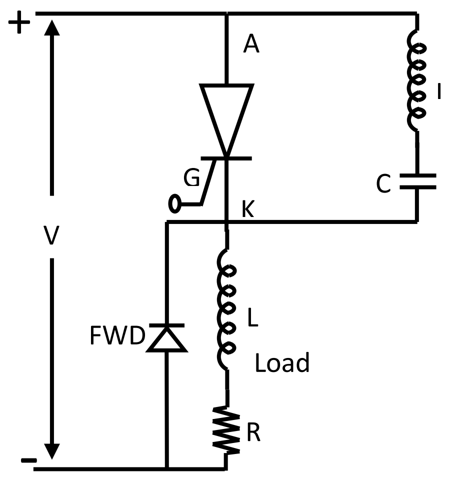


Figure 13 Class 'B' Commutation

Class C: using auxiliary SCR

Figure 14 shows Class C Commutation.

This circuit uses two SCRs. From two SCRs one acts as a main and other as auxiliary. When the input is applied the current is divided into two arms and the capacitor charges to its maximum value. When it is charged to maximum value it discharges and forced the main SCR to turn off. The same procedure is applied when capacitor charges in opposite direction.

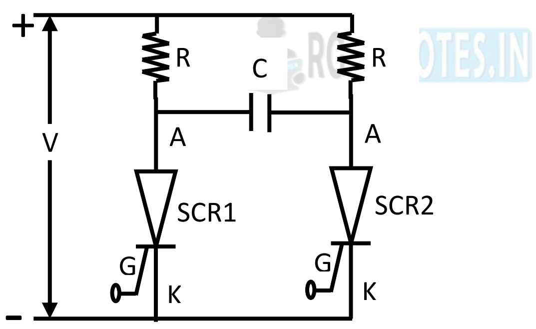


Figure 14 class 'C' Commutation

Class D: Figure 15 shows Class D Commutation.

Class D Commutation uses an auxiliary SCR to commutate the main SCR. The main SCR forms the power circuit while the diode D, inductor L and SCR_A forms the commutation circuit.

When the DC supply voltage V is applied, both SCRs are in OFF state and hence the capacitor voltage is zero. In order to charge the capacitor, SCR_A must be triggered first. So the capacitor charges through the path V+ - C+ – SCR_A- R_L- V-.

When the capacitor is fully charged then the SCR_A turned OFF because no current flow through the SCR_A. If the SCR_M is triggered, the current flows in two directions; one is the load current path V+ – SCR_M- R_L - V- and another one is commutation current path C+ – SCR_A - L- D- C.

When capacitor is completely discharges, its polarities will be reversed but due to the presence of diode the reverse discharge is not possible. When the SCR_A is triggered, capacitor starts discharging through C+ – SCR_A- SCR_M - C-. When this discharging current is more than the load current the SCR_M is turned OFF.

Again, the capacitor starts charging through the SCR_M to a supply voltage V and then the SCR_M is turned OFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated.

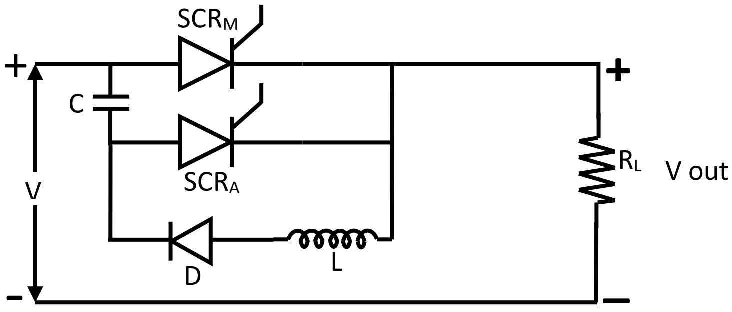


Figure 15 class 'D' Commutation

Class E: External Pulse Source for Commutation

Class E Commutation uses an external pulse source to produce the reverse voltage across the SCR. The circuit is shown in figure 16. Pulse source used is pulse transformer with coupling between the primary and secondary winding. If the SCR is needed to be commutated, pulse duration equal to the turn OFF time of the SCR is applied. The SCR is turned ON then the load current flows through the pulse transformer. If the pulse is applied to the primary of the pulse transformer, a voltage is induced in the secondary winding of the pulse transformer. This induced voltage is applied across the SCR as a reverse bias and hence the SCR is turned OFF. The capacitor offers zero impedance to the high frequency pulse.

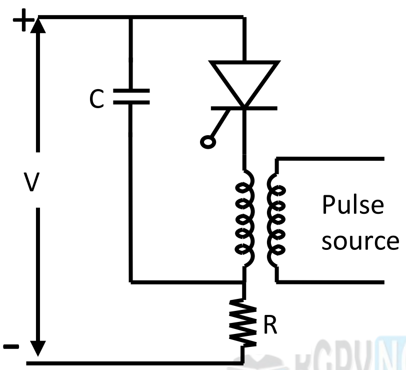


Figure 16 class 'E' Commutation

Comparison of thyristor and transistor

S.N.	Thyristor	Transistor
1	Thyristor is four layer device	Transistor is three layer device
2	Thyristor operates on higher voltage and current ratings	Transistor operates on lower voltage and current ratings
3	Rating of thyristor is in K Watts	Rating of transistor is in Watts
4	Power handling capacity is good	Power handling capacity is poor
5	Thyristor needs only a pulse to make it conducting ON state	Transistor needs a continuous current for keeping it in a conducting state
6	Internal power losses in a thyristor are much smaller	Internal power losses in a transistor are much larger than thyristor
7	Thyristors have higher voltage drop, and need turn-off circuit arrangement	Transistors have lower voltage drop, and need no turn-off circuit arrangement

Thermal characteristics of SCR

Internal heat is developed in SCR due to following reasons;

(i) ON state conduction losses,
(ii) Switching losses and
(iii) Off state losses caused by the blocking current

Heat is also generated due to overload and temperature variation. These losses occur in thin wafer type of fabricated SCR. Heat sinks made up of copper or aluminum are always used with SCR to maintain the temperature of the device, so that it can work on faster rate. Aluminum is used as heat sink because of low weight and high thermal conductivity.

The below parameter play important role while selecting SCR:

(i) **Junction Temperature T_J:** It is the temperature within the SCR which establishes the internal thermal resistance.
(ii) **Thermal Resistance θ:** The thermal resistance is the ratio of the temperature difference across it in the direction of heat flow and power giving rise to this temperature difference. It is expressed by (°C/W).
(iii) **Thermal resistance-Junction to case θ_{JC}:** It is the ratio of the difference between the junction temperature T_j and the case resistance Tc to the total power loss P. It is expressed by:

$$\theta_{JC} = \frac{T_j - T_c}{P}$$

(iv) **Thermal resistance-case to heat sink θ_{CS}:** It is the ratio of the difference between the case temperature T_c and the heat sink temperature T_s to the total power loss. It is expressed by:

$$\theta_{CS} = \frac{T_C - T_S}{P}$$

(v) **Thermal resistance-heat sink to cooling medium θ_{SC}:** It is the ratio of the difference between the sink temperature T_s and the cooling medium temperature T_A to the total power loss P. It is expressed by:

$$\theta_{SA} = \frac{T_S - T_A}{P}$$

(vi) **Thermal resistance- junction to cooling medium θ_{JA}:** It is the ratio of the temperature difference between the junction temperature T_J and the cooling medium temperature T_A to the total power loss P.

$$\theta_{JA} = \frac{T_J - T_A}{P}$$

For conventional cooling, power loss is given by

$$P = \frac{T_j - T_c}{\theta_{JC}} = \frac{T_C - T_S}{\theta_{CS}} = \frac{T_S - T_A}{\theta_{SA}}$$

$$Also\ P = \frac{T_j - T_A}{\theta_{JA}}$$

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

Heat flow and temperature diagram of a SCR is shown in figure 16:

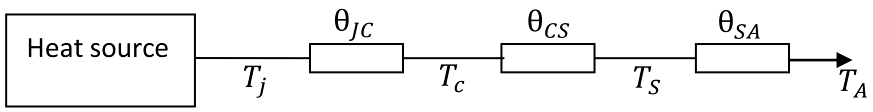


Figure 16 Heat flow and temperature diagram of a SCR

Causes of damage to SCR

When the voltage and current rating exceeds beyond the limit the damage to SCR takes place. Most of the SCR get damaged due to the reverse voltage applied across to it. Such destruction of SCRs results in melting of silicon near the junction because of the leakage currents. Excessive reverse power dissipation destroys the device. Over voltage in forward biased condition also damage the SCR. Semiconductors cannot withstand on higher voltage w. r. t. to the given rating of the device. Transient voltages occur due to make and break of the AC contractors which creates the spikes in the operation of SCR and hence damaged.

Snubber circuit: Preventing Damage to SCR

A relative sudden interruption of reverse anode current towards the end of the commutation, result to causes a large e. m. f. to be induced in the anode circuit. This high transient voltage may causes damage to the SCR. To avoid such damage a snubber circuit which is series combination of resistor and capacitor is connected in parallel with the SCR such that the energy is trapped in anode circuit during commutation transients finds a bypass path through this R-C circuit and thus no damage to SCR takes place. The R-C network controls the rate of change of voltage across the SCR during the blocking state. Figure 17 shows the circuit diagram of preventing damage to SCR using snubber circuit. Resistance R prevents damage caused by minority charge carrier storage during commutation. Capacitor C provides a path for reverse current when the SCR is suddenly blocks at the end of the minority carrier storage time, but charges with polarity during forward blocking and then discharges rapidly through the SCR at turn ON.

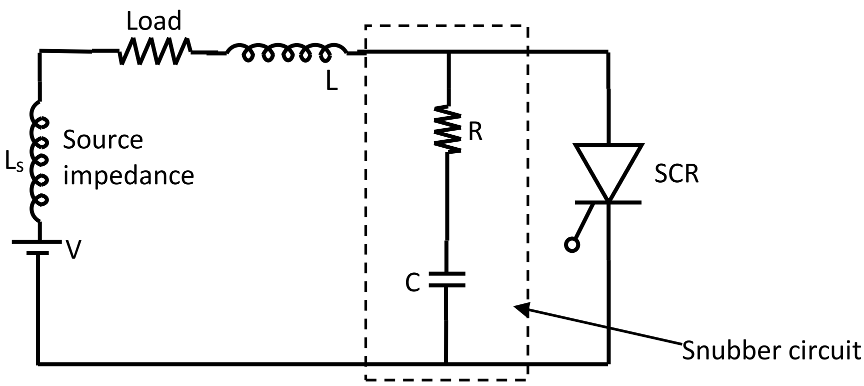


Figure 17 Preventing damage to SCR using snubber circuit

When a sudden voltage appears across the SCR the current is bypassed to the RC network. This is because the capacitor acts as a short circuit which reduces the voltage across the SCR to zero. As the time increases, voltage across the capacitor builds up at slow rate such that dv/dt across the capacitor is too small to turn ON the SCR. Therefore, the dv/dt across the SCR and the capacitor is less than the maximum dv/dt rating of the SCR.

Normally, the capacitor is charged to a voltage equal the maximum supply voltage which is the forward blocking voltage of the SCR. If the SCR is turned ON, the capacitor starts discharging which causes a high current to flow through the SCR. This produces a high di/dt that leads to damage the SCR. And hence, to limit the high di/dt and peak discharge current, a small resistance is placed in series with the capacitor as shown in above. The snubber circuit can also be connected to any switching circuit to limit the high surge or transient voltages.

SCR overvoltage protection circuit

The thyristor crowbar circuit shown is in figure 18

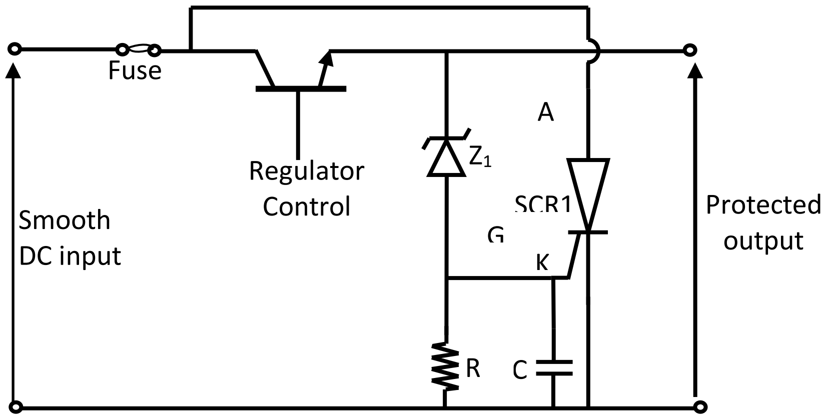


Figure 18 SCR overvoltage protection circuit

The SCR over voltage protection circuit is connected between the output of the power supply and ground. The Zener diode voltage is chosen to be slightly above that of the output. A 5 volt rail may run with a 6.2 volt Zener diode. When the Zener diode voltage is reached, current will flow through the Zener and trigger the silicon controlled rectifier. This will then provide a short circuit to ground, thereby protecting the circuitry that is being supplied from any damage and also blowing the fuse that will then remove the voltage from the series regulator.

The ability of SCR is to carry a relatively high current of five ampere and short current peak of 50 and more amps. The small resistor, often around 100 ohm from the gate of the SCR to ground is required so that the zener can supply a reasonable current when it turns on. It also clamps the gate voltage at ground potential until the zener current flows. The capacitor is present to ensure that short spikes do not trigger the circuit.

Series and parallel operation of SCR

When a single SCR of required rating is not available or when high reliability is required then the SCRs are required to be connected in series connection. When a single SCR is not capable to handle the current requirements then parallel connection is required. Series and parallel connection is required to be connected to suit the voltage and current requirements of the circuit for particular applications. Series and parallel combinations are also often used when it is required to control low- voltage high current circuits or high voltage low currents circuits because a SCR of suitable voltage and current rating may not be available.

Series Connected SCR:

Series connected SCR is required to enhance their peak inverse voltage. The properties of two SCR of the same make and rating are never same. The SCR with minimum leakage current has maximum voltage across it. The voltage and current characteristics of these devices are non linear, they divide the total applied voltage in inverse proportion of their leakage currents. Therefore some sort of equalization method must be applied to distribute the voltage equally across the SCR. The figure 19 shows the circuit diagram and related waveform of series connected SCR.

The power dissipated in the resistor R is low when the resistance is large. The transient sharing of voltage is accomplished by connecting a capacitor across each SCR. The resistance R_T in series with the capacitor C is used to prevent a flow of large discharge current through the SCR during turn ON.

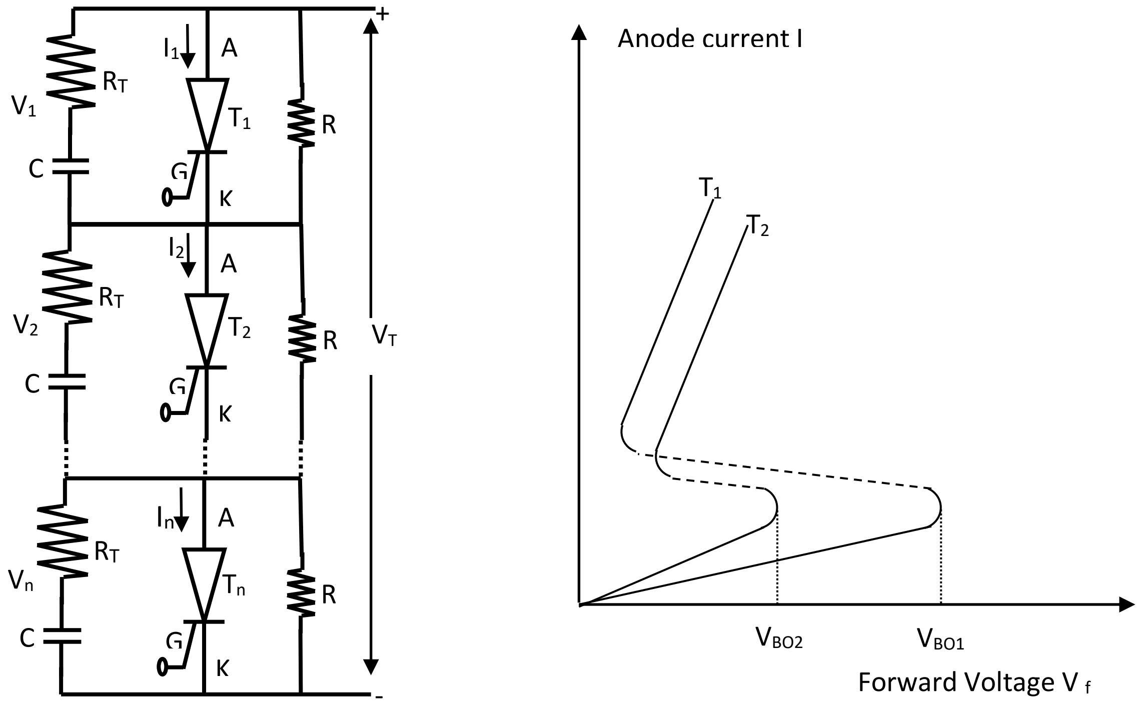


Figure 19 Series Connected SCRs with related waveforms

Parallel Connection of SCR

If it is required to deliver a load current that is much larger than that which can be controlled by the largest available single SCR than the parallel connection of two SCR is required. Because of the unequal dynamics resistances of both the SCR the current flowing through both the devices do not remain same. The non uniformity of the forward characteristics of the SCRs is the major factor responsible for current imbalance. The problem during the operation is the differences in turn on time, delay time, finger voltage and the loop inductances. The parallel connection also required the knowledge of latching current, holding current, on stage voltage drop and thermal resistances. Figure 20 shows the parallel connection of two SCRs for handling the load current.

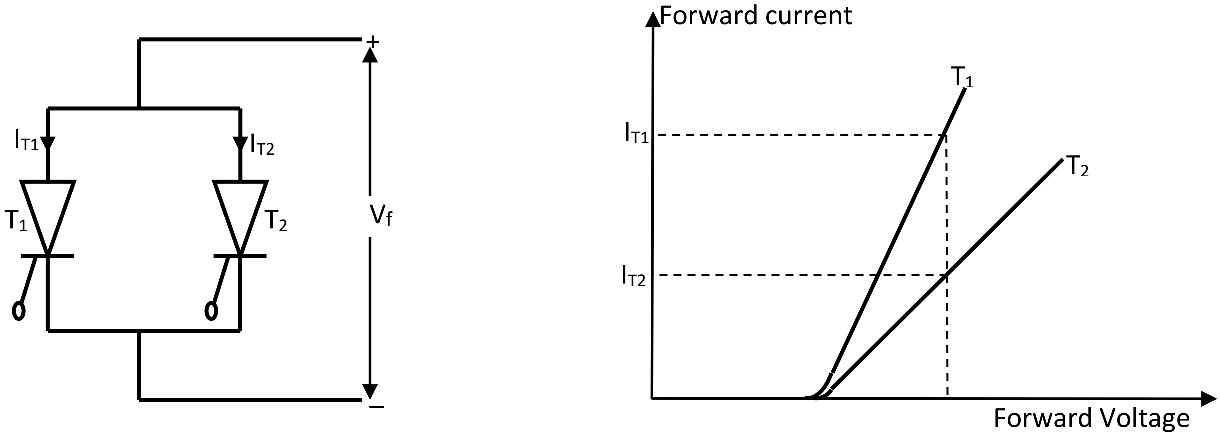


Figure 20 Parallel Connection of two SCR with related waveform

When the two or more SCRs are connected to an AC source and fired at an angle α which is quite close to zero, all the SCRs would not turn simultaneously. As a result imbalance current flows through the SCRs.

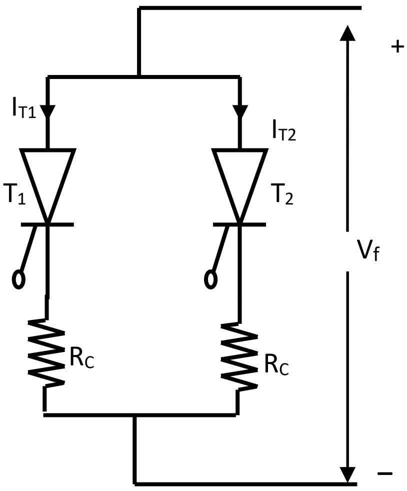
Equalization of current imbalance:

The imbalance of current can be reduced by the flowing methods:

1. Resistance compensation method
2. Inductive compensation method

1. Resistance compensation method

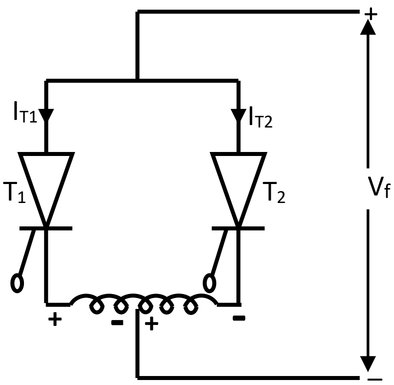
   If the two SCRs of different forward current rating I_{T1} and I_{T2} are to be operated then the same value of resistance R_C can be used for each unit to ensure proper current sharing by the SCRs. The 20 (a) shows the resistance compensation method.



Let V_{T1} and V_{T2} is respective voltage drop across the two SCRs and forward current I_{T1} and I_{T2} flows through two SCR. As the SCRs are connected in parallel so voltage drop across the two branches must remain same. By adding resistances in series with each SCR increases the power losses.

Figure 20(a) Resistance compensation method

2. Inductive compensation method



For providing balance condition between two SCRs a balancing inductor is used to improve the regulation. If SCR T_1 carries a changing and large current, the net induced e. m. f. in series inductor will tends to oppose that current. Because of the coupling and direction of the induced current voltage in series with that of the inductor of SCR T_2, it increases the current in T_2, thereby producing a balancing action. The Inductive compensation method is shown in figure 20(b).

Figure 20(b) Inductive compensation method

Half wave rectifier with resistive load

As shown in figure 21 primary of transformer is connected to AC mains supply with which SCR becomes forward bias in positive half cycle. T_1 is triggered at an angle α, T_1 conducts and voltage is applied across R.

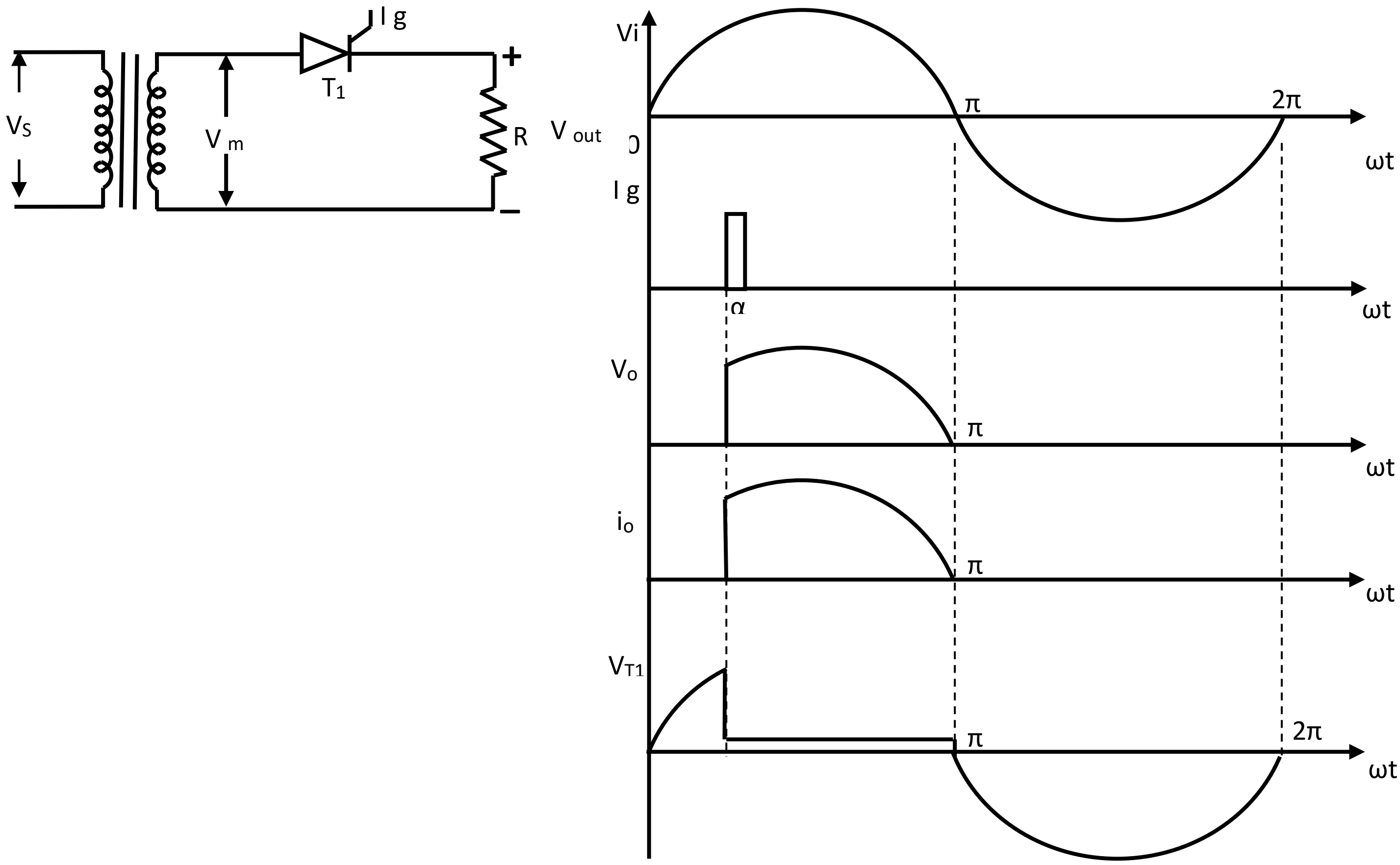


Figure 21 half wave controlled rectifier circuit and related waveform

- During positive half cycle of the applied input signal, the SCR is forward biased and T_1 is in forward blocking state.
- When the gate trigger pulse is applied at α angle, T_1 comes into forward conducting state.
- As the load is resistive so output voltage and current is in same phase, so at α angle, output voltage change abruptly then follow the applied positive input signal.
- After π angle negative half cycle is applied as input signal, the SCR is reversed biased and T_1 is in reverse blocking state.
- The voltage across the T_1 increases as per the applied input signal up to α angle, on α angle the voltage across the T_1 decreases abruptly and remains constant up to π angle and after that the voltage drop increases according to applied input signal.

Half wave rectifier with resistive and inductive load with fly wheel diode

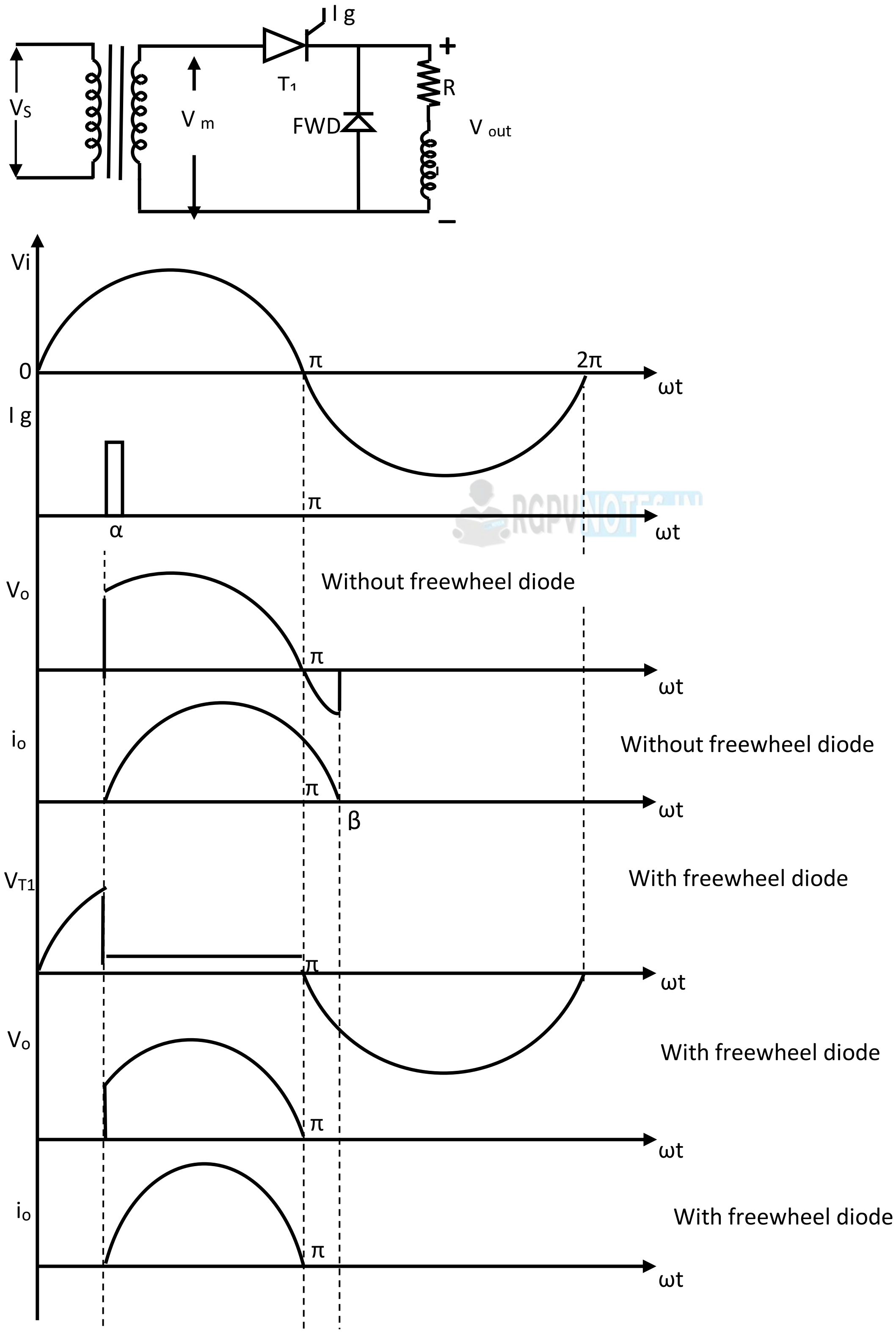


Figure 22 Half wave rectifier with resistive and inductive load with fly wheel diode and related waveform

The DC output voltage is controlled by varying the triggering angle α at which the SCR starts conduction. The i_o current flows through the inductive load. The SCR turn off by using natural commutation process when the input voltage reaches the π angle. During the positive waveform of the applied input signal the SCR conducts for positive half when triggered. Output voltage increases abruptly at α angle and then follows the applied input. When applied signal reaches up to π angle the output voltage reverses and waveform continuous up to angle β which is decided by the time constant$\left(T = \frac{L}{R}\right)$ of the inductive load. The SCR will be turned off by natural commutation when the SCR current becomes zero. The i_o current initially opposed by inductor and then flows through the resistor and inductor. It flows in positive direction for some angle β when freewheel diode is not used. When free wheel diode is used at that time the output voltage is represented according to applied trigger pulse and current ends at π angle.

Single phase full wave rectifier

Single phase full wave rectifier consists of four diodes which are connected in bridge form. When the positive half cycle is applied across the bridge circuit the T_1 and T_2 are triggered at α angle. The i_o current flows through the inductive load. The SCR turn off by using natural commutation process when the input voltage reaches the π angle. During the positive waveform of the applied input signal the SCRs T_1 and T_2 conducts for positive half when triggered. Output voltage increases abruptly at α angle and then follows the applied input. When applied signal reaches up to π angle the output voltage reverses and waveform continuous up to angle π + α which is decided by the time constant $\left(T = \frac{L}{R}\right)$ of the inductive load and current flows in positive direction. When the negative half cycle appears across the bridge circuit the T_3 and T_4 are triggered at π + α angle. The i_o current flows through the inductive load. The SCR turn off by using natural commutation process when the input voltage reaches the 2π+α angle. During the negative waveform of the applied input signal the SCRs T_3 and T_4 conducts for positive half when triggered. Output voltage increases abruptly at π + α angle and then follows the applied input. When applied signal reaches up to 2π angle the output voltage reverses and waveform continuous up to angle 2π+α which is decided by the time constant $\left(T = \frac{L}{R}\right)$ of the inductive load and current flows in positive direction. So in both the cycle of the applied input signal the current flows in only one direction. The figure 23 shows Single phase full wave rectifier circuit with resistive and inductive load and its related waveforms.

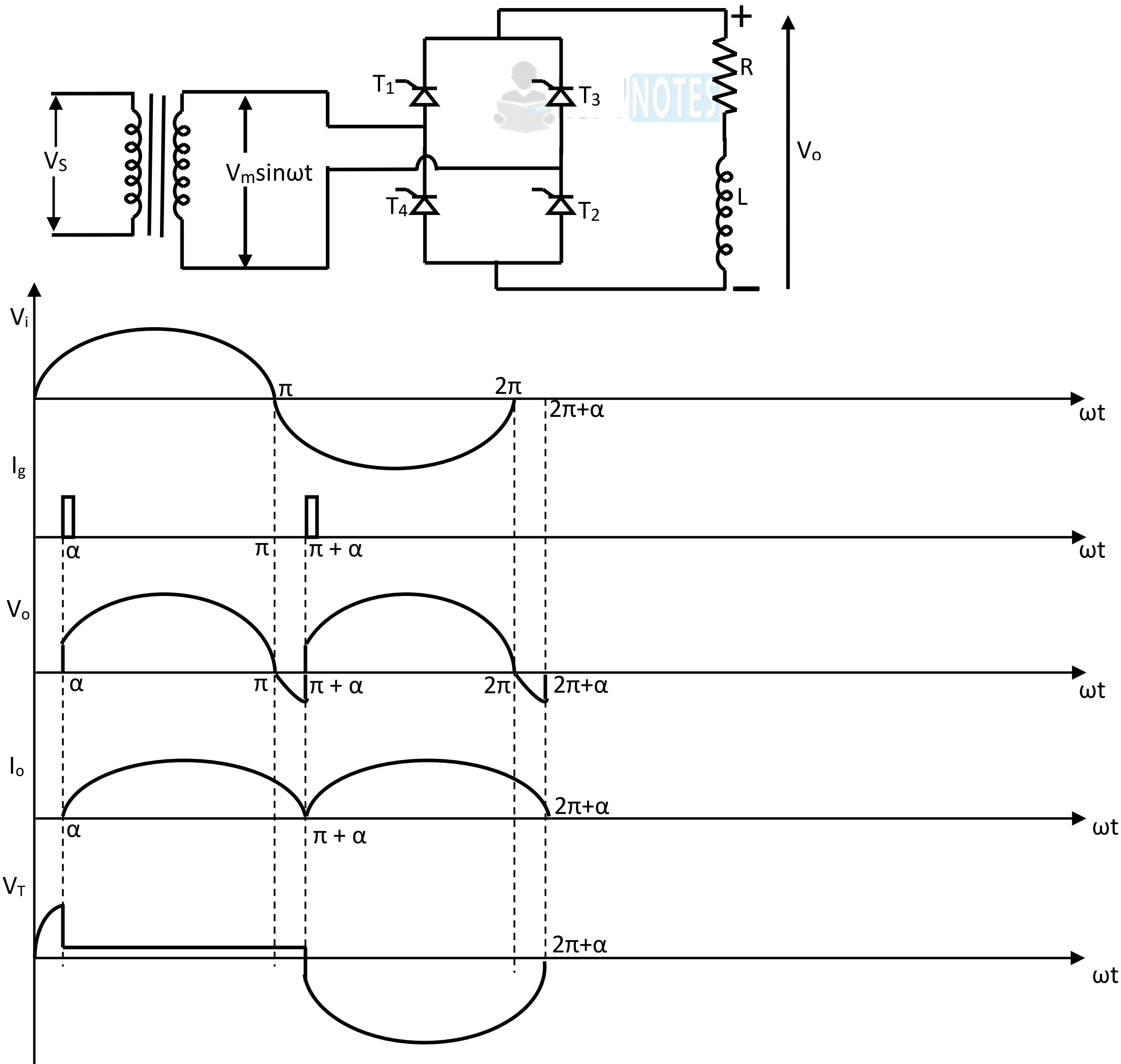


Figure 23 single phase full wave rectifier with resistive and inductive load with related waveforms

Three phase full wave rectifier with resistive and inductive load

A three-phase fully-controlled bridge rectifier can be constructed using six SCRs which are connected in bridge form is as shown in figure 24 with resistive and inductive load.

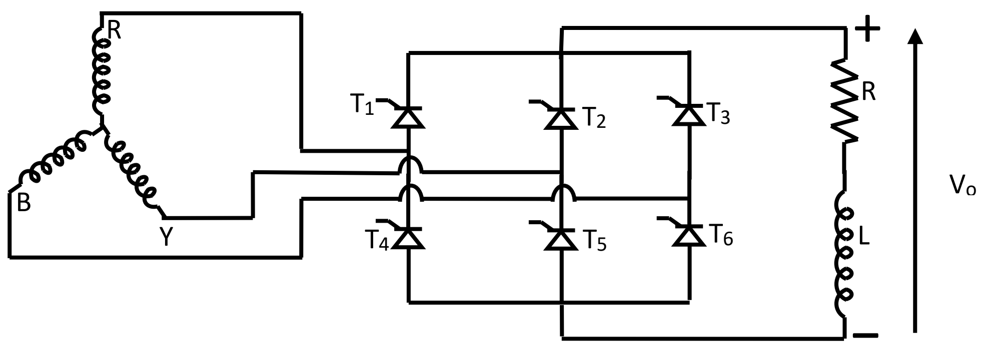


Figure 24 Three phase full wave rectifier

Three phase full wave rectifier is well suited for large dc power drives. It provides full wave controlled rectification such that it does not contain any dc component in the source current. The changeover of conduction from one SCR to the other can takes place only if the phase voltage of the incoming SCR is more than that of outgoing SCR. The turn ON of the incoming SCR would reverse bias the outgoing SCR and thus turn it off by line commutation. The figure 25 shows the waveforms of three phase full wave controlled rectifier.

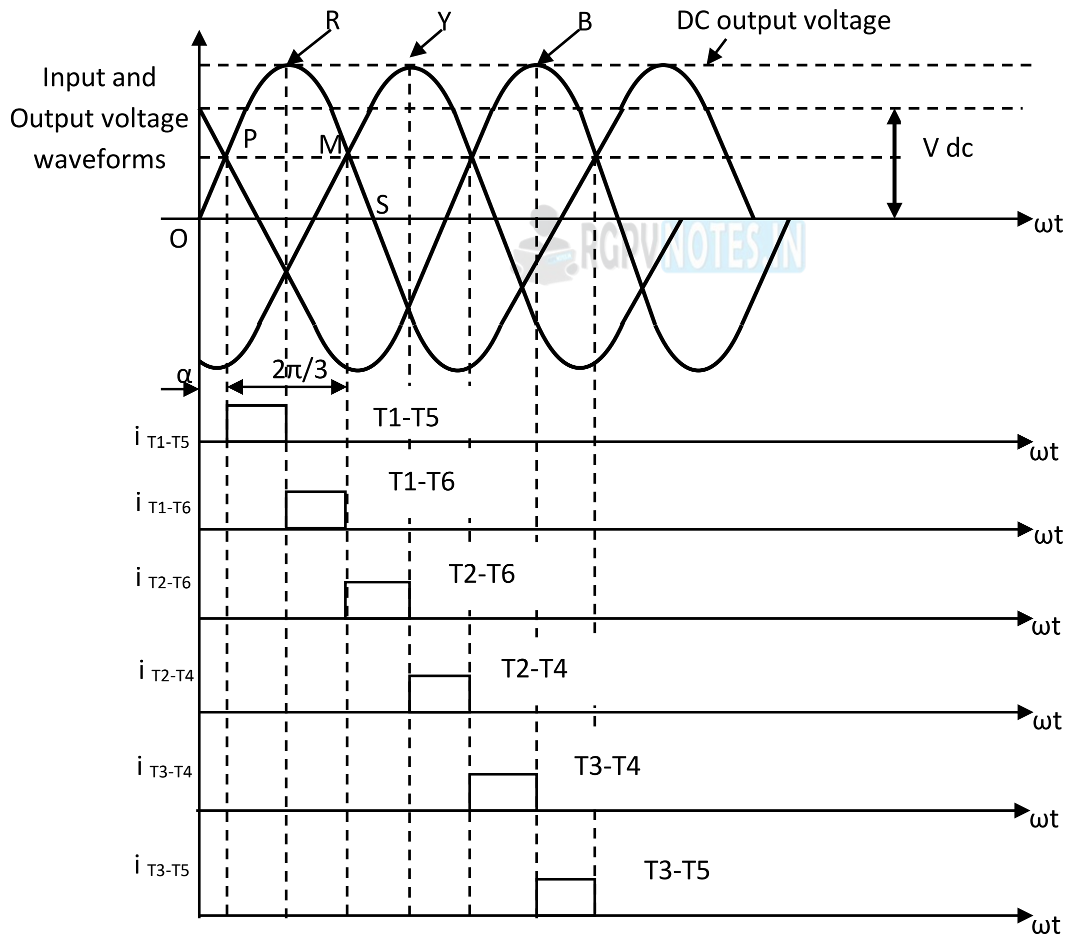


Figure 25 Waveforms of three phase full wave controlled rectifier

From the figure 25 it is seen that T1 can be triggered anywhere during the interval OPMS (when phase-R voltage is higher than those of phase-B and phase-Y). Let T1 be turned ON at point P (triggering angle α=OP).The return path will be routed through T5 during the period from α to π/2 and through T6 during the period from π/2 to point M. Prior to point P, T3 was conducting but the turn ON of T1 will reverse bias T3 and turn it off. Since there are six SCRs, one SCR will be triggered every 60 degree. It should be remembered that a SCR conducts if the anode is at a positive potential with reference to its cathode. The conduction pattern of the SCR has six modes and each SCR conducts over a span of PM [for OP=30°, PM=π-(2xπ/6=2π/3]. The firing sequence has been outlined in Table I. Assuming no overlap and only two SCRs will be conducting at a time. The output voltage waveform is repetitive every π/3.

Table I firing sequence

Mode	1	2	3	4	5	6
Conducting SCRs	5-1	1-6	6-2	2-4	4-3	3-5
Incoming SCR	6	2	4	3	5	1
Outgoing SCR	5	1	6	2	4	3

For any current to flow in the load at least one device from the top group (T_1, T_2, T_3) and one from the bottom group (T_4, T_5, T_6) must conduct. It is always required that for every cycle two SCR must conduct. Then from symmetry consideration it is required that each SCR conducts for 120° of the input cycle. Now the SCRs are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. SCRs are fired at an interval of 180° and in that case they can conduct one by one only. It provides six possible conduction modes for the converter in the continuous conduction mode of operation. These are T_1T_5, T_1T_6, T_6T_2, T_2T_4, T_4T_3, and T3T5.The firing sequence is defined in table.

