Unit I

Chapter 1

Thyristors

Syllabus

Construction, VI characteristics (input, output and transfer if any), Switching characteristics of SCR, GTO, Various repetitive and non-repetitive ratings of rating of SCR, GTO and their significance, Requirement of typical triggering / driver (such as opto isolator) circuits for various power devices, Importance of series and parallel operation of various power devices.

Chapter Contents

1.1 Introduction to Power Electronics :

- In the recent past, the power electronics has radically modernized the concept of power conversion and the control of electric motor drives. **The word Power Electronics is a combination of three terms namely power, electronics and control.**
- **Power :** Power is the term related with the generation, transmission and distribution of electric power.
- **Electronics** covers the solid state devices and circuits to process the signal for meeting certain control objectives.
- **Control** explains the steady state and dynamic characteristics of a closed loop control system.
- In short Power Electronics is defined as the branch of solid state electronics which deals with the applications of the conversion and control of electric power.

1.1.1 Principle of Power Electronics :

- Power electronics is based on the principle of switching of the power semiconductor devices. Power handling capacity and speed of switching are the two most important criterions related to the power devices.
- The microprocessors and microcontrollers are being used for control and for synthesizing the control strategies of the power semiconductor devices.
- In short power semi conductors act as muscles and microprocessors act as brain for a modern power electronics equipment.

Need of high power semiconductor devices :

- For all the applications mentioned earlier we need to use the devices which can handle a large power, large current and withstand very high voltages.
- For almost all these high power applications, we have to use these devices as switches.
- That means the device should be either fully on or fully off. Operation as a switch will reduce the power dissipation in these switches to a great extent.
- Thus we need power semiconductor devices which can be operated as switches.

1.1.2 Requirements of Power Devices :

- The general requirements of all power semiconductor devices are as follows :

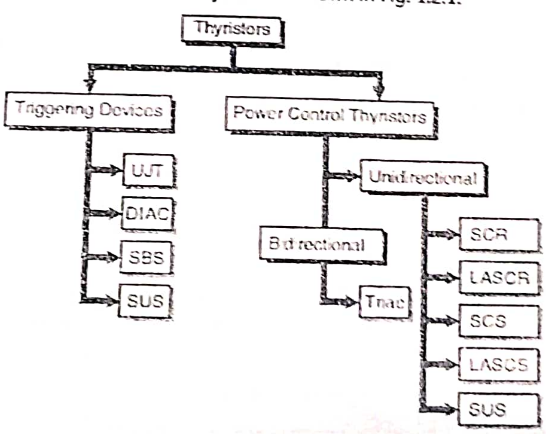
1. They should be capable of handling large current and power.
2. In the off state they should be able to withstand very high voltage.
3. The on state voltage drop across them should be small.
4. The on state resistance should be small.
5. Very high off state resistance.
6. It should be turned on and off completely and quickly.
7. Capability to operate as a switch at very high frequency.
8. It should have a high dv/dt and di/dt ratings.
9. It should have a small thermal resistance so as to dissipate heat effectively.
10. It should be able to withstand to large fault currents.
11. The temperature coefficient should be negative, so that parallel operation becomes easy.
12. Its cost should be low.

1.2 Thyristors :

- Thyristors is a general term which includes devices such as SCR, Triac, GTO, LASCR, RCT, SCS, ... and many more.
- Thus thyristors is a family of devices. SCR i.e. silicon controlled rectifier is the most popular device of the thyristor family.
- The classification of thyristors is as follows :

Classification of thyristors :

- Classification of thyristors is shown in Fig. 1.2.1.



(1-22) **Fig. 1.2.1 : Classification of thyristors**

1.3 Silicon Controlled Rectifier (SCR) : SPPU : May 07, Dec. 11, Dec. 13, May 18

University Questions

Q. 1 Given the constructional details of a SCR. Sketch its schematic diagram and the circuit symbol. **(May 07, 8 Marks)**

Q. 2 Draw and explain the construction of SCR with their performance parameters. What is the effect of gate current on SCR characteristics ? **(Dec. 11, 2 Marks)**

Q. 3 Draw construction diagram of SCR ? Explain steady state characteristics of SCR. **(Dec. 13, 5 Marks)**

Q. 4 Draw the construction of SCR and explain the operation using two transistor analogy with expression of anode current. **(May 18, 7 Marks)**

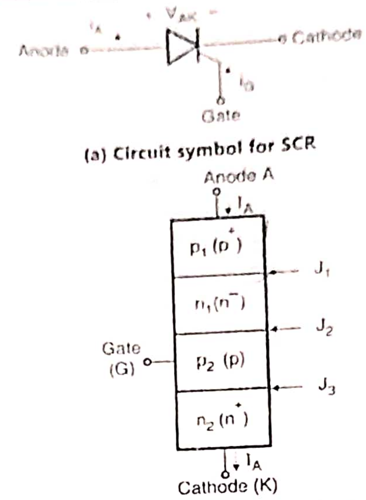
- SCR is one of the oldest types of solid state power device.
- It was invented in 1957 by the General Electric Research Laboratories.
- SCRs have the highest power handling capacity of all the power semiconductor devices.
- They have a four layer construction with three user accessable terminals namely anode, cathode and gate.
- SCR is a latching type device that can be turned on by the control terminal (gate) but once turned on, the gate loses control on it (i.e. it cannot be turned off by the gate).

Important features of SCR :

1. It is a latching type device.
2. It can handle a very large power.
3. It is a current controlled device, because the gate current controls SCR.
4. It acts as an open or closed switch but it cannot be used as an amplifier.
5. The on-state voltage drop is very low.
6. It can handle thousands of amperes of current.

Basic Structure of SCR :

- The basic structure of SCR is as shown in Fig. 1.3.1(b). It is a four layer p-n-p-n device, with three terminals brought out for the user, namely Anode, Cathode and Gate.



(a) Circuit symbol for SCR

p^+ heavily doped layer p moderately doped layer

n^- lightly doped layer n^+ heavily doped layer

(b) Basic structure of SCR

(I-23) **Fig. 1.3.1 : Structural details of SCR**

- The "gate" terminal is the controlling terminal that can turn on the device whenever required.
- The symbol for SCR is as shown in Fig. 1.3.1(a). It is the symbol of a rectifying diode with a third additional control terminal, i.e. gate.
- The direction of forward anode current, voltage across the thyristor and direction of conventional gate current are as shown in Fig. 1.3.1(a).

Number of junctions :

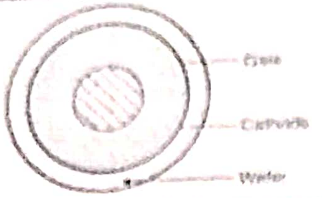
- As seen in the Fig. 1.3.1(b), there are three junctions J_1, J_2 and J_3.
- In order to turn on SCR, the anode must be at a higher positive potential than cathode. That means SCR should be forward biased.

Current directions :

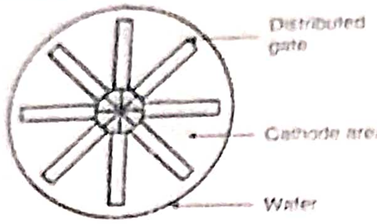
- The directions of the anode and gate current in Fig. 1.3.1(a) are conventional current directions.
- It clearly indicates that SCR is a unidirectional device and that the gate current can be only positive.
- The gate current can flow only in one direction i.e. into the gate terminal.

1.3.1 Gate Cathode Layouts :

- Top views of two different gate and cathode layouts are as shown in Fig. 1.3.1(c) and Fig. 1.3.1(d).



(c) Gate Cathode layout for the localised gate electrode



(d) Gate cathode area layout for distributed gate electrode

(1-24) Fig. 1.3.1 : Structural details of an SCR

- The localised gate cathode structure is for smaller SCRs whereas the distributed gate structure is for SCRs having larger size.

1.4 Static V-I Characteristic of SCR :

SPPU : May 13, Dec. 13, May 16, Dec. 16, May 17, May 18, March 19

University Questions

Q. 1 Explain holding current and latching current in SCR. **(May 13, 4 Marks)**

Q. 2 Draw construction diagram of SCR ? Explain steady state characteristics of SCR. **(Dec. 13, 5 Marks)**

Q. 3 What are power devices ? Explain with characteristics any one power device used for power control applications. **(May 16, 4 Marks)**

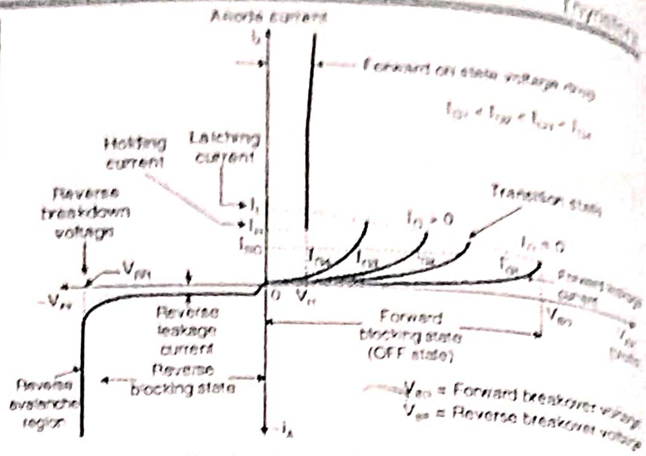
Q. 4 Draw and explain the steady state characteristics of SCR. **(Dec. 16, 6 Marks)**

Q. 5 Draw steady state characteristics of SCR. Explain : I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 17, 7 Marks)**

Q. 6 Draw steady state I-V characteristics of SCR. Explain the parameters I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 18, 7 Marks)**

Q. 7 Explain following rating of SCR :
1. Holding current
2. Latching current
3. V_{BO} **(March 19, 6 Marks)**

- The I-V characteristics of SCR is a graph of anode current I_A on y axis and anode to cathode voltage plotted on the x axis as shown in Fig. 1.4.1.



(1-25) Fig. 1.4.1 : I-V characteristic of SCR

- The I-V characteristics can be split into two parts namely the forward characteristics and reverse characteristics.
- The characteristics in the reverse direction (anode to cathode voltage negative) is similar to a reverse biased diode.
- For small reverse voltage a small reverse leakage current flows until the avalanche breakdown takes place at reverse breakover voltage V_{BR}.
- As soon as the reverse breakdown takes place due to avalanche breakdown, a large current flows through SCR whereas the voltage across the device remains constant.
- It is dangerous to operate SCR in the reverse breakdown state because it may get damaged due to overheating.
- The region from 0 volts upto V_{BR} volts in which the SCR is reverse biased and non- conducting is called as "reverse blocking state". Reverse blocking means that the SCR is reverse biased and in the non-conducting (blocking) state.

1.4.1 Forward V-I (Static) Characteristics :

SPPU : May 13, Dec. 13, May 16, Dec. 16, May 17, May 18, March 19

University Questions

Q. 1 Explain holding current and latching current in SCR. **(May 13, 4 Marks)**

Q. 2 Draw construction diagram of SCR ? Explain steady state characteristics of SCR. **(Dec. 13, 5 Marks)**

Q. 3 What are power devices ? Explain with characteristics any one power device used for power control applications. **(May 16, 4 Marks)**

Q. 4 Draw and explain the steady state characteristics of SCR. **(Dec. 16, 6 Marks)**

Q. 5 Draw steady state characteristics of SCR. Explain : I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 17, 7 Marks)**

Q. 6 Draw steady state I-V characteristics of SCR. Explain the parameters I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 18, 7 Marks)**

Q. 7 Explain following rating of SCR :

1. Holding current
2. Latching current
3. V_{BO} **(March 19, 6 Marks)**

- The anode is positive with respect to cathode. Hence SCR is forward biased.
- The forward characteristics is divided into three regions of operation namely :
  1. Forward blocking state.
  2. Transition-state.
  3. On-state.

1. **Forward blocking state :**

- This is the high voltage low current mode of operation in which SCR is in the "OFF" state.
- The current through it is "Forward Leakage Current". This current flows due to thermally generated minority carriers.

2. **Transition-state :**

SCR remains in the blocking state as long as the forward anode to cathode voltage is less than the break over voltage.

- As soon as V_{AK} becomes greater than the break over value, the anode current i_A increases sharply to a high value and the voltage across SCR reduces sharply to a low value (on-state voltage).
- The switching of SCR from off-state to on-state and vice versa takes place in a short time.

This change over state is called as transition-state. As this is an unstable state, it is shown by dotted line in Fig 1.4.1.

3. **The low voltage high current mode or the On-state :**

The voltage across SCR is low in this state. In the on-state the SCR anode currents is large and on-state voltage drop is small.

Unstable state :

- These two stable states or modes are connected together by an unstable mode (called as the transition mode) of operation that appears as a negative resistance on the I-V characteristics. (Dotted line in Fig. 1.4.1).

1.4.2 Reverse Characteristics :

SPPU : May 13, Dec. 13, May 16, Dec. 16, May 17, May 18, March 19

University Questions

Q. 1 Explain holding current and latching current in SCR. **(May 13, 4 Marks)**

Q. 2 Draw construction diagram of SCR ? Explain steady state characteristics of SCR. **(Dec. 13, 5 Marks)**

Q. 3 What are power devices ? Explain with characteristics any one power device used for power control applications. **(May 16, 4 Marks)**

Q. 4 Draw and explain the steady state characteristics of SCR. **(Dec. 16, 6 Marks)**

Q. 5 Draw steady state characteristics of SCR. Explain : I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 17, 7 Marks)**

Q. 6 Draw steady state I-V characteristics of SCR. Explain the parameters I_L, I_H, V_{BO}, V_{BR} and show them on the characteristics. **(May 18, 7 Marks)**

Q. 7 Explain following rating of SCR :

1. Holding current
2. Latching current
3. V_{BO} **(March 19, 6 Marks)**

- The reverse characteristics of SCR is similar to that of a reverse biased diode.
- For reverse voltages less than the reverse breakdown voltage, a very small leakage current flows through the SCR.
- But as soon as the reverse voltage reaches breakdown value the avalanche breakdown takes place and a large reverse current flows.
- The operation in breakdown region should be avoided as it can damage the SCR permanently.

Important terms :

- The important voltage and current terms in the I-V characteristics are as follows :

Sayali

1. **The forward break over voltage (V_{BO}) :**

- This is the maximum forward voltage that can be applied between anode and cathode, without initiating forward conduction.
- This voltage is defined for a zero gate current. In short this is the maximum forward voltage across SCR in its off-state.

2. **The forward leakage current :**

- The small forward current is flowing in the forward blocking state of the device.
- This current is generated due to the minority current carriers and therefore is dependent on the operating temperature.

3. **The holding current (I_H) :**

- It represents the minimum current that can flow through SCR and still "hold" it in the on-state. The voltage associated with the holding current is termed as holding voltage V_H.
- If the forward anode current is reduced below holding current, SCR will be turned off.
- The holding current is defined for zero gate current (I_G = 0). It is denoted by I_H and its value is few tens of mA (typically).

4. **On-state voltage :**

- Note that the voltage across SCR in its on-state is very low as compared to the off-state voltage.
- It can be shown that the on-state voltage is equal to drop across one junction (i.e. of the order of 1 to 1.5 Volts).

5. **Latching current (I_L) :**

- It is minimum anode current that must flow through SCR to latch it into the on-state.
- The latching current is higher than the holding current. The latching current is important when SCR is being turned on.

Difference between holding and latching currents :

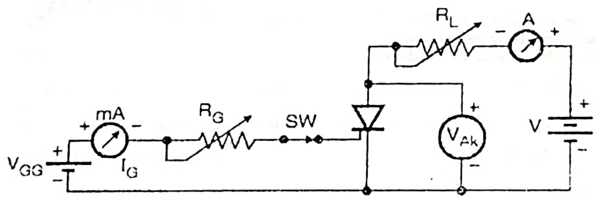
1. The latching current is important only at the time of SCR turn-on, whereas holding current is important only at the time of SCR turn-off.
2. If the anode current goes below the holding current then the conducting SCR turns off. The holding current is defined for I_G = 0, whereas if anode current at the time of turn on is higher than latching current then only SCR will latch into its on-state.
3. If I_A < I_L then SCR does not latch. It will remain on as long as I_G is being supplied. As soon as I_A is removed, SCR will turn-off.
4. Latching current is always higher than the holding current.
5. The values of I_L and I_H are constant. They do not depend on the gate current magnitude.

Effect of gate current :

- Look at Fig. 1.4.1. It shows that as we increase the positive gate current from I_{G1} to I_{G4}, the breakover voltage of SCR V_{BO} reduces progressively.
- Thus SCR will turn-on at lower anode to cathode voltages as we increase the gate current.

How to turn off SCR ?

- The gate current can turn on SCR but once turned on, the gate loses control.
- Even if we reduce the gate current to zero, SCR continues to conduct. We can turn-off a conducting SCR by :
  1. Reducing its anode current below the holding current for a minimum specified time.
  2. Applying a reverse voltage across the SCR.
- The experimental setup for plotting SCR characteristics is as shown in Fig. 1.4.2.



(I-26) **Fig. 1.4.2 : Experimental setup to plot the I-V characteristics of SCR**

1.5 Operation of SCR :

- Operation of SCR can be studied under two different operating conditions.
- They are as follows :

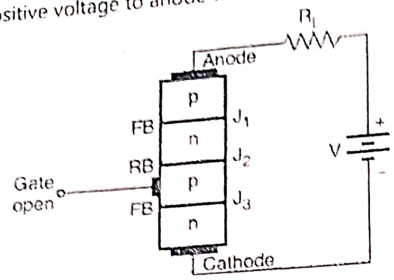
1.5.1 Operation without Gate Current :

SPPU : Dec. 19

University Questions

Q. 1 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- Refer to Fig. 1.5.1(a). The gate terminal of SCR is left open so that $I_G = 0$. SCR is forward biased by applying a positive voltage to anode with respect to cathode.



FB : Forward biased
RB : Reverse biased

(I-27) **Fig. 1.5.1(a) : Operation of SCR without gate current**

- Out of the three junctions, the junctions J_1 and J_3 are forward biased and junction J_2 is reverse biased.
- Therefore current does not flow through the SCR. The entire applied voltage appears across the junction J_2.
- As the anode to cathode voltage is increased, the voltage across junction J_2 increases.
- At a certain voltage this junction will breakdown and SCR will start conducting. This voltage is called as forward breakover voltage (V_{BO}).
- Thus it is possible to turn on an SCR without any gate current by exceeding its forward voltage beyond V_{BO}.

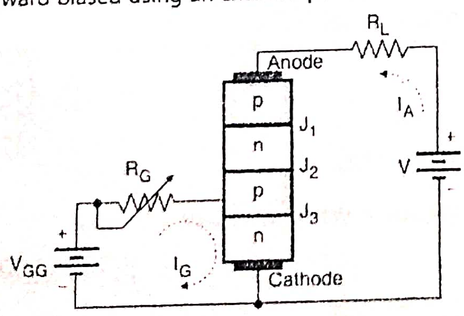
1.5.2 Operation with Gate Current :

SPPU : Dec. 19

University Questions

Q. 1 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- Now refer to Fig. 1.5.1(b). It shows that SCR is forward biased as before and the gate cathode junction also is forward biased using an external power source.

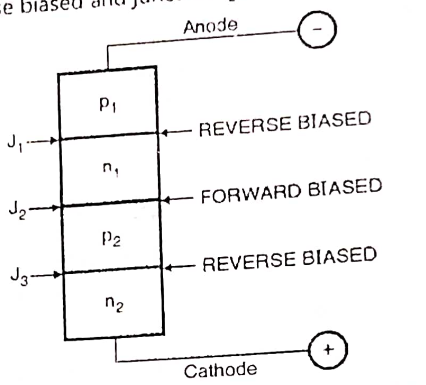


(I-27) **Fig. 1.5.1(b) : Operation of SCR with gate current**

- The gate current I_G starts flowing which can be adjusted by the resistance R_G.
- As explained in section 1.4, the value of gate current will decide break over voltage of SCR.
- As I_G increases, break over voltage will decrease i.e. SCR will turn-on at lower and lower voltages.

1.5.3 Reverse Blocking Capacity :

- In the reverse blocking state, anode is biased negative with respect to cathode.
- Therefore the junctions J_1 and J_3 in Fig. 1.5.2(a) are reverse biased and junction J_2 is forward biased.



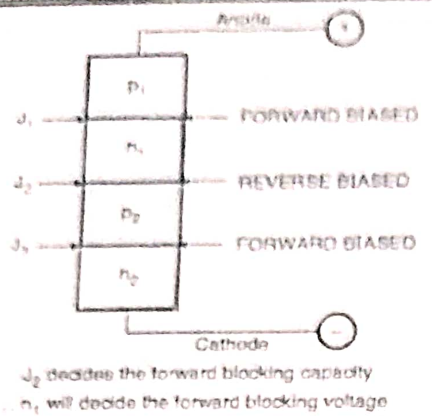
J_1 and J_3 decides the reverse blocking capacity.

(I-28) **Fig. 1.5.2(a) : SCR in reverse blocking state**

- Out of the two reverse biased junctions J_1 and J_3, the lower junction J_3 has a low break down voltage due to the heavy doping on both sides of it.
- Therefore the reverse blocking capacity of SCR depends entirely on junction J_1.
- The reverse blocking capacity of junction J_1 is usually decided by the length of n^- (n_1) region.

1.5.4 Forward Blocking Capacity of SCR :

- In the forward blocking state, the SCR has to block a forward voltage because anode is biased positive with respect to cathode.
- Therefore the junctions J_1 and J_3 are forward biased, and junction J_2 is reverse biased.
- The junction J_2 has to block the entire anode to cathode voltage.
- In order to achieve this the n^- layer (n_1) in Fig. 1.5.2(b) is lightly doped and made wide enough.
- The depletion region of the reverse biased J_2 junction appears in this layer (n_1 layer).
- Thus this junction (J_2) decides the forward blocking voltage.



(I-29) **Fig. 1.5.2(b) : SCR in forward blocking state**

Why reverse voltage rating is higher than forward voltage rating :

- The reverse voltage rating of the device is the sum of ratings of J_1 and J_3, while the forward voltage rating is the rating of J_2 junction.
- Since the p_2 layer (gate) is lightly doped and narrower than p_1 (anode) layer the voltage blocking capacity of J_1 is larger than that of J_2.
- Also this means the blocking capacity of (J_1 + J_3) is even larger than that of J_2. Hence for SCR the reverse voltage rating is usually greater than its forward voltage rating.
- Therefore the forward voltage is used as a criteria while designing thyristorised circuits.
- The forward and reverse blocking voltages are dependent on the junction temperature.
- They reduce with increase in junction temperature beyond 150°C.
- Therefore most manufacturers specify the maximum junction temperature for their thyristors at 125°C.

1.6 Two Transistor Equivalent Circuit :

SPPU : Dec. 11, Dec. 12, May 13, May 15, Feb. 16, May 17, May 18

University Questions

Q. 1 Draw two transistor analogy of SCR. Show that : $I_A = (I_{CBO1} + I_{CBO1}) / (1 - (\alpha_1 + \alpha_2))$

Also explain regenerative action of transistors in SCR. **(Dec. 11, 7 Marks)**

Q. 2 Draw and explain two transistor analogy of SCR. Also derive an expression for I_A. **(Dec. 12, 6 Marks)**

Q. 3 Draw two transistor analogy of SCR. Derive an expression for I_A. **(May 13, 5 Marks)**

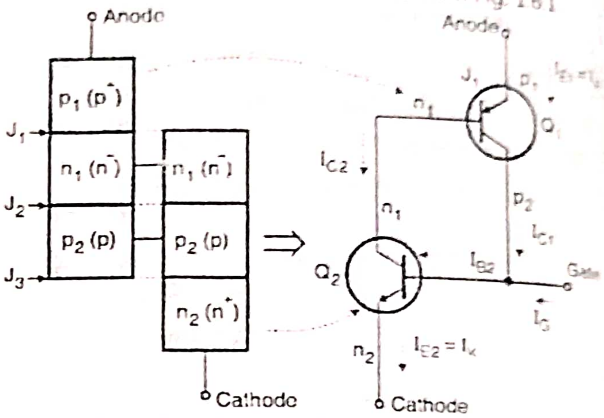
Q. 4 Draw two transistor analogy of SCR and derive an expression for its anode current I_A. **(May 15, 7 Marks)**

Q. 5 Draw and explain two transistor analogy of SCR. **(Feb. 16, 6 Marks)**

Q. 6 Explain two transistor analogy of an SCR. Derive anode current equation of SCR. **(May 17, 7 Marks)**

Q. 7 Draw the construction of SCR and explain the operation using two transistor analogy with expression of anode current **(May 18, 7 Marks)**

- The operation of SCR can be explained with the help of the one dimensional model as shown in Fig. 1.6.1.



(I-30) **Fig. 1.6.1 : Two transistor equivalent circuit of a thyristor**

- The device is considered to be an ideal device. A low frequency equivalent circuit made up of a p-n-p and n-p-n transistors Q_1 and Q_2 as shown in Fig. 1.6.1, which is easily derived from the one dimensional model of an SCR.

SCR operation :

- The anode is made positive with respect to cathode and gate current is supplied.
- The gate current acts as base current for Q_2 and it turns on. Its collector current $I_{C2} = \beta_2 I_G$ starts flowing.
- But collector current of Q_2 acts as base current for Q_1 hence it starts conducting. Its collector current $I_{C1} = \beta_1 I_{B1} = \beta_1 \beta_2 I_G$ now starts flowing.
- The collector current of Q_1 acts as base current of Q_2 and collector current of Q_2 in turn acts as base current of Q_1.
- Due to this type of connection, the current multiplication takes place which is called as cumulative current multiplication and both the transistors will saturate.

- The saturated transistors are equivalent to closed switches. Hence the SCR will get latched into on-state and acts as a closed switch.
- Even if the gate current is reduced to zero, the two internal transistors will supply base current to each other and hence will remain in saturation.
- Hence once latched, the SCR does not turn off even if we reduce the gate current to zero.

Expression for the anode current :

- Assume that both the transistors Q_1 and Q_2 in Fig. 1.6.1 are in the active region. The transistor common base and common emitter current gains are α_1, α_2 and β_1, β_2 respectively.
- A bipolar transistor can be described in its active region at low frequencies by the Ebers-Moll equations.
- For the transistors Q_1 and Q_2 these equations are :

$$I_{C1} = \alpha_1 I_{E1} + I_{CO1} \quad ...(1.6.1)$$

$$\text{And} \quad I_{C2} = \alpha_2 I_{E2} + I_{CO2} \quad ...(1.6.2)$$

- Where I_{CO1} and I_{CO2} are the leakage currents of the transistors.

$$\text{and} \quad \alpha = \frac{\beta}{(1 + \beta)} \quad ...(1.6.3)$$

- If we note that $I_A = I_{E1}$ and that $I_K = I_{E2} = I_A + I_G$ and setting the sum of all the currents into one of the transistors to zero, then from Fig. 1.6.1,

$$I_{E2} = I_{C2} + I_{B2} \quad ...(1.6.4)$$

$$\text{But} \quad I_{E2} = I_A + I_G$$

$$\therefore \quad I_A + I_G = I_{C2} + I_{B2} \quad ...(1.6.5)$$

$$\text{But} \quad I_{B2} = I_{C1} + I_G$$

$$\therefore \quad I_A + I_G = I_{C2} + I_{C1} + I_G \quad ...(1.6.6)$$

$$\text{But} \quad I_{C2} = \alpha_2 I_{E2} + I_{CO2} \text{ and } I_{C1} = \alpha_1 I_{E1} + I_{CO1}$$

$$\therefore \quad I_A = \alpha_2 I_{E2} + I_{CO2} + \alpha_1 I_{E1} + I_{CO1} \quad ...(1.6.7)$$

$$\text{But} \quad I_{E2} = I_A + I_G \text{ and } I_{E1} = I_A$$

Substituting all these values, Equation (1.6.7) can be written as,

$$I_A = \alpha_2 (I_A + I_G) + I_{CO2} + \alpha_1 I_A + I_{CO1} \quad ...(1.6.8)$$

$$\therefore \quad I_A - \alpha_2 I_A - \alpha_1 I_A = \alpha_2 I_G + I_{CO1} + I_{CO2}$$

$$\therefore \quad I_A = \left[\frac{\alpha_2 I_G + I_{CO1} + I_{CO2}}{1 - (\alpha_1 + \alpha_2)} \right] \quad ...(1.6.9)$$

In the blocking state (off-state) the value of $(\alpha_1 + \alpha_2)$ is much less than unity hence the denominator is large and anode current I_A is quite small.

How does SCR turn on ?

- In Equation (1.6.9), as long as the values of α_1 and α_2 are small, the anode current I_A will remain low and SCR will be in the off-state.
- If $(\alpha_1 + \alpha_2)$ approaches unity the denominator of Equation (1.6.9) will be very small and SCR will be at the breakdown point, ready to enter into the transition-state.
- The current gains of the two transistors Q_1 and Q_2 would be high (greater than one) and the collector current of one transistor acts as base current for the other one and gets multiplied by its current gain β.
- This current then again acts as base current of the first transistor and gets multiplied by its current gain.
- This cumulative current multiplication action would soon increase the anode current to such a value that SCR will enter into its On-state. This is the turn on process of SCR.

How do the values of "α" increase ?

- The key to the turn on process is to understand how the values of α_1 and α_2 of two transistors Q_1 and Q_2 increase from the small values in blocking state to the higher values required to turn SCR on.
- As the forward anode-cathode voltage is increased, the depletion region of junction J_2 grows into the n_1 (n^-) layer.
- This layer is the "base" for the upper p-n-p transistor Q_1.
- Due to the growth of depletion region of J_2 into n_1 layer the effective thickness of the base region of p_1 n_1 p_2 transistor (Q_1) reduces and hence α_1 i.e. α of Q_1 increases.
- Similarly the extension of the depletion region layer J_2 into the p_2 layer (the base of the n-p-n transistor Q_2) will cause increase in the value of α_2.

1.6.1 SCR as a Switch : SPPU : March 19

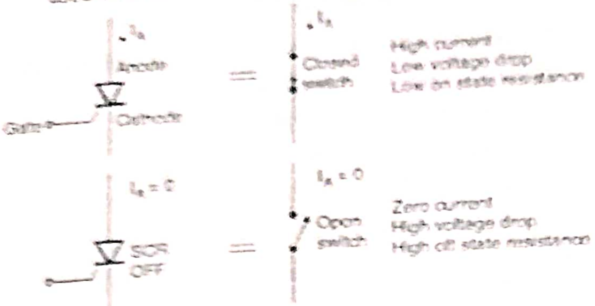
University Questions

Q. 1 Explain how the following device can be operated as switch with necessary driving conditions : SCR.

(March 19, 6 Marks)

- The SCR has only two states of operation i.e. it can be either fully ON or completely OFF.
- There is no "active" region of operation like transistor. Therefore SCR is equivalent to a switch, as shown in Fig. 1.6.2.

- As it cannot operate in the active region, it cannot be used as an amplifier



(I-31) Fig. 1.6.2 : SCR as a switch

1.6.2 SCR Turn ON Methods :

- SCR is turned on by increasing the anode current. This can be achieved with one of the following ways :
  1. By raising the temperature (Thermal triggering).
  2. By focusing light (Optical triggering).
  3. By applying high voltage (Forward voltage triggering).
  4. By applying voltage at high dv/dt (dv/dt triggering).
  5. By increasing the gate current (Gate triggering).

By raising the temperature (Thermal triggering) :

- If the temperature of SCR increases, there is an increase in the number of electron-hole pairs.
- This will increase the leakage current. Therefore the value of α_1 and α_2 will increase.
- If $(\alpha_1 + \alpha_2)$ tends to unity, then SCR may be turned on.
- This is called as thermal triggering of thyristors. It is an undesirable feature.
- The break over voltage goes on decreasing with increase in temperature.
- In short, due to increase in temperature the thermally generated leakage current increases.
- This current gets multiplied internally and the SCR is turned on.

Note :	SCR turn on due to increased temperature and it should be avoided because it may cause thermal runaway.

By focusing light (Illumination triggering) :

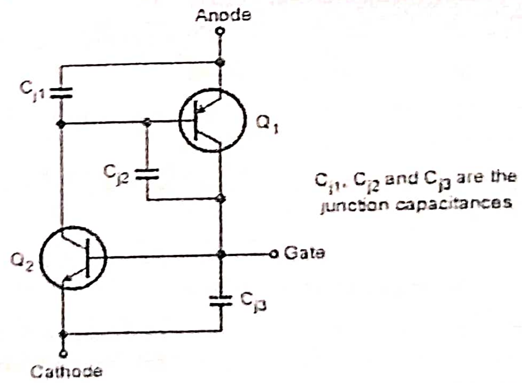
- If light of appropriate frequency and intensity is allowed to strike SCR junction, then the photons will strike the electrons and increase the number of electron hole pairs. SCR may turn on due to the increased leakage current.
- This principle is used to turn on the light activated SCR (LASCR).

By applying high voltage (Forward voltage triggering) :

- When we increase the forward positive voltage applied between the anode and cathode terminals of a thyristor, the leakage current of the thyristor increases.
- Due to the internal current multiplication taking place inside, this current increases. Assume that $I_G = 0$.
- As soon as the forward voltage reaches the breakover voltage value (V_{BO}), the middle junction J_2 (which is reverse biased) will break down and the thyristor will be turned on.
- This is called as forward voltage triggering and it can take place even when the gate is open.
- This type of triggering takes place only at V_{BO}, so we can not trigger a thyristor at different values of α.
- We should avoid this type of turn on because it may prove to be destructive.

By applying voltage at high dv/dt (dv/dt triggering) :

- Assume that the gate current $I_G = 0$ and we suddenly apply a very high forward voltage between anode and cathode of a thyristor.
- Then it is said that the rate of change of voltage i.e. dv/dt of the forward voltage is very high.
- Such a situation is called as the **transient operating condition.**
- Under the transient conditions the capacitances of the transient model will influence the characteristics of SCR. The transient model of SCR is shown in Fig. 1.6.3.



(I-44) Fig. 1.6.3 : Transient model of SCR

- The equivalent circuit of SCR which shows the junction capacitances is as shown in Fig. 1.6.3.

- If SCR is in the blocking (off) state, a fast rising forward voltage applied across it would cause high current flow through the junction capacitances as they offer low reactance to any suddenly changing voltages.
- The current through capacitor C_{j2} can be expressed as :

$$I_{j2} = \frac{d\,(q_{j2})}{dt} = \frac{d}{dt}(C_{j2}\,V_{j2})$$

$$= V_{j2}\frac{d\,C_{j2}}{dt} + C_{j2}\frac{d\,V_{j2}}{dt}$$

- Where C_{j2} and V_{j2} are the capacitance and voltage of junction J_2 and q_{j2} is the charge in the junction.
- If the rate of rise of voltage dv/dt is large then i_{j2} will be large and this would result in increased leakage current.
- The high value of leakage current may cause $(\alpha_1 + \alpha_2)$ tending to unity and result in undesirable turn on of SCR.
- However large current through the junction capacitance may also damage the device.
- This is called as dv/dt triggering of thyristor.
- A high dv/dt may result in the accidental turn on of a thyristor.
- It may even damage the thyristor. Hence the thyristors should be protected against high dv/dt. Care should be taken to limit the applied dv/dt below the value specified by the manufacturer.

By increasing the gate current (Gate triggering) :

- The breakdown voltage will decrease with increase in the gate current.
- In gate triggering a gate current pulse of sufficient amplitude and duration is applied to the gate terminal of a forward biased thyristor to turn it on.
- We can turn on the thyristor at the desired value of firing angle (α) using gate triggering.
- Gate triggering is the most desirable and practically popular method of thyristor triggering.
- The gate signal should be removed, once the thyristor is turned on.
- The gate signal should not be applied continuously in order to avoid gate power dissipation.
- Gate current should not be applied when the thyristor is reverse biased, because then the thyristor may fail due to increased leakage current.
- The gate triggering pulse should be wider than the time taken by the anode current to the holding current I_h.
- This pulse width should be longer than the turn on time t_{on} of thyristor.

1.6.3 Merits of Gate Turn on :

- The gate turn on method is the most preferred method because it has the following advantages :
  1. Less power consumption.
  2. It is possible to turn on the SCR precisely at the desired value of anode to cathode voltage.
  3. If the supply voltage is AC then it is possible to turn on an SCR at firing angle α to the desired value.
  4. Triggering circuits with this technique are easy to design.
  5. Turn-on gain is the ratio of anode current to the gate current. For gate turn on method the turn on gain is very large (small gate current is required to turn on the SCR).
  6. Pulsed triggering circuit proves to be very flexible.

1.7 Dynamic Characteristics of SCR :

SPPU : Dec. 19

University Questions

Q. 1 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- The I-V characteristics (static characteristics) of SCR discussed in section 1.4 can give all the information about the behaviour of thyristor in the forward blocking, reverse blocking and on-state.
- But it cannot provide any information about the transition-state (represented by dotted line).
- Therefore to know about SCR behaviour at the time or turn on and the turn off we must understand the dynamic characteristics or switching characteristics of SCR.
- The dynamic characteristics can be further classified into two categories namely :
  1. Turn-on characteristics
  2. Turn-off characteristics.
- The turn on characteristics is useful in knowing the behaviour of SCR at the time of turn on while the turn off characteristics is useful to understand its behaviour when the device is being turned off.

1.7.1 Turn-On Characteristics of SCR :

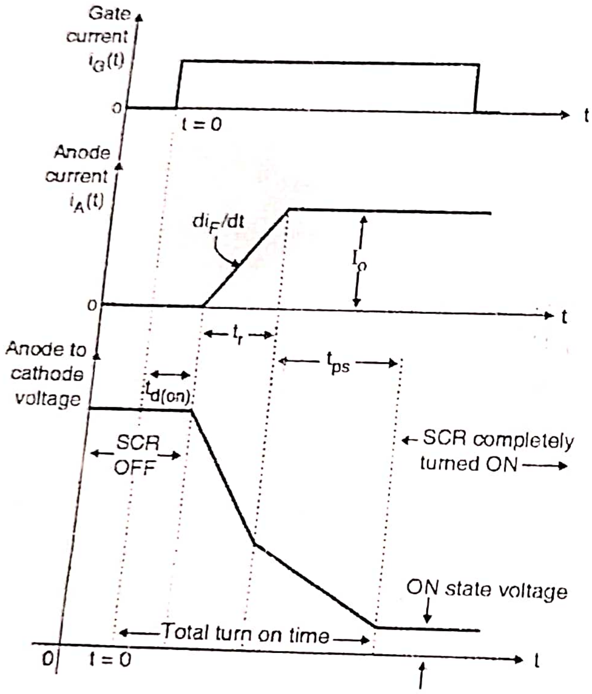
SPPU : March 19, Dec. 19

University Questions

Q. 1 Draw & explain switching characteristics of SCR. **(March 19, 4 Marks)**

Q. 2 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- SCR is turned on by applying a current pulse of specified magnitude and duration to the gate of the device.
- The gate current is applied at t = 0 as shown in Fig. 1.7.1.



(1-35) **Fig. 1.7.1 : SCR voltage and current waveforms at the time of turn on**

- The waveforms for the anode current and anode to cathode voltage at the time of turn-on are as shown in Fig. 1.7.1.
- The forward anode current increases at a constant rate di_f/dt. The total time taken by SCR to turn on completely can be subdivided into three time intervals. They are :

1. The turn-on delay time $t_{d\,(on)}$
2. The rise time (t_r) and
3. The spreading time (t_{ps})

$$\therefore t_{on} = t_{d\,(on)} + t_r + t_{ps} \qquad ...(1.7.1)$$

1. **Turn-on delay time $t_{d\,(on)}$:**

- During the turn on delay time $t_{d\,(on)}$ the SCR appears to remain the forward blocking i.e. off state.
- The voltage across SCR remains constant and high, and anode current through it is zero as shown in Fig. 1.7.1.
- But as the gate current has already been applied, excess carriers are injected into the p_2 layer (the base of n-p-n transistor in the equivalent circuit.) This increases the sum ($\alpha_1 + \alpha_2$).
- This sum finally reaches unity, and SCR turns on, due to regeneration.
- At the end of this interval, the voltage across SCR begins to reduce and the anode current starts increasing.

2. **Rise time interval (t_r) :**

- During the rise time interval (t_r) the following events take place :
- The anode current rises at a rate di_F/dt. This rate is large enough so that the anode current reaches its steady state value (I_o) within a short time.
- The rise time interval (t_r) comes to an end as soon as the anode current reaches its steady state value (I_o).
- The anode to cathode voltage begins to drop rapidly during the rise time interval. (see Fig. 1.7.1)
- Even after the rise time interval is over the plasma will continue to spread over the lateral area of SCR until SCR is completely shorted out by the large number of excess carriers.

3. **Plasma spreading interval (t_{ps}) :**

- The time required for the plasma to spread from the region around the gate to the entire device cross-section is the "Plasma Spreading Time (t_{ps})".

1.7.2 Turn-off Process :

SPPU : Dec. 19

University Questions

Q. 1 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- Once SCR is turned on, it gets latched into its on-state and acts like a closed switch.
- The gate terminal loses control over SCR i.e. even though the gate pulses are removed SCR remains in the on-state.

A conducting SCR can be turned off with the help of an external circuit, by reducing the anode current below its holding current for a minimum specified time.

- During this time, the stored charge inside the device will be removed due to internal recombination and carrier sweep out.
- Due to this, the transistors Q_1 and Q_2 in the equivalent circuit of Fig. 1.7.1 come out of saturation and enter into active region.
- The values of α_1 and α_2 will decrease, the regeneration will decrease and the conducting SCR will turn-off.
- The minimum time required for the recombination and carrier sweep out should be provided before the device is turned on again.
- This is necessary for the successful turn-off of SCR.

1.7.3 Turn-off Characteristics (Dynamic turn off Characteristics) of SCR :

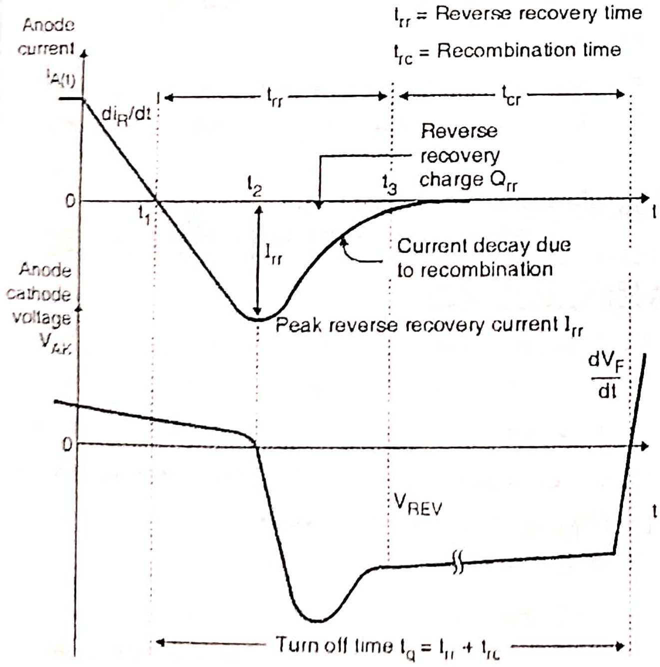
SPPU : March 19, Dec. 19

University Questions

Q. 1 Draw & explain switching characteristics of SCR. **(March 19, 4 Marks)**

Q. 2 Draw the dynamic characteristics of SCR and explain the turn on and turn off process of SCR in detail. **(Dec. 19, 7 Marks)**

- The turn off characteristics using the forced commutation is shown in Fig. 1.7.2.



(1-37) **Fig. 1.7.2 : SCR voltage and current waveforms during turn-off**

- The successful turn-off of a conducting SCR requires that it should be reverse biased by the external circuit for a minimum time period.
- The process to turn-off SCR is also called as "commutation".
- The turn-on time of SCR is appreciably shorter than the turn off time. The turn-off waveforms of SCR are as shown in Fig. 1.7.2.

1. The current through the conducting SCR starts decreasing at t = 0 at a fixed rate di_R/dt. This rate of change of current is decided by the external circuit. As the current decreases, the excess carrier in the four layers of SCR decrease from their steady state values, due to the internal recombination and carrier sweep out.
2. Due to the two outer junctions J_1 and J_3, the turn-off characteristics is similar to that of a diode. The peak reverse recovery current is denoted by I_{rr} and its magnitude is much higher than the normal reverse blocking current I_r.
3. **Reverse recovery time t_{rr} :** The reverse recovery time t_{rr} is the time required for the minority carriers to recombine with the opposite charges and get neutralized. It is the time from zero crossover point of SCR current to 25% of the peak reverse recovery current I_{rr}.
4. **Recombination time t_{rc} :** This is the time required for the recombination of excess charges in the middle p-n junction J_2. A negative reverse voltage will reduce this time.

1.7.4 Turn-off Time (t_q) :

- Device manufactures specify a turn-off time t_q for their SCRs, which represents the minimum time SCR should remain in the reverse blocking mode (i.e. reverse biased) before any forward voltage is reapplied.
- That means for successful commutation (turn-off) of SCR it is necessary to reverse bias it for a period equal to or greater than (t_q) before reapplying a forward voltage.
- As shown in Fig. 1.7.2 the turn off time (t_q) of SCR is sum of reverse recovery period (t_{rr}) and the recombination time (t_{rc}) and is of the order of 40 μs to 200 μs. Thus

$$t_q = t_{rr} + t_{rc} \quad ...(1.7.2)$$

- The turn-off time of SCR is dependent on :
  1. The current through SCR (I_a)
  2. di/dt at the time of commutation (turn-off)
  3. The junction temperature and
  4. Magnitude of reverse voltage
- Increase in the values of factors 1, 2 and 3 will increase the turn off time, whereas with increase in the reverse voltage the turn off time will decrease.
- The commutation circuit used to turn off SCR must have a turn off time t_{off} greater than t_q for successful commutation.

$$\therefore \text{ Circuit turn off time } t_{off} > t_q \quad \text{...(1.7.3)}$$

- All possible efforts should be made in order to minimize the turn off time.

Difference between SCR turn off time and circuit turn off time :

- SCR turn off time is the time taken by the conducting SCR to completely turn off. It is denoted by t_q.
- The circuit turn off time t_{off} is the time for which SCR is reverse biased by an external commutation circuit, to ensure successful commutation.

Reverse recovery charge Q_{rr} :

- It is defined as the amount of charge which has to be recovered during the turn off process. It is the area enclosed by the path of reverse recovery current (shaded portion of $i_A(t)$ in Fig. 1.7.2).
- The value of reverse recovery charge Q_{rr} depends on the rate at which the anode current decreases and the peak value of on-state current before turn off.
- Reverse recovery charge decides the time required to turn off SCR. Larger Q_{rr} more is the time required to turn off and slower is SCR.

> **Note :** The turn on and turn off time of SCR are important because they decide the maximum switching frequency of SCR. These time periods also decide the power dissipation taking place in SCR at the time of turn on and turn off. Ideally the turn on and turn off time periods are zero and practically they should be as short as possible.

Ex. 1.7.1 : Calculate the peak reverse recovery current for SCR, if the reverse recovery time t_{rr} = 10 μ sec and reverse recovery charge Q_{rr} = 150 μC.

Soln. :

Given : t_{rr} = 10 μs, Q_{rr} = 150 μC

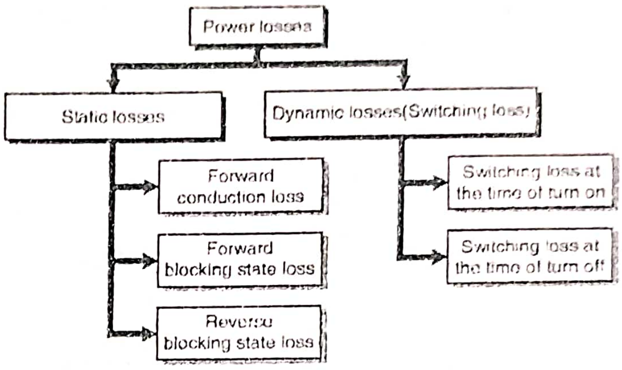
$$\text{Peak reverse recovery current} = \frac{2 \times \text{Reverse recovery charge}}{\text{Reverse recovery time}}$$

$$\therefore I_{rr} = \frac{2 \times Q_{rr}}{t_{rr}} = \frac{2 \times 150 \times 10^{-6}}{10 \times 10^{-6}}$$

$$\therefore I_{rr} = 30\text{A} \quad \text{...Ans.}$$

1.8 Various Losses in Power Devices :

- There are various static and dynamic power losses that take place in any power device.
- The classification of power losses is as shown in Fig. 1.8.1.



(1-39) **Fig. 1.8.1 : Classification of power losses**

1.8.1 Static Losses :

- These are the power losses taking place in a power device, when they are either in the on-state or off state.
- These are also known as the steady state power losses.

Forward conduction loss :

- This is the power loss taking place in a device when it is conducting fully.
- It is equal to the product of on-state voltage drop and on-state current flowing through the device.
- As the on-state voltage drop of a switching device is small, this power loss is also small.

Forward blocking state loss :

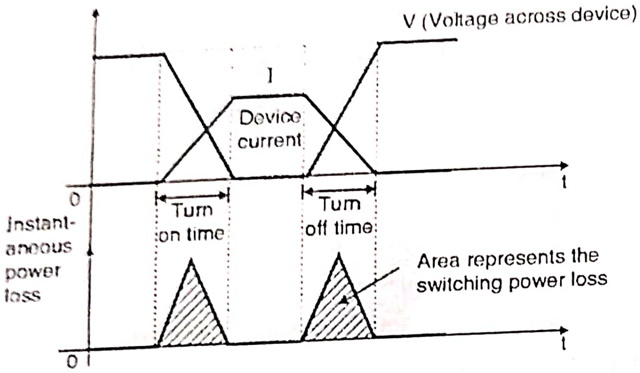
- During the forward blocking state the device withstands the entire supply voltage.
- But the forward current is negligible (leakage current). So the forward blocking state power loss is negligible.

Reverse blocking state power loss :

- The reverse leakage current flowing through the device is negligibly small and reverse voltage across the device is high.
- So the reverse blocking state power loss which is the product of these two is negligible.

1.8.2 Switching Losses (Dynamic Losses) :

- This is a major component of the total power loss taking place in a power device.
- The switching losses take place when a device is either being turned on or when it is being turned off.
- A power device does not turn on or off instantaneously. It takes a finite time to turn on or off as shown in Fig. 1.8.2.
- During the turn-on and turn-off durations, the voltage across the device and current through it, both are high.
- So the instantaneous power loss in the device is high as shown in Fig. 1.8.2.



(1-40) **Fig. 1.8.2 : Switching losses**

- The area under the power curve of Fig. 1.8.2 represents the switching power loss.
- In order to reduce the switching loss, the turn-on and turn-off times should be reduced to their minimum values.
- The switching power loss increases with increase in frequency.
- The switching loss has to be minimized to avoid the device damage due to excessive heating.

1.9 SCR Ratings :

- There are different ratings that are specified by the device manufacturers and they are mentioned in SCR manuals.
- The designer must make use of this data in order to select a device which has adequate ratings.
- The specified ratings should not be exceeded, in order to operate SCR reliably.

1.9.1 Current Ratings :

SPPU : Dec. 06, May 07, Dec. 07, May 10, Dec. 10, May 12

University Questions

Q. 1 Describe following ratings as applicable to SCR with the help of neat diagram.

1. I^2t rating (short circuit) 2. dv/dt rating

(Dec. 06, May 10, 4 Marks)

Q. 2 Describe following ratings as applicable to SCR with the help of neat diagram :

1. Surge current rating 2. dv/dt rating.

(Dec. 06, 4 Marks)

Q. 3 Explain in detail the following current ratings of SCR :

1. I^2t rating 2. di/dt rating. **(May 07, 5 Marks)**

Q. 4 Describe following ratings as applicable to SCR.

1. di/dt rating 2. I^2t rating **(Dec. 07, 8 Marks)**

Q. 5 Describe the following ratings as applicable to SCR :

1. Surge current rating 2. dv/dt rating.

(May 10, 4 Marks)

Q. 6 Explain in detail the following current ratings of SCR in detail :

1. Average on state current 2. I^2t rating.

(Dec. 10, 4 Marks)

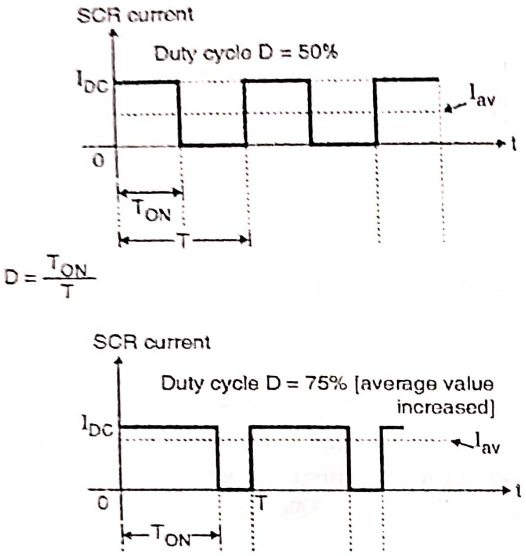
Q. 7 Describe the following ratings as applicable to SCR :

1. Surge current rating
2. I^2t rating 3. $\frac{di}{dt}$ rating. **(May 12, 6 Marks)**

Average current rating (Recurrent) :

- This is the average current SCR can safely carry repetitively without exceeding the junction temperature limits.
- The power dissipation in the on-state is controlled by the average current rating of SCR. The average current rating depends on :
  1. The case temperature and
  2. Conduction angle (the time for which a device operates per cycle).
- The average value of SCR current also depends on the shape of the current flowing through it.

- If SCR current is rectangular in shape, then the average current is proportional to the duty cycle (D) of the waveform which is the ratio of on time to the total time.
- With increase in the duty cycle, the average current value increases even though the peak value of current is same (IDC) as shown in Fig. 1.9.1(a).



(I-41) **Fig. 1.9.1(a) : Average value of rectangular currents through a thyristor**

RMS current rating :

- The power loss and heating of a SCR depends on the rms value of SCR current.
- The RMS and average values are identical for a direct current (pure dc not the pulsating one).
- The RMS current rating as shown on the specification sheet for individual SCR's is necessary to prevent excessive heating in the resistive elements of SCRs such as joints, leads, interfaces etc.
- The RMS current rating is repetitive (recurrent) type of current rating and if proper cooling methods are used then this rating can be increased.

Surge current rating :

- The surge current rating indicates the maximum possible non-repetitive or surge current which the device can withstand without damaging itself.
- SCR can be subjected to the surge current rating only once in its lifetime. The surge current is assumed to be sinusoidal at 50 Hz. It is specified in terms of number of surge cycles with a specific peak value.
- As the duration of the surge increases the surge current rating decreases.

I^2t rating :

- This rating gives an idea about the maximum energy a power device can absorb or dissipate without getting damaged because I^2 R represents power and I^2 Rt represents energy.
- The current I is the RMS value of device current for an interval "t". The I^2t rating of the device is used for selection of I^2t rating of a fuse or protecting device.
- The I^2t rating of the fuse should be less than that of the device, otherwise it will not be successful in protecting the device against overcurrent. The period "t" is one cycle period.

di/dt rating :

- This indicates the maximum tolerable rate of rise of the anode current.
- At the time of turn on the anode current is not evenly distributed throughout the device.
- The current flows in the form of "filaments" of small diameter, formed inside the device.
- If the rate of anode current increase is very high then a very short time after we turn on the device, a large current will be forced through these "filaments".
- The resistance offered to the flow of current by these filaments is high due to their small diameter.
- Therefore the power dissipation in the filaments is excessively large and it is localized, which will develop localized "hot spots" to damage SCR.
- Therefore the applied di/dt should not be allowed to exceed the specified di/dt rating.
- A special circuit called snubber circuit is used alon with the SCR to protect it against higher di/dt or dv/dt than their specified values.

1.9.2 Voltage Ratings :

SPPU : Dec. 06, May 10, May 12, March 19

University Questions

Q. 1 Describe following ratings as applicable to SCR with the help of neat diagram :

1. Surge current rating
2. dv/dt rating. **(Dec. 06, 4 Marks)**

Q. 2 Describe the following ratings as applicable to SCR :

1. Surge current rating 2. dv/dt rating. **(May 10, 4 Marks)**

Q. 3 Describe the following ratings as applicable to SCR $\frac{dv}{dt}$ rating (May 12, 2 Marks)

Q. 4 Explain following rating of SCR : V_{RRM}. (March 19, 6 Marks)

Reverse voltage rating (V_{RRM}) and (V_{RSM}) :

- In the reverse direction (anode negative with respect to cathode) the SCR behaves like a conventional rectifier diode.
- Two types of reverse voltage ratings have been assigned.
  1. Repetitive peak reverse voltage with gate open V_{RRM} and
  2. Non-repetitive peak reverse voltage with gate open V_{RSM}.
- If the applied reverse voltage exceeds these values then, the device will go into breakdown and may destroy itself.
- This is also called as reverse blocking voltage of SCR.
- Where there is a possibility of excessive reverse transient voltages, additional V_{RRM} margin may be built into the circuit by adding a rectifier diode in series with the controlled rectifier.

Peak off-state blocking voltage V_{DRM} :

- The peak off-state blocking voltage V_{DRM} is given on the specification sheet of a thyristor for maximum allowable junction temperature (worst case) with a specified gate bias condition.
- This is also called as forward blocking voltage of SCR.
- The large SCRs are specified for a peak off-state blocking voltage rating with the gate open, whereas smaller SCRs are usually characterized for a peak off-state blocking voltage with a specified gate to cathode bias resistor.
- The SCR will remain in off-state if its peak off-state voltage rating is not exceeded. Exceeding this voltage may turn on the SCR.

Peak positive anode voltage (PFV) :

- Some SCRs are assigned a PFV rating. This rating is usually at or above the V_{DRM} rating.
- It is the maximum positive voltage that can be applied between the anode and cathode without damaging the thyristor.
- If the applied voltage is higher than PFV, then the thyristor will be turned on and get damaged. This is also known as the forward blocking voltage.
- The PFV rating is of great practical importance when SCRs are tested for their actual break over voltage characteristics $_{V(BO)}$ at room temperature ; most of the times a device will have a $_{V(BO)}$ beyond its PFV rating at lower temperatures as compared to the maximum rated junction temperatures ($_{Tj\ max}$).
- If the applied voltage is higher than PVF, then the SCR will be turned on and get damaged.

On-state voltage drop (V_T or V_F) :

- The voltage drop across the SCR in the on-state at a given anode current and temperature. It varies between 1 and 1.5 Volts.
- This voltage drop decides the power loss taking place in SCR while conducting.

Forward static dv/dt rating :

- It is the maximum rate of rise of anode to cathode voltage that will not turn on the SCR with gate terminal open.
- If dv/dt of the applied voltage is greater than the specified value for a given thyristor, it will turn-on without gate drive. This may even lead to damage of the thyristor, if current is not limited to a safe value.

Dynamic dv/dt rating :

- The dynamic dv/dt rating is greater than the static dv/dt rating.
- It is defined as the maximum allowable rate of rise of voltage which will not cause the failure of commutation (of an already turned off SCR) and will not turn the SCR on when it is being turned off.
- A special circuit called snubber circuit is used alon with the SCR to protect it against higher di/dt or dv/dt than their specified values.

1.9.3 Advantages of SCR :

1. It can handle large voltages, currents and power.
2. The voltage drop across conducting SCR is small. This will reduce the power dissipation in the SCR.
3. Easy to turn on.
4. Triggering circuits are simple.
5. It can be protected with the help of a fuse.
6. We can control the power delivered to the load.

1.9.4 Drawbacks of SCR :

1. It can conduct only in one direction. So it can control power only during one half cycle of ac.
2. It can turn on accidentally due to high dv/dt of the source voltage.
3. It is not easy to turn off the conducting SCR. We have to use special circuits called commutation circuits to turn off a conducting SCR.
4. SCR cannot be used at high frequencies. The maximum frequency of its operation is 400 Hz.
5. Gate current cannot be negative.

1.9.5 Applications of SCR :

1. Controlled rectifiers.
2. DC to DC converters or choppers.
3. DC to AC converters or inverters.
4. As static switch.
5. Battery chargers.
6. Speed control of DC and AC motors.
7. Lamp dimmers fan, speed regulators.
8. AC voltage stabilizers.

1.10 SCR Types :

- Depending on the physical construction, the turn on, turn off behaviour, the SCR are classified into following categories :
  1. Phase - control SCRs (Converter grade SCRs).
  2. Fast - switching SCRs (Inverter grade SCRs).
  3. Gate turn – off SCRs (GTOs).
  4. Bidirectional triode SCRs (TRIACs).
  5. Reverse conducting SCRs (RCTs).
  6. Static induction SCRs (SITs).
  7. Light - activated silicon controlled rectifiers (LASCRs).
  8. FET - controlled SCRs (FET - CTHs).
  9. MOS - controlled SCRs (MCTs).

1.10.1 Phase Control SCRs (Converter Grade SCRs) :

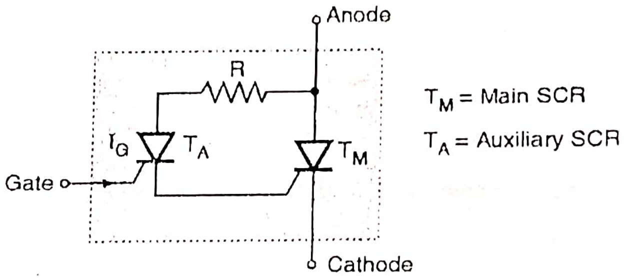
- This SCR is designed to operate at the line frequency (50 Hz) and it is turned off by natural commutation (by reducing the anode current below holding current naturally).
- It is a slow SCR with a turn off time t_q = 50 to 100 μs. Phase control SCR is also called as "converter grade SCR", as it is ideally suited for the "converter applications".

Typical ratings of SCR :

- Some of the important rating of a SCR are as follows :

Sr. No.	Description	Value
1.	On-state voltage V_T	1.5 to 2.5 Volts
2.	Turn off time t_q	50 to 100 μs
3.	Maximum rate of change of voltage dv/dt :	1000 V/μs
4.	Maximum rate of change of current di/dt :	500 A/μs
5.	Maximum switching frequency	400 Hz

- Now a day's SCRs with amplifying gate are available.
- Inside these SCRs an auxiliary SCR T_A is turned on by the external gate signal and T_A is further used to turn on the main SCR T_M (see Fig. 1.10.1). T_A can produce large gate current required to turn on the main SCR.



(1-46(a)) Fig. 1.10.1 : Structure of amplifying gate SCR

1.10.2 Fast Switching SCRs (Inverter Grade SCRs) : SPPU : May 16

University Questions

Q. 1 Explain in brief difference between converter grade SCRs and inverter grade SCRs. **(May 16, 4 Marks)**

- These SCRs are designed to operate at higher switching frequencies. They have fast turn off times in the range 5 to 50 μs.
- These SCRs are ideally suited for the high frequency applications such as inverters, choppers etc. Hence they are also called as **inverter grade SCRs.**

- Forced commutating circuits are required to be used to turn off these SCRs. Some of the important ratings of this SCR are as follows.

Important ratings of inverter grade SCRs :

Sr. No.	Description	Value
1.	Turn-off time (t_q)	5 to 50 μs
2.	Maximum rate of change of voltage dv/dt	1000 V/μs
3	Maximum rate of change of current di/dt	1000 A/μs
4.	On-state voltage (V_T)	1.7 V
5.	Reverse blocking capacity	10 V

- These SCRs have a very very low reverse blocking capacity (typically 10 V).
- That means if a reverse voltage is applied then these devices can get damaged very easily.

Difference between converter grade and inverter grade SCRs :

- We can differentiate between these two SCR types on the basis of following points :

Sr. No.	Parameter	Converter grade SCR	Inverter grade SCR
1.	Maximum operating frequency	400 Hz	1 kHz
2.	Type of commutation	Natural	Forced
3	Turn off time	50 to 100 μs	5 to 50 μs
4.	Reverse blocking capacity	High	Low
5.	Applications	Low frequency ac mains based applications like controlled rectifiers, AC regulators etc.	High frequency dc input based applications like inverters, choppers etc.

1.11 Triggering Devices for SCRs :

- The triggering devices are used to turn on the SCR. These are low power devices.
- The two commonly used triggering devices for SCR are :

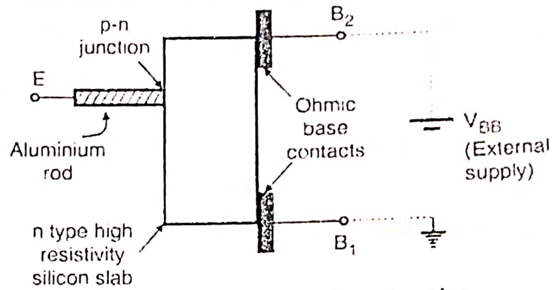
1. UJT and 2. PUT

1.11.1 Unijunction Transistor (UJT) :

- The process of turning on an SCR is called as triggering. Various triggering devices are used to trigger the SCR.
- The most popular device used for SCR triggering is UJT.

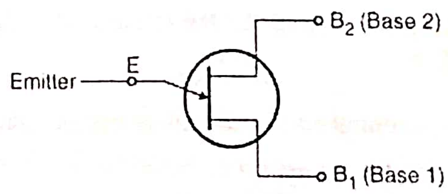
Construction :

- The UJT is a three terminal device having the basic construction as shown in Fig. 1.11.1(a).



(I-51) **Fig. 1.11.1(a) : UJT construction**

- A slab of lightly doped n type silicon material is used as substrate and two base contacts are attached to both ends.
- These terminals are called as base 1 (B_1) and base 2 (B_2) terminals of UJT.
- An aluminium rod is allowed to the opposite surface of n type substrate to form an emitter.
- This aluminium rod forms the only p-n junction of the device with the n type silicon slab.
- This is called as unijunction device as there is only one junction present.
- It is also called as duo (double) base diode due to the presence of two base contacts.
- The aluminium rod is alloyed to the silicon slab at a point closer to base 2 contact than the base 1 contact.
- The base 2 (B_2) terminal is made positive with respect to base 1(B_1) terminal by V_{BB} volts as shown in Fig. 1.11.1(a).
- The symbol for UJT is as shown in Fig. 1.11.1(b). The arrowhead points towards the direction of conventional current flow, when the UJT is in the forward biased, active or conducting state.

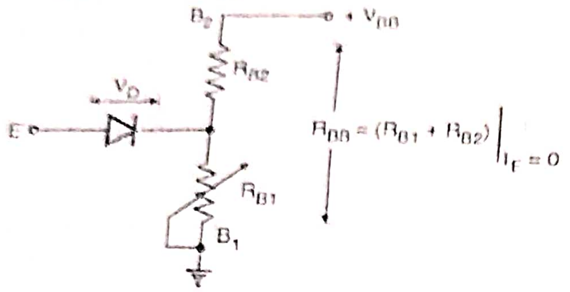


(I-51) **Fig. 1.11.1(b) : UJT symbol**

- The UJT is a three terminal device. The three terminals that are brought out for user are emitter (E) base 1 (B_1) and base 2 (B_2) as shown in Fig. 1.11.1(b)

Equivalent Circuit of UJT :

The equivalent circuit of UJT is as shown in Fig. 1.11.2. It shows two resistances R_{B1} and R_{B2} and a diode which represents the only junction.



(1-52) **Fig. 1.11.2 : Equivalent circuit of UJT**

- The inter-base resistance R_{BB} is the resistance between the terminals B_1 and B_2 of UJT and is defined at zero emitter current as follows :

$$R_{BB} = R_{B1} + R_{B2} \text{ ...at } I_E = 0 \quad ...(1.11.1)$$

- From the equivalent circuit of UJT we can write that,

$$\text{Voltage across } R_{B1} = V_{RB1} = \frac{R_{B1}}{R_{B1} + R_{B2}} \times V_{BB} \Bigg|_{I_E = 0} \quad ...(1.11.2)$$

$$= \eta V_{BB} \quad ...(1.11.3)$$

Intrinsic Standoff Ratio (η) :

- The letter "η" in Equation (1.11.3) is called as the "intrinsic standoff ratio" of UJT and is defined as,

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} \Bigg|_{I_E = 0}$$

$$\text{or} \quad \eta = \frac{R_{B1}}{R_{BB}} \Bigg|_{I_E = 0} \quad ...(1.11.4)$$

Operation of UJT :

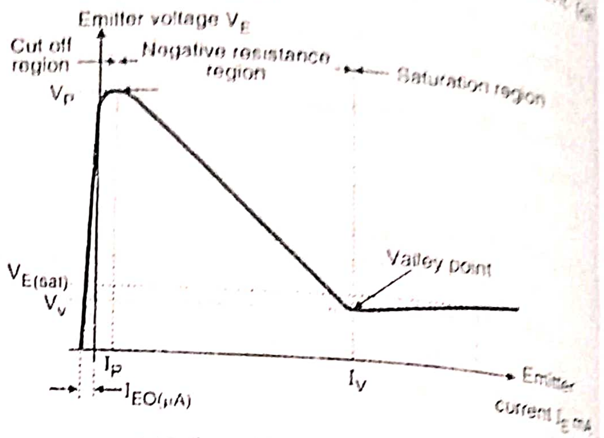
- Refer to the equivalent circuit of Fig. 1.11.2. As soon as the emitter voltage V_E is greater than ($\eta V_{BB} + V_D$), the diode in Fig. 1.11.2 is forward biased and the emitter current will start flowing.
- This is how the UJT is turned on. The emitter voltage at which the UJT turns on is called as the "peak" voltage and is given as :

$$V_P = \eta V_{BB} + V_D \quad ...(1.11.5)$$

- Thus V_P is a particular value of V_E.
- For all the values of V_E below V_P the diode D in the equivalent circuit in Fig. 1.11.2 will remain reverse biased and $I_E = 0$ hence UJT is in the off state.

UJT Characteristics :

- The UJT characteristic is as shown in Fig. 1.11.3. This is emitter voltage (on Y-axis) versus emitter current (on X-axis) characteristics.



(1-53) **Fig. 1.11.3 : UJT characteristics**

- For the emitter potentials less than V_P (peak point potential) the UJT is in the OFF state and the magnitude of I_E is not greater than I_{EO}.
- The current I_{EO} is very similar to the reverse leakage current I_{CO} of a bipolar transistor. This region is known as the cut off region.
- As the emitter potential increases and reaches V_P = ($\eta V_{BB} + V_D$) the UJT starts conducting.
- Then with increase in emitter current I_E the emitter voltage decreases as shown in Fig. 1.11.3.
- The reduction in voltage across UJT is due to the reduction in resistance R_{B1} with increase in the value of I_E.
- This region of operation is known as a "Negative Resistance" region. It is a stable region and can be used in various applications.
- Eventually the "Valley Point" will be reached which marks the end of negative resistance region.
- If we increase I_E further, the UJT will enter into the saturation region.
- The saturation region is a positive resistance region as V_E increases with increase in I_E.

Applications of UJT :

1. As a triggering device for SCR and Triac.
2. In the relaxation oscillator.

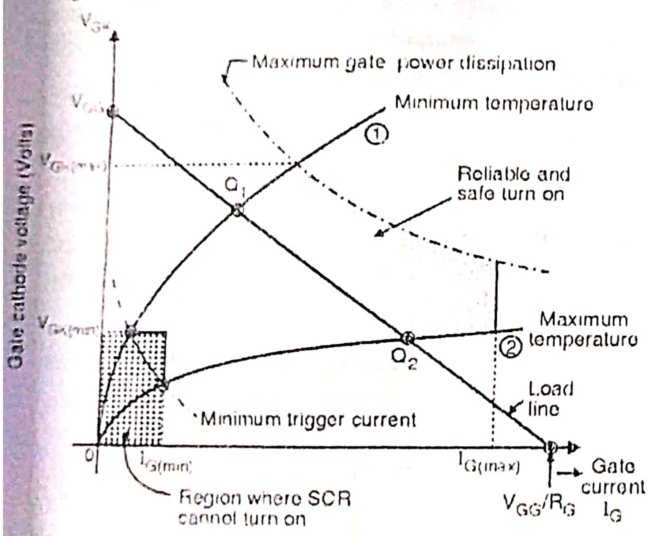
1.12 SCR Gate Characteristics :

SPPU : May 19

University Questions

Q. 1 Explain the nature of gate characteristics and analyze the gate circuit requirements. **(May 19, 7 Marks)**

- As discussed in this chapter, a pulses of gate current is needed to turn on SCR. But once SCR comes into conduction, the gate will have no control over its operation.
- Let us now discuss the triggering circuit requirements and the actual triggering circuits for an SCR.
- The curves of Fig. 1.12.1 are called as the gate triggering characteristics. These curves can be used to design the gate triggering circuit for SCR.



(1-71) **Fig. 1.12.1 : Gate triggering characteristics**

- These curves can be used to estimate the magnitude of gate current applied to turn on SCR successfully.
- The gate triggering characteristics is a graph of gate current I_G on the X-axis and gate to cathode voltage V_{ak} on the Y-axis.
- The two curves marked ① and ② in Fig. 1.12.1 are the gate characteristics of an SCR at minimum and maximum temperatures respectively.
- For a given SCR, the range of variation possible in the gate characteristics is specified by these two curves in Fig. 1.12.1.
- The minimum gate current and minimum gate to cathode voltage needed to trigger SCR at different temperatures are greater than the minimum trigger current (dotted line) $I_{G(min)}$ in Fig. 1.12.1.
- That means if the operating point is in the dotted area of Fig. 1.12.1, then SCR cannot be turned on. The minimum gate current curve is sometimes called as "Locus of minimum firing points".
- The load line of a gate pulse amplifier is as shown in Fig. 1.12.1. Q_1 and Q_2 are operating points. These Q points correspond to the points of intersection between the dc load line and the two gating characteristics.
- The gate currents corresponding to these operating points should be greater than that specified by the minimum gate current curve.
- The maximum gate to cathode voltage and maximum gate current are denoted by $V_{GK(max)}$ or $I_{G(max)}$ respectively. User should not exceed these values to avoid damage to the gate junction due to excessive power dissipation.
- Similarly the minimum values of gate voltage and gate current for the successful turn on of SCR are shown by $V_{GK(min)}$ and $I_{G(min)}$.
- The maximum gate power dissipation $P_{G(max)}$ shown by the dotted line should never be exceeded. Fig. 1.12.1 gives a graph that gives the variation of maximum gate power dissipation. The operating point should never be outside the $P_{G(max)}$ curve.
- The shaded region shown in Fig. 1.12.1 shows the region corresponding to safe and reliable turn on of SCR. The operating point of the gate triggering circuit should always be placed within this region.
- The gate characteristics shown in Fig. 1.12.1 are for the dc values of gate voltage and gate current. However dc (continuous) gate drive will increase the gate power dissipation unnecessarily.

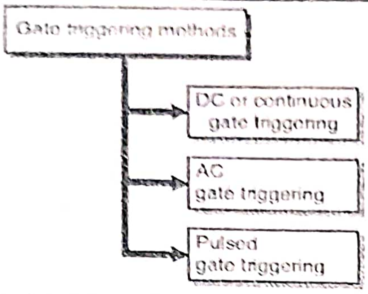
1.12.1 Types of Gate Triggering :

SPPU : May 11

University Questions

Q. 1 Explain triggering methods for SCR. **(May 11, 6 Marks)**

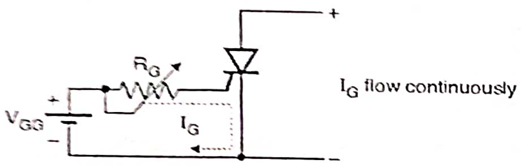
- Fig. 1.12.2 shows the classification of gate triggering methods.



(1-72) **Fig. 1.12.2 : Gate triggering methods**

DC triggering :

- A dc voltage of adequate magnitude and correct polarity is applied between the gate and cathode terminals as shown in Fig. 1.12.3.



(1-73) **Fig. 1.12.3 : DC gate triggering of SCR**

- So gate to cathode junction is continuously be forward biased and a continuous gate current is allowed to flow.
- The magnitude of gate current can be controlled by varying the value of R_G.
- If the gate current is sufficiently high, then the SCR will turn on.
- Even after turning on (triggering) the SCR, the gate current will continue to flow.
- The disadvantage of this technique is that the continuous gate current causes a large gate power loss. Another disadvantage is that there is no isolation between the gate circuit and anode circuit.

1.12.2 Pulsed Triggering of SCR :

SPPU : May 06, May 11

University Questions

Q. 1 Why is a high-frequency pulse train preferred for gating SCRs as compared to DC triggering ? **(May 06, 4 Marks)**

Q. 2 Explain triggering methods for SCR. **(May 11, 6 Marks)**

- The continuous (DC) operation increases the gate power dissipation.
- Therefore a pulsed triggering of SCR is generally used.
- In the pulsed triggering technique, a gate current pulse is used for triggering SCR instead of a continuous gate current.
- Once SCR is turned on, the gate current is reduced to zero. Most of the times, a train of high frequency pulses (instead of only one pulse) applied at the gate of the SCR.
- This is called as multiple pulse triggering. The pulse frequency is of the order of 5 to 10 kHz.

Advantages of pulsed triggering :

1. Gate power dissipation is reduced as the gate current flows for a short duration.
2. The short duration gate triggering pulses can be easily passed through a pulse transformer used for isolation between trigger circuit and SCR.

AC gate triggering :

- In this method a rectified ac voltage is applied between the gate and cathode terminals of the SCR.
- This rectified voltage is obtained from the ac mains supply directly.

Advantages of ac gate triggering :

1. The gate triggering circuit is automatically synchronized with the ac mains.
2. No need to use additional dc source in the gate triggering circuit.
3. It is easy to achieve the firing angle control.

Disadvantage :

- It is possible to apply the gate current only during the positive half cycle of ac mains.

AC gate triggering circuits :

- The examples of ac gate triggering circuits are :
  1. Simple resistances trigger circuit 2. RC triggering

1.12.3 Requirements of Gate Drive for SCR :

SPPU : Dec. 12, May 19

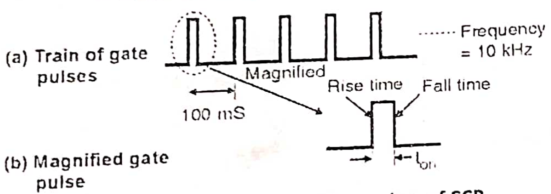
University Questions

Q. 1 What are different design considerations of gate drive circuit of a SCR ? **(Dec. 12, 5 Marks)**

Q. 2 Explain the nature of gate characteristics and analyze the gate circuit requirements. **(May 19, 7 Marks)**

- Some of the important requirements of gate drive of SCR are as follows :

1. The amplitude of gate voltage should be sufficient to forward bias the gate cathode junction and it should be within limits specified by the gate characteristics of Fig. 1.12.1.
2. The amplitude of gate current should be greater than the minimum gate current $I_{G\ (min)}$ specified by the gate characteristics and less than the maximum gate current $I_{G\ (max)}$ specified by the gate characteristics of Fig. 1.12.1.
3. The on time (width) of each pulse in the pulse train should be at least equal to the turn-on time of the SCR, otherwise successful turn on will not be possible. The width of each gate pulse has to be increased further if the load is inductive so as to allow the anode current to reach the latching current value.
4. The triggering pulses should be rectangular in shape as shown in Fig. 1.12.4, with very short rise time and fall time.

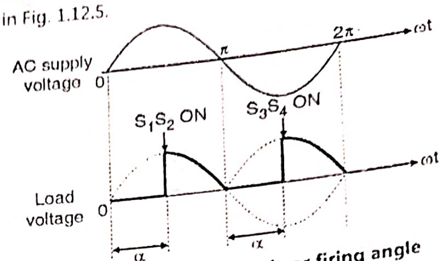


(I-74) **Fig. 1.12.4 : Gate triggering pulses of SCR**

5. A train of identical pulses should be applied to the gate for the entire conduction period of SCR. This multiple pulse triggering will help retriggering of SCR if it turns off due to load fluctuations.
6. Isolation must be provided between the gate triggering circuit and SCR in order to protect the low power triggering circuit. At the same time, pulses from the triggering circuit should be "coupled" to SCR. This is achieved by using a "pulse transformer" or "opto-coupler".
7. **Synchronization** : If the SCR is operating on ac mains, then it is necessary to synchronize the triggering circuit with ac mains.

1.12.4 Delay Angle and Conduction Angle :

- The delay angle or firing angle is the value of "ωt" at which a thyristor or pair of thyristors is turned on.
- It is denoted by α and measured with respect to the zero crossing instant of the ac supply voltage as shown in Fig. 1.12.5.



(I-75) **Fig. 1.12.5 : Delay angle or firing angle**

- The value of delay angle α varies from 0° to 180° or from zero to 2π radians.

Conduction angle (β) :

- It is the duration or angle for which a thyristor remains on.
- For example, the value of β for each thyristor is $(\pi - \alpha)$ for the waveforms of Fig. 1.12.5.

1.13 Isolation Circuits :

- It is necessary to isolate the low power control circuit from the high power anode circuit of SCR.
- At the same time it is necessary to couple the triggering pulses from the control circuit to the gate.
- We can achieve this by using the following coupling/isolating devices :
  1. Pulse transformer 2. Opto coupler.

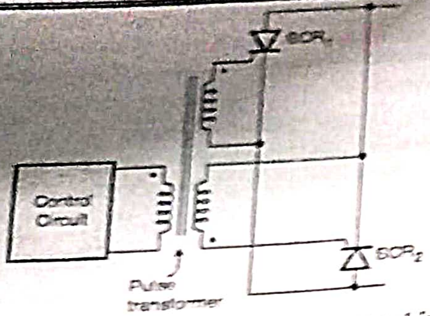
1.13.1 Pulse Transformers :

SPPU : May 08, May 11

University Questions

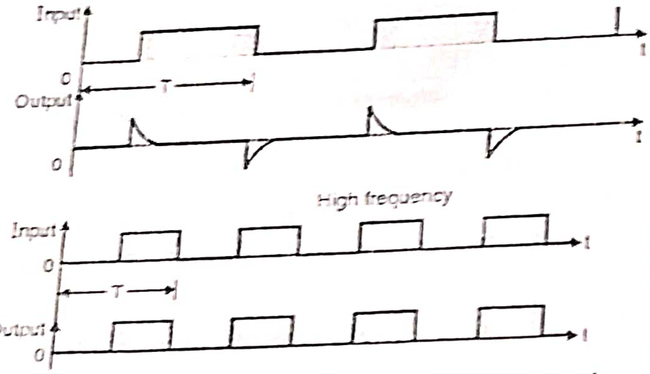
Q. 1 Write a short note on methods of isolating control and power circuits in power converters. **(May 08, May 11, 4 Marks)**

- Pulse transformers are used to couple pulses from a triggering circuit to a SCR.
- They provide electrical isolation between the two circuits.
- The pulse transformers which are generally used for SCR control are either 1:1 two winding, or 1:1:1 three winding types.
- The three winding transformer is used to drive a pair of anti-parallel SCRs are shown in Fig. 1.13.1(a).



(1-108) **Fig. 1.13.1(a) : Use of pulse transformer to drive a pair of antiparallel SCRs**

- The most important requirement is that the efficiency of the pulse transformer must be high.
- Practically, some loss is expected to take place and must be compensated by increasing the drive from the control circuit that drives the primary winding of the pulse transformer.
- The effect of the frequency and pulse width on the output of a pulse transformer is as shown in Fig. 1.13.1(b).



(1-109) **Fig. 1.13.1(b) : Output voltage waveforms of a pulse transformer**

- There are two operating conditions :
  1. When the operating frequency is large or the width of the input pulse (T) is small, then the same pulse appears at the output of pulse transformer.
  2. When T is large or frequency is low, derivative of the input pulse is obtained at the output.

1.13.2 Opto Couplers / Isolators :

SPPU : May 08, May 11

University Questions

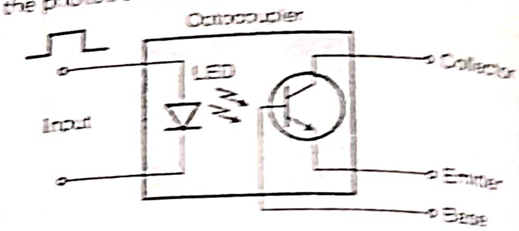
Q. 1 Write a short note on methods of isolating control and power circuits in power converters.

(May 08, May 11, 4 Marks)

- Opto coupler or opto isolator is a combination of light source and light detector in the same package.
- They are used to couple signal from one point to other optically, by providing a complete electrical isolation between them.
- This kind of isolation is provided between a low power control circuit and high power output circuit, to protect the control circuit.

LED-phototransistor Opto-Coupler :

- The LED-phototransistor opto coupler is as shown in Fig. 1.13.2. An infrared LED acts as the light source and the phototransistor acts as a photo detector.



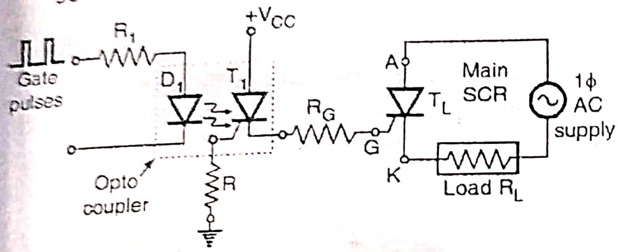
(1-110(a)) **Fig. 1.13.2 : LED-phototransistor opto coupler**

- This is the most popularly used opto-coupler, because it does not need any additional amplification.
- When the pulse at the input goes high, the LED turns ON. The light emitted by the LED is focused on the junction of the phototransistor.
- In response to this light photocurrent starts flowing which acts as base current for the phototransistor.
- The collector current of phototransistor starts flowing. As soon as the input pulse reduces to zero the LED turns OFF and the collector current of phototransistor reduces to zero.
- Thus the pulse at the input is optically coupled to the output side. The waveforms of Fig. 1.13.3 will help you to understand the operation.

(1-111) **Fig. 1.13.3 : Waveforms of LED-phototransistor optocoupler**

1.13.3 Opto-Isolator Driving Circuit for SCR :

- In thyristor converters, different potential exit at various points of the circuit.
- The power circuit operates on a high voltage which is generally higher than 100 V.
- However the gate circuit operates on a lower voltage, which is typically 12 to 30 V.
- Therefore in order to avoid the gate circuit getting exposed to a high voltage it is necessary to use an isolator circuit between an individual thyristor and its gate pulse generator circuit should be isolated from each other using either a pulse transformer or an optical coupler.
- An optocoupler can be a phototransistor or a photo SCR as shown in Fig. 1.13.4



(I-2036) **Fig. 1.13.4 : Opto-isolator driving circuit for SCR**

Operation :

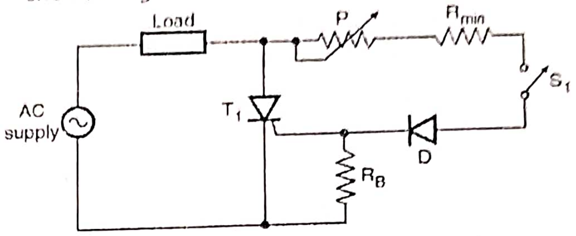
- The gate pulses produced by a gate triggering circuit are applied to the input side of opto coupler.
- Due to the gate pulse, current flows through the LED D_1 and the limiting resistance R_1.
- The LED emits light which is incident on the photo SCR T_1. Thus the gate pulse in the electrical form is converted into an optical pulse.
- The photo SCR T_1 will turn on due to the light incident on it and starts conducting. Its anode current will flow through R_G and act as a gate current pulse for the main SCR T_L. This will turn on T_L.
- This type of isolation circuit increases the cost and weight of the firing circuit.

1.14 SCR Triggering Circuits :

- To turn on SCR we can use any one of the following triggering circuits :
  1. Simple resistor triggering circuit
  2. RC triggering circuit
  3. UJT relaxation oscillator

1.14.1 Simple Resistor Trigger Circuit (R-Trigger Circuit) :

- This circuit is the simplest and most economical means for triggering SCR.
- The circuit diagram for the resistor trigger circuit is as shown in Fig. 1.14.1.

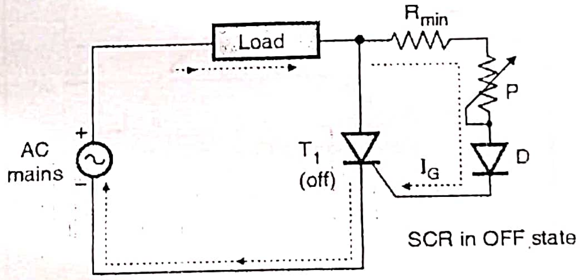


(I-76) **Fig. 1.14.1 : Simple resistor trigger circuit**

- The potentiometer "P" decides the value of peak gate current. The diode D is used to prevent reverse voltage from being applied across the gate cathode junction.
- The diode can be connected across the gate cathode junction also.

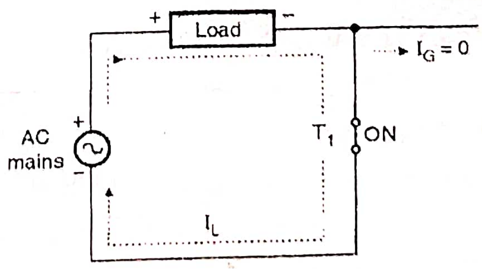
Operation of the circuit :

- The conduction is initiated by closing the switch S_1, shown in Fig. 1.14.1.
- In the positive half cycle of AC supply, the current flows through load, P, D, R_{min} and the gate cathode junction of the SCR as shown in Fig. 1.14.2.



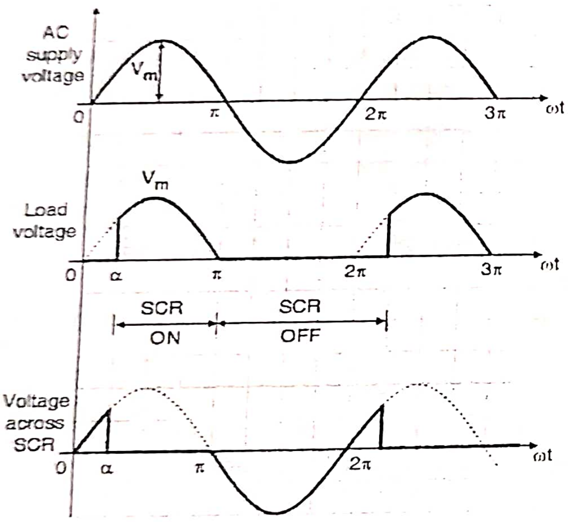
(I-77) **Fig. 1.14.2 : Equivalent circuit (SCR OFF)**

- When the SCR is turned on, the voltage across it reduces to its on state voltage value, which is very small.
- The gate current is then reduces to almost zero, as shown in Fig. 1.14.3.

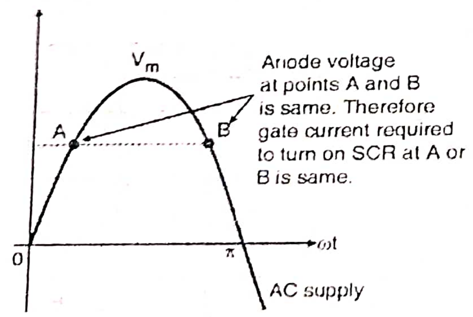


(I-77) **Fig. 1.14.3 : Equivalent circuit (SCR ON)**

- The SCR continues to conduct up to π radians, if the load is purely resistive. For inductive load, the SCR will continue to conduct even in the negative half cycle of the ac supply.
- The firing angle (α) of the SCR (i.e. the instant at which the SCR is turned on. The firing angle is measured from the instant of zero crossing of AC supply.) can be varied by changing the value of the potentiometer "P".
- By varying "P", the value of peak gate current can be changed which in turn decides the instant of firing for the SCR.
- The firing angle is minimum when "P" is adjusted to its minimum value and it increases with increase in the value of "P". The maximum value of firing angle $\alpha_{max} = 90°$.
- The waveforms for load voltage and voltage across the SCR are as shown in Fig. 1.14.4(a). For a resistive load, the SCR turns on at $\omega t = \alpha$ and turns off at $\omega t = \pi$ due to natural commutation.



(a) Voltage waveforms for a resistive load with R triggering circuit



(b) Why is α_{max} restricted to 90° ?

(I-78) **Fig. 1.14.4**

Why is the maximum firing angle restricted to 90° ?

- The maximum firing angle α_{max} cannot be greater than 90° because the ac supply voltage and the gate voltage producing the gate current are in phase.
- As shown in Fig. 1.14.4(b), the voltage at points A and B is same, therefore the gate current required to turn on the SCR at these points is going to be the same.
- Since the SCR will trigger and latch into conduction the first time I_G reaches its required value, it will turn on always at point A rather than B even though everything is identical about these points.

Component values :

- In order to maintain the gate current below the peak gate current of the SCR, I_{gm} a limiting resistance R_{min} is connected.

$$\therefore \quad R_{min} \geq \frac{V_m}{I_{gm}}$$

Where V_m = Peak supply voltage ...(1.14.1)

- Resistance R_B is called as stabilizing resistor. The value of this resistance is selected such that voltage across it does not exceed the forward maximum gate voltage V_{gm}.

$$\therefore \quad R_B \leq \frac{(R + R_{min})V_{gm}}{V_m - V_{gm}}$$

- The SCR will turn on when the instantaneous anode voltage is,

$$v = V_d + V_{gt} + I_{gt}(R + R_{min})$$

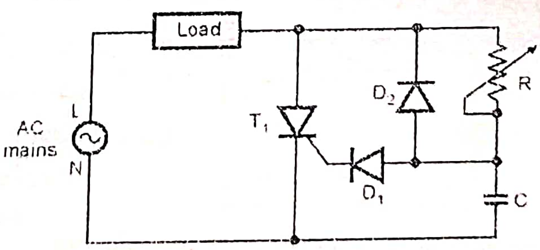
Where V_d = Voltage drop across diode.

V_{gt} = Gate voltage to trigger corresponding to I_{gt}.

I_{gt} = Gate current to trigger the SCR.

1.14.2 Half Wave RC Triggering Circuit :

- Fig. 1.14.5 shows an RC circuit which gives a full, half cycle control (α_{max} = 180°), i.e. the variation in α is between 0° and 180°.

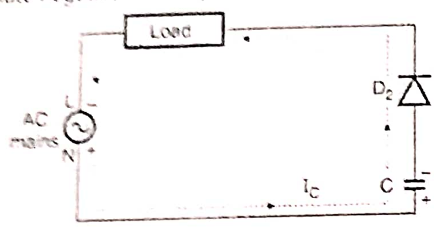


(I-79) **Fig. 1.14.5 : RC triggering circuit**

- The value of α_{max} is not restricted to 90°. This has become possible because of the use of a capacitor in the triggering circuit.

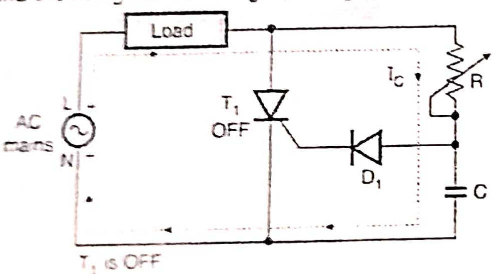
Operation of the circuit :

- In the negative half cycle of the AC supply, diode D_2 is forward biased.
- It will short circuit the potentiometer "R" and the capacitor "C" is charged to negative peak voltage through D_2 as shown in Fig. 1.14.6(a), with its upper plate negative with respect to its lower plate.



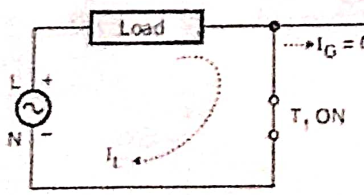
(I-80) Fig. 1.14.6(a) : Operation in the negative half cycle

- In the positive half cycle, D_2 is reverse biased. The capacitor C will charge through R to the trigger point of the SCR in a time determined by the RC time constant and the rising anode voltage (see Fig. 1.14.6(b).



(I-80) Fig. 1.14.6(b) : Operation in the positive half cycle of the supply

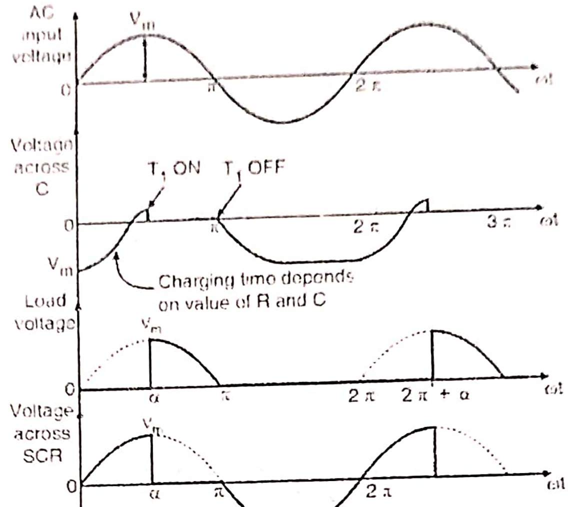
- The diode D_1 will isolate and protect the gate cathode junction against reverse (negative) voltage.
- As soon as the capacitor voltage becomes sufficiently positive to forward bias diode D_1 and the gate cathode junction of SCR, the SCR will be turned on.
- As soon as the SCR is turned on, the voltage across it reduces to a very low value and the gate current goes to zero. (See Fig. 1.14.6(c)).



(c) Equivalent circuit when SCR is turned ON

(I-80) Fig. 1.14.6

- The waveforms for RC triggering circuit are shown in Fig. 1.14.7. The firing angle α can be changed from 0° to 180° by varying the potentiometer R.

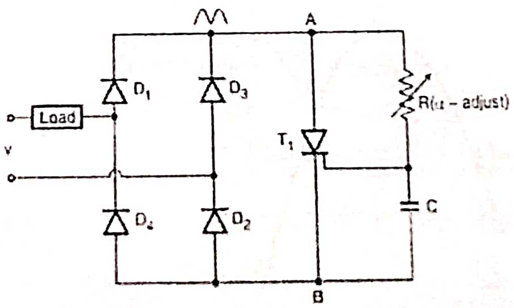


(I-81) Fig. 1.14.7 : Waveforms for RC triggering circuit with resistive load

- Note that a positive as well as negative voltage appears across the capacitor.
- Therefore a non-polarized capacitor such as paper or polysterene type capacitor should be used.
- As seen from the Fig. 1.14.7 the capacitor voltage and the AC line voltage differ in phase.
- By adjusting the value of R it is possible to vary the delay in turning on the SCR from 0 to 10 msec and hence vary the firing angle from 0° to 180°.
- From the load voltage waveform of Fig. 1.14.7 it is evident that this is a "half wave" circuit because α can be controlled in only one half cycle of the supply voltage.

1.14.3 Full Wave RC Triggering Circuit :

- The full wave RC triggering circuit is as shown in Fig. 1.14.8.



(I-82) Fig. 1.14.8 : Full wave RC triggering circuit

Operation :

- The diodes D_1 through D_4 form a bridge rectifier. So between points A and B we get a full wave rectified voltage.
- The capacitor charges through R. So by varying the value of R we can vary the firing angle α.
- The firing angle can be controlled in both the half cycles of the ac supply. Hence this is a full wave circuit.
- RC values are chosen using the following rule.

$$RC \geq \frac{50\,T}{2} = \frac{25}{f}$$

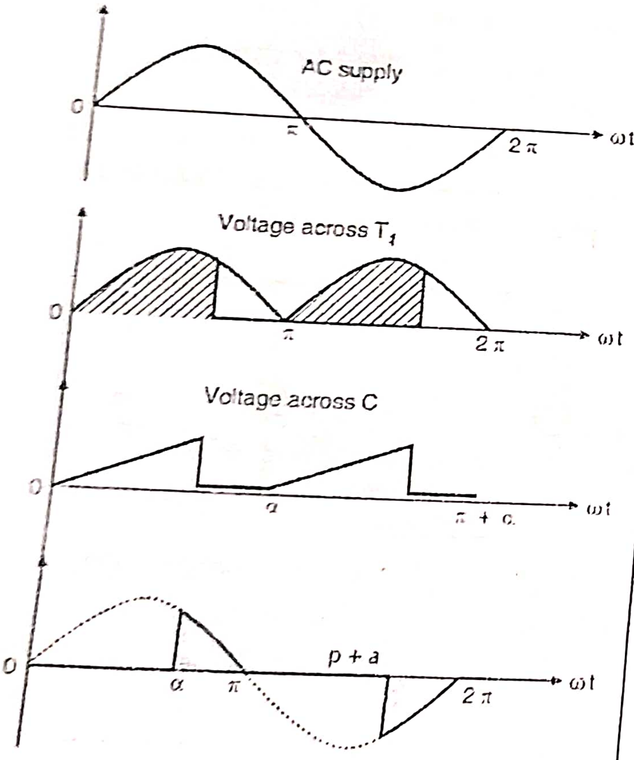
But $f = \omega / 2\pi$

$$\therefore \quad RC \geq \frac{25}{\omega / 2\pi} \approx \frac{157}{\omega} \quad ...(1.14.2)$$

- The value of R is selected using the following equation,

$$R \leq \frac{v - V_{gt}}{I_{gt}}$$

- The waveforms for RC full wave circuit are shown in Fig. 1.14.9.



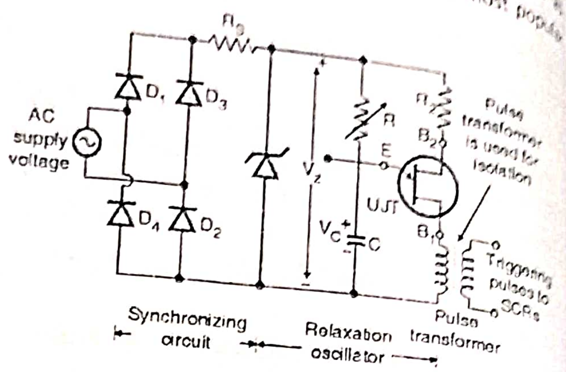
(I-83) **Fig. 1.14.9 : Waveforms for full wave RC triggering circuit**

Features of RC triggering :

1. *Firing angle α can be adjusted between 0 to 180°.*
2. *This circuit is automatically synchronized with ac supply.*

1.14.4 Synchronized UJT Relaxation Oscillator for Triggering SCR :

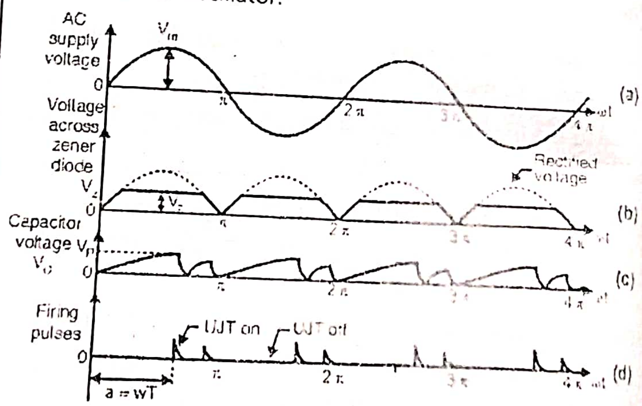
- The synchronized triggering circuit using a UJT is shown in Fig. 1.14.10. This is one of the most popular triggering circuits.



(I-84) **Fig. 1.14.10 : UJT relaxation oscillator**

Operation :

- The ac supply voltage is rectified by the bridge rectifier formed by the diodes D_1, D_2, D_3 and D_4. This full wave rectified voltage is then applied to a zener diode via a current limiting resistor R_S.
- The zener diode will clamp this rectified voltage to V_Z as shown in the waveforms of Fig. 1.14.11(b). The zener voltage V_Z is then used as supply voltage V_{BB} for the relaxation oscillator.



(a) AC supply voltage **(b) Zener voltage V_z**

(c) Capacitor voltage V_C **(d) Firing pulses**

(I-85) **Fig. 1.14.11 : Waveforms of UJT relaxation oscillator**

- The capacitor charges through the potentiometer R.
- When the capacitor voltage equals the peak voltage V_P of the UJT, it turns on.
- Then the capacitor discharges through emitter (E), base (B_1) and primary winding of the pulse transformer.
- Due to primary current, a pulse is generated on the secondary side of the pulse transformer.

- The capacitor voltage and secondary pulses are as shown in Figs. 1.14.11(c) and (d) respectively.
- These pulses are used as triggering pulses for the SCR.
- As the capacitor discharges and V_C reaches the point voltage V_V, the UJT is turned off and the capacitor starts charging again, through R.
- The charging rate of the capacitor is decided by the value of R.
- Therefore it is possible to change the firing angle α by varying the potentiometer R. The firing angle can be changed from 0 to 180°.
- Resistance R_2 of Fig. 1.14.10 will partly compensate for the effect of temperature on the oscillator frequency.

Synchronization :

- The voltage across the zener diode is used as supply voltage for the relaxation oscillator.
- This voltage (V_z) passes through zero at $\omega t = 0, 2\pi, 3\pi$, etc. as shown in Fig. 1.14.11(b).
- Therefore the capacitor voltage also becomes zero at these instants of time.
- Thus we achieve the synchronization with the zero crossing instants of supply voltage.

Expression for frequency of relaxation oscillator :

- The expression for the frequency of relaxation oscillator, is given by :

$$f = \frac{1}{T}$$

$$\text{But } T = T_1 \quad \therefore f = \frac{1}{T_1} = \frac{1}{RC \log_e [1/(1-\eta)]} \quad ...(1.14.3)$$

Design equations for UJT relaxation oscillator :

- The important design equations for the UJT relaxation oscillator are as follows :

$$T = RC \log_e \left[\frac{1}{1-\eta}\right] \quad ...(1.14.4)$$

$$f = \frac{1}{RC \log_e [1/(1-\eta)]} \quad ...(1.14.5)$$

$$V_P = \eta V_{BB} + V_D \quad ...(1.14.6)$$

- From Fig. 1.14.11 it is clear that $\alpha = \omega T$.

$$\therefore \alpha = \omega RC \log_e \left[\frac{1}{1-\eta}\right] \quad ...(1.14.7)$$

$$R_2 = \frac{10^4}{\eta V_{BB}}$$

- The maximum value of R,

$$R_{max} = \frac{V_{BB} - V_P}{I_P} \quad ...(1.14.8)$$

- The minimum value of R,

$$R_{min} = \frac{V_{BB} - V_V}{I_V} \quad ...(1.14.9)$$

Where V_P = Peak voltage of UJT

V_V = Valley point voltage of UJT,

I_P = Peak current

I_V = Valley point current

Features of UJT triggering circuit :

1. Firing angle can be changed from 0 to 180°.
2. Firing angle does not depend on supply (mains) voltage fluctuations.
3. Isolation between gate and anode circuits is provided.
4. It can be used for triggering more than one SCR at a time.
5. This circuit is synchronized with the ac mains.

Design example :

Ex. 1.14.1 : Design the triggering circuit for SCR using UJT. The UJT parameters are : V_{BB} = 30V, η = 0.51, I_p = 10 μA, V_v = 3.5 V, I_v = 10 mA frequency of oscillations is 50 Hz, width of the trigger pulse 50 μS.

Soln. :

- The peak voltage,

$$V_P = \eta V_S + V_D \quad ...(1)$$

$$\therefore V_P = (0.51 \times 30) + 0.7 = 16 \text{ V} \quad ...(2)$$

- The UJT will be triggered when the capacitor voltage $V_C = V_P$ = 16 Volts. The capacitor will then discharge through the UJT and R_3 from V_P to V_V. The discharge time "T_2" should be equal to the gate pulse width i.e. 50 μ sec.

To calculate the value of R_1 :

∴ Discharge equation is,

$$V_V = (V_P - V_D)\, e^{-T_2/R_1 C} \quad ...(3)$$

- Assuming, C = 0.1 μF and substituting other values,

$$3.5 = (16 - 0.7)\, e^{-T_2/0.1 \times 10^{-6} R_1}$$

$$\therefore \frac{-T_2}{0.1 \times 10^{-6} R_1} = -1.475$$

But T_2 = 50 μ sec

- The capacitor voltage and secondary pulses are as shown in Figs. 1.14.11(c) and (d) respectively.
- These pulses are used as triggering pulses for the SCR.
- As the capacitor discharges and V_C reaches the point voltage V_V, the UJT is turned off and the capacitor starts charging again, through R.
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$$V_P = \eta V_{BB} + V_D \quad ...(1.14.6)$$

- From Fig. 1.14.11 it is clear that $\alpha = \omega T$.

$$\therefore \alpha = \omega RC \log_e \left[\frac{1}{1-\eta}\right] \quad ...(1.14.7)$$

$$R_2 = \frac{10^4}{\eta V_{BB}}$$

- The maximum value of R,

$$R_{max} = \frac{V_{BB} - V_P}{I_P} \quad ...(1.14.8)$$

- The minimum value of R,

$$R_{min} = \frac{V_{BB} - V_V}{I_V} \quad ...(1.14.9)$$

Where V_P = Peak voltage of UJT
V_V = Valley point voltage of UJT.
I_P = Peak current
I_V = Valley point current

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1. Firing angle can be changed from 0 to 180°.
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