2 Thyristors

Objectives

- *Thyristors family and detailed study of Silicon Controlled Rectifier (SCR).*
- *Characteristics of SCR.*
- *Gate characteristics, ratings and triggering of SCR.*
- *Protection of power devices from* dv/dt *and over voltages by snubber circuit.*
- *Protection of power devices against hot spots and* di/dt .

2.1 Introduction

- Thyristors are the class of devices that mainly work on the principle of internal regeneration. Before the invention of high power transistors, thyristors were mainly used for power conversion.
- There is a big family of thyristors. Some of the commonly used members of the thyristor family are listed below :
  1. Silicon controlled rectifiers (SCR)
  2. Gate turn-off thyristor (GTO)
  3. Reverse conducting thyristor (RCT)
  4. Static induction thyristor (SITH)
  5. Gate assisted turn-off thyristor (GATT)
  6. Light activated silicon controlled rectifier (LASCR)
  7. MOS-controlled thyristor (MCT)
  8. TRIAC
- Silicon Controlled Rectifier (SCR) is most commonly used thyristor. It is used in almost all of the power converters. It is an attractive device for controlled rectifiers (AC-DC converters) as mentioned in its name as well.

- Thyristors mainly lack in switching speeds compared to power transistors. But their power handling capabilities are very high.
- The drive requirements of thyristors are also simple compared to power transistors.

2.2 Silicon Controlled Rectifier (SCR)

The SCR is one of the commonly used member of thyristor family. It is used in number of applications such as controlled rectifiers, inverters, AC regulators and cycloconverters.

2.2.1 Construction of SCR

Answer following question after reading this topic.

1. *Give the constructional details of a SCR. Sketch its schematic diagram and the circuit symbol.* **Marks[8], May-2007**

Most likely and **asked in** previous University Exam

- We know that SCR is a four layer device. Fig. 2.2.1 (a) shows the symbol of the SCR. It has three terminals : Anode (A), Cathode (K) and Gate (G). A small positive voltage between gate and cathode turns on the SCR.

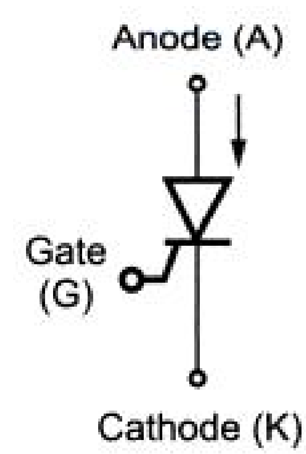
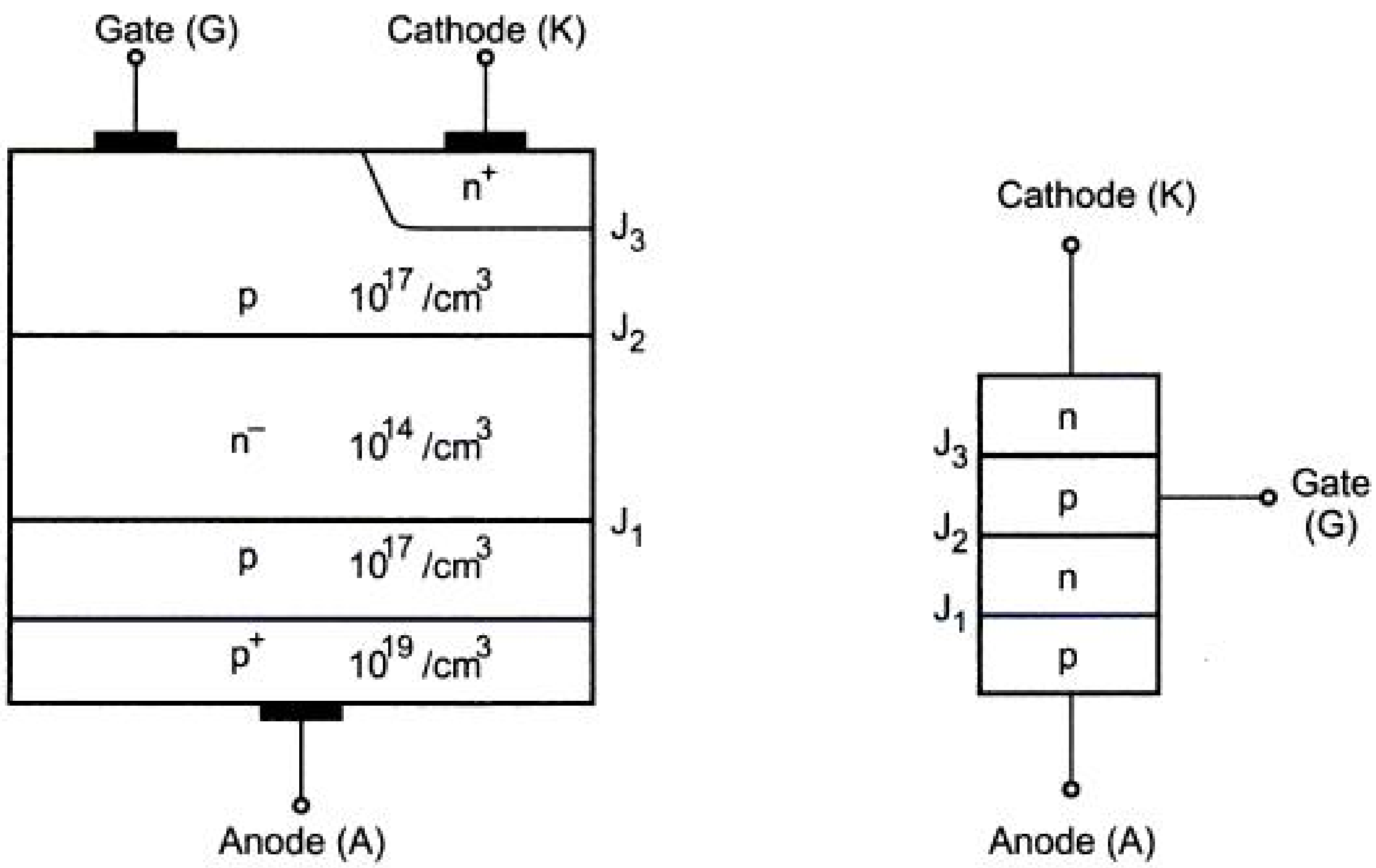


Fig. 2.2.1 (a) Symbol

- Fig. 2.2.1(b) shows the detailed structure. The p^+ layer is doped at $1019 / cm^3$. The player is doped at $10^{17} / cm^3$. The p and p^+ layers from anode (A) of the SCR. The thickness of the p-layer is 30 to 50 μm. The n^- layer is lightly doped. The doping level of this layer is $10^{14} / cm^3$. The width of n^- layer is 50 to 1000 μm. This layer absorbs depletion layer of the junction J_2.
- When SCR is forward biased (V_{AK} positive), junction J_2 is reverse biased. And J_1 and J_3 are forward biased. The depletion layer of J_2 is absorbed by n^- layer when SCR is forward biased. The width of n^- layer decides forward blocking capability of the SCR. The next p-layer, having doping level of $10^{17} / cm^3$ forms the gate of SCR. The width of this layer is 30 to 100 μm. The next, i.e. n^+ layer (doping level of $10^{19} / cm^3$) forms the cathode of SCR.

- Fig. 2.2.1(c) shows the simplified structure of SCR. The gate - cathode junction is J_3. When this junction is forward biased, (i.e. gate signal applied) SCR can be turn-on. Due to gate signal, current starts flowing across J_3. Some carriers flow across J_2 also. Hence, internal regeneration starts and SCR turns on. This process is explained in detail with the help of two transistor analogy in next section.



(b) Structure of SCR **(c) Simplified structure of SCR**

Fig. 2.2.1

2.2.2 Merits, Demerits and Applications of SCR

Answer following question after reading this topic.

1. *Give the comparison between power diodes and thyristors.* **Marks[5], May-2007**

Most likely and **asked in** previous University Exam

Merits of SCR

i. Very small amount of gate drive is required since SCR is a regenerative device.

ii. SCRs with high voltage and current ratings are available.

iii. On-state losses in SCRs are reduced.

Demerits of SCR

i. Gate has no control, once the SCR is turned on.

ii. External circuits are required to turn-off the SCR.

iii. Operating frequencies are very low.

iv. Snubbers (RC circuits) are required for dv/dt protection.

Applications of SCR

i. SCRs are best suitable for controlled rectifiers.

ii. AC regulators, lighting and heating applications.

iii. DC motor drives, large power supplies and electronic circuit breakers.

Comparison between Power Diodes and Thyristors

Sr. No.	Power Diodes	Thyristors
1.	These devices are not controlled.	These devices are controlled by gate.
2.	These devices normally have one junction.	These devices have more than one junction.
3.	These are used for rectification, freewheeling and feedback.	These are used for controlled rectification AC regulation, inversion and DC-DC conversion.
4.	These are used as protection for thyristors.	Thyrsitors are main power conversion devices.
5.	The diodes of this type are fast recovery diodes, schottky diodes, etc.	SCR, TRIAC, GTO are the devices of thyristor family.

2.3 SCR Characteristics and Modes of Operation

Answer following questions after reading this topic.

1. *With the help of characteristics, explain the modes of operation of the thyristor.*
2. *Draw forward and reverse characteristics of SCR. Show I_L, I_H, V_{BO} and V_{BR} on the characteristic.* **Marks[4], May-2000**
3. *Describe the different modes of operation of a thyristor with the help of its static V-I characteristics.* **Marks[4], May-2007**

Most likely and **asked in** previous University Exam

The working of the SCR can be discussed into three modes : Reverse blocking mode, forward blocking mode and forward conduction mode. Fig. 2.3.1 shows the V-I characteristics of the SCR.

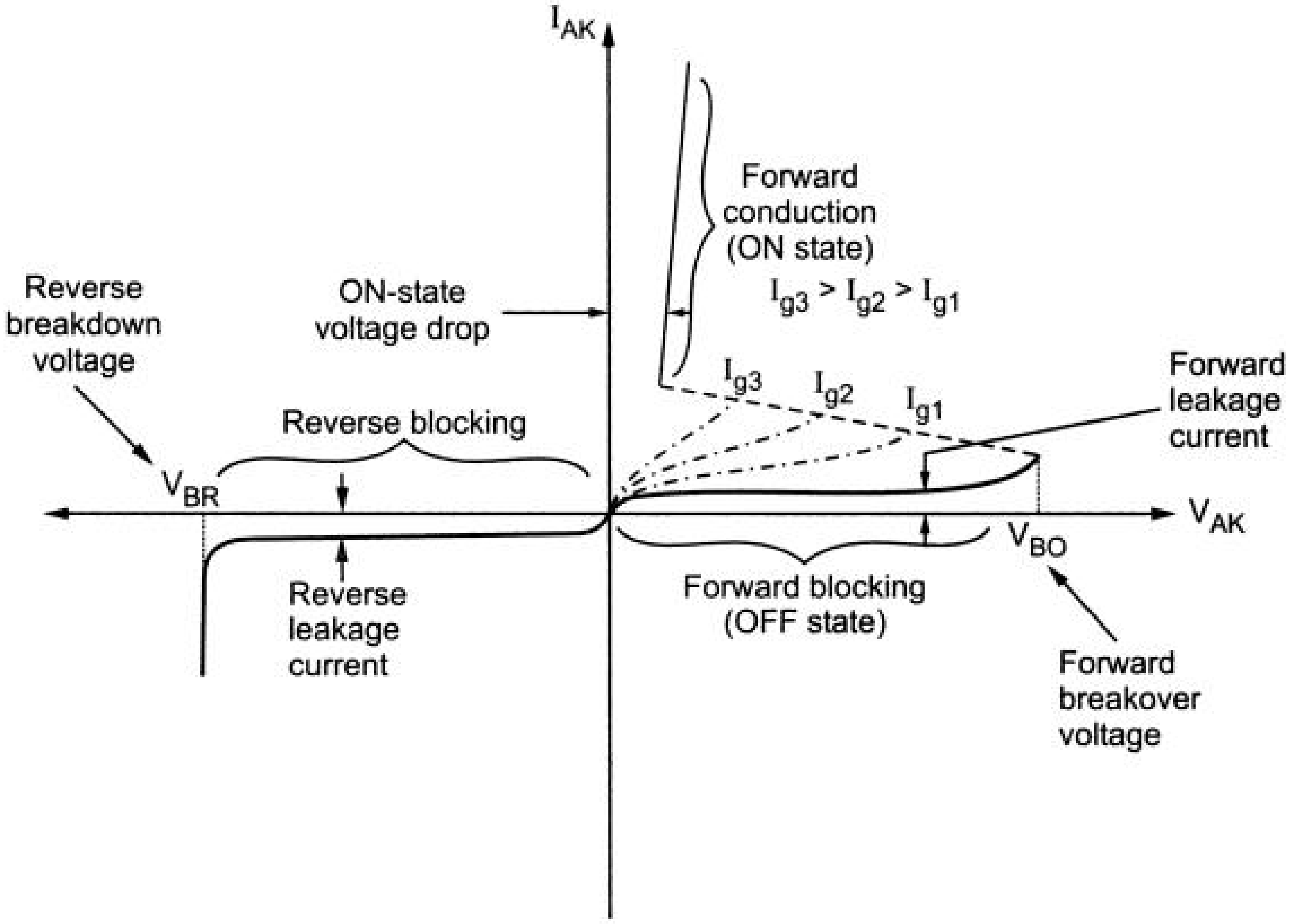


Fig. 2.3.1 Static V-I characteristics of a SCR

The characteristics shown in the Fig. 2.3.1 are called static characteristics. The anode to cathode current I_{AK} is plotted with respect to anode to cathode voltage V_{AK}. The voltage 'V_{BO}' is the forward break over voltage. 'V_{BR}' is the reverse break-down voltage. And I_{g1}, I_{g2}, I_{g3} are the gate currents applied to the SCR.

2.3.1 Reverse Blocking Mode

Fig. 2.3.2 shows the situation when the thyristor will be in reverse blocking mode.

In the Fig. 2.3.2, observe that the anode (A) is made negative with respect to cathode (K). The gate is kept open. There are three PN junctions in the SCR : J_1, J_2 and J_3. Due to this reverse bias, junctions J_1 and J_3 are also reverse biased. And junction J_2 is forward biased. The SCR doesnot conduct due to this reverse bias. A very small current flows from cathode to anode. This current is called *reverse leakage current* of the SCR. This mode is called reverse blocking mode. Fig. 2.3.1 shows the characteristic of SCR in reverse blocking mode. Observe that reverse voltage increases but very small current flows. At reverse break down voltage (V_{BR}), the reverse current increases rapidly. At the time of reverse breakdown, the high voltage is present across the SCR and heavy current flows through it. Hence large power dissipation

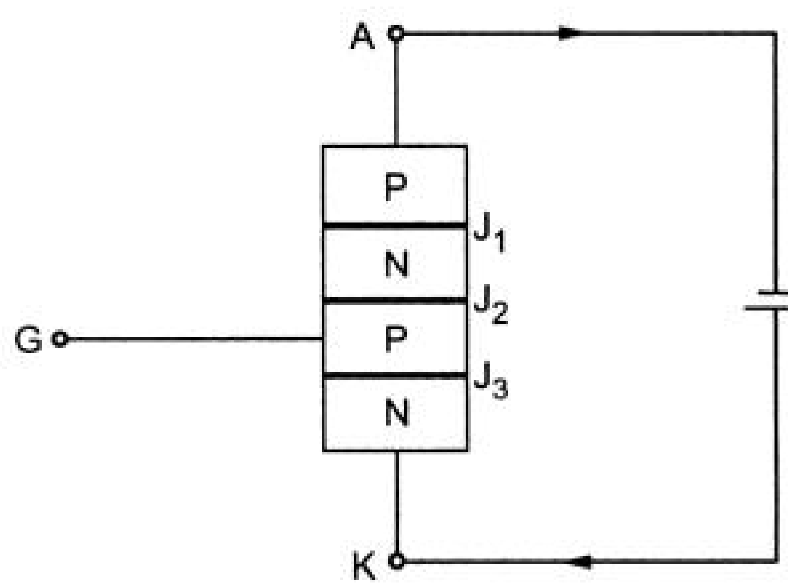


Fig. 2.3.2 A reverse biased SCR

takes place in the thyristor. Due to this dissipation, the junction temperature exceeds the permissible value and the SCR is damaged. Hence a reverse voltage across the SCR should never exceed V_{BR}.

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

2.3.2 Forward Blocking Mode

Answer following question after reading this topic.

1. *In SCR forward breakover voltage is greater than the reverse breakover voltage - State true or false and justify.*
Marks [2], Dec.-2002

Most likely and **Important** Question

The SCR is said to be forward biased when anode is made positive with respect to cathode as shown in Fig. 2.3.3. Due to this forward bias the junction J_1 and J_3 is forward biased and J_2 is reverse biased. Hence the forward voltage is to be hold by junction J_2. A very small current flows from anode to cathode. This current is called forward leakage current. This current is of the order of few milliamperes. In the forward blocking mode, the thyristor is forward biased but it doesnot turn-on. In the forward blocking mode a very small forward leakage current flows. In the forward blocking mode the voltage (V_{AK}) can be increased till V_{BO}. This situation is shown in Fig. 2.3.1. When the forward voltage reaches V_{BO}, the SCR turns on. The SCR goes from forward blocking mode to forward conduction mode. Normally gate drive is applied for this purpose. The highest voltage to be sustained in forward blocking mode is forward break-over voltage, V_{BO}.

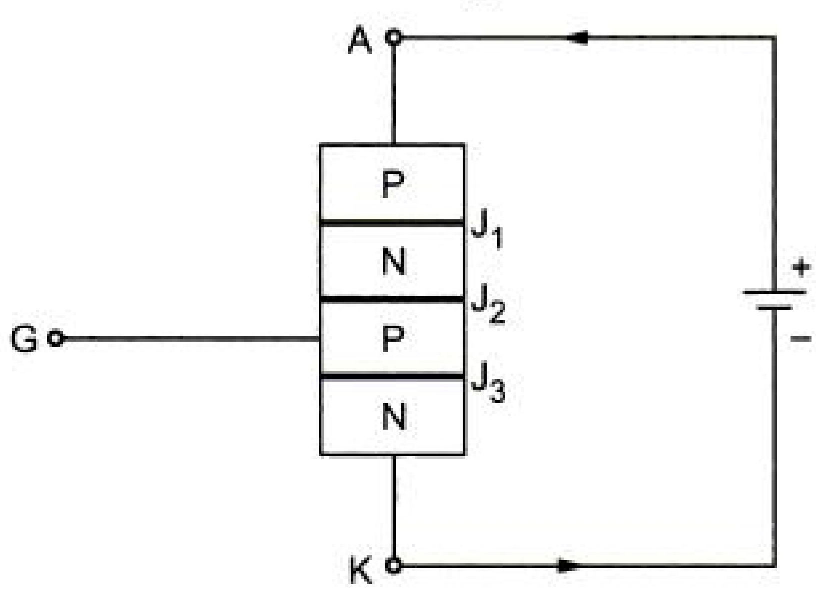


Fig. 2.3.3 SCR in forward biased condition

When the voltage increases above V_{BO}, the SCR goes into forward conduction mode (i.e. turns-on) even if gate drive is not applied. Thus SCR is not damaged if voltage $V_{AK} > V_{BO}$, rather it is turned-on.

The forward breakover voltage is obtained due to blocking capability of junction J_2. The reverse breakover voltage is obtained due to blocking capabilities of junctions J_1 and J_3. The blocking capability of ($J_1 + J_3$) combined is higher than that of J_2. Therefore reverse blocking voltage is higher than forward blocking voltage of SCR.

2.3.3 Forward Conduction Mode

When the SCR is forward biased, then it can go into forward conduction by following techniques :

i) When $V_{AK} > V_{BO}$

ii) When gate drive is applied

iii) When $\frac{dv}{dt}$ exceeds permissible value

iv) When gate cathode junction is exposed to light

Here note that the SCR can go in the forward conduction mode only if it is in the forward blocking mode earlier.

i) When $V_{AK} > V_{BO}$

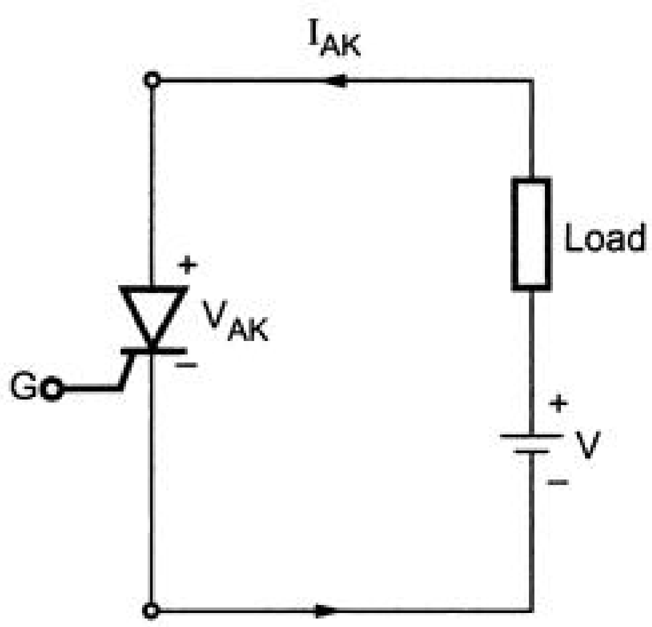


Fig. 2.3.4 Use of SCR in forward conduction

The SCR is driven into forward conduction mode when anode to cathode voltage (V_{AK}) exceeds the forward break-over voltage (V_{BO}). The SCR is said to have *turned-on* when it operates in forward conduction mode. When $V_{AK} > V_{BO}$, the SCR is driven in forward conduction even if gate is open. From Fig. 2.3.3, it is clear that junction J_2 is reverse biased during forward blocking mode $(V_{AK} < V_{BO})$. When V_{AK} exceeds V_{BO}, the avalanche break-down of junction J_2 takes place even if gate drive is not applied. Hence heavy current starts flowing through the SCR and anode to cathode voltage falls to very small value. This is shown in Fig. 2.3.1. The dotted line (...........) indicates switching of SCR from forward blocking state (i.e. OFF) to forward conduction state (i.e. ON). The anode to cathode current of the SCR is only limited by the load. Fig. 2.3.4 shows such situation :

When the SCR conducts in the forward conduction mode, it is said to have turned 'ON'. The anode to cathode voltage is less than 2 volts. This voltage is normally neglected in calculations. Then the current through the load and SCR will be,

$$I_{AK} = \frac{V}{Load} \qquad \text{... (2.3.1)}$$

Thus the SCR current is only limited by the load, once the SCR turns 'on'.

ii) When gate drive is applied

A positive gate to cathode signal is applied whenever the SCR is to be driven into forward conduction mode (ON state). This is also called *gate triggering* of the SCR. Such situation is shown by the typical circuit of Fig. 2.3.5. The SCR is in forward blocking mode when gate drive is not applied. When the positive gate to cathode voltage is applied, current flows from gate to cathode. This current adds to the forward leakage current. Hence avalanche break-down of junction J_2 takes place at lower anode to cathode voltage also. Thus SCR is driven into forward conduction mode (ON state) even if $V_{AK} < V_{BO}$. Fig. 2.3.1 shows the characteristic by center (–·–·–·–) lines when gate drive is applied. Observe that, as the gate current is increased, the SCR turns-on at lower and lower values of anode to cathode voltages. All these anode to cathode voltages are less than V_{BO}. Thus gate triggering is the most convenient way of triggering the SCR.

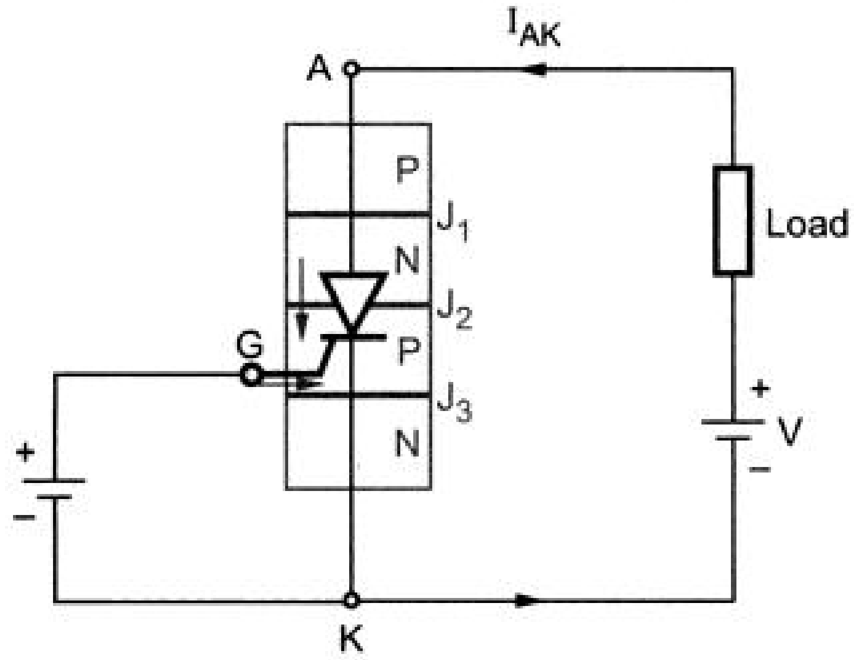


Fig. 2.3.5 Gate triggering is used to turn-on the SCR

Once the thyristor goes into forward conduction mode, the gate has no control over the conduction of thyristor. The current I_{AK} is only limited by the load, i.e.,

$$I_{AK} = \frac{V}{Load}$$

The SCR cannot be driven back into forward blocking mode by removing the gate drive. There are some other techniques. We will discuss those techniques next.

iii) When $\frac{dv}{dt}$ exceeds permissible value

Here $\frac{dv}{dt}$ is the rate of change of anode to cathode voltage with respect to time. Whenever the SCR is in forward blocking state, only forward leakage current flows through the SCR. In such state an equivalent internal capacitor is formed inside the SCR from anode to gate and gate to cathode. Fig. 2.3.6 shows such internal circuit. Whenever the voltage applied across

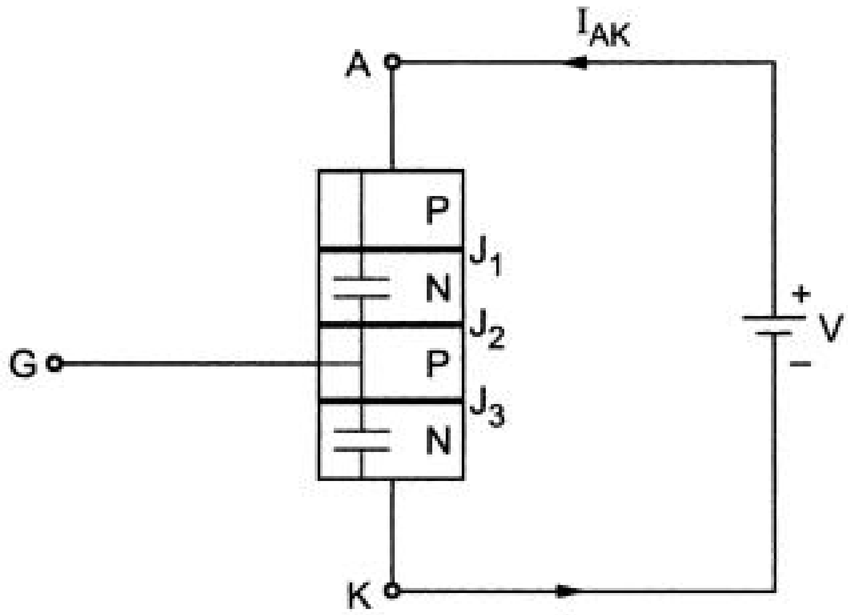


Fig. 2.3.6 SCR turns on by $\frac{dv}{dt}$ due to current flow in equivalent internal capacitor

the SCR changes rapidly, a transient current flows through the SCR. This transient current flows due to rapid voltage variations $\left(\frac{dv}{dt}\right)$ and internal capacitance. This current adds to the forward leakage current. And hence the SCR turns on even if $V_{AK} < V_{BO}$ or gate drive is not applied.

The $\frac{dv}{dt}$ turn-on makes false triggering (unwanted) of the SCR. It is never used for triggering. Every SCR has $\frac{dv}{dt}$ rating. It is expressed in volts per microseconds ($V / \mu s$). The voltage variations across the SCR must be kept less than permissible value of $\frac{dv}{dt}$ to avoid false triggering. Normally a small resistance is connected between gate and cathode to avoid false triggering of SCR due to $\frac{dv}{dt}$. This resistance acts as a external path for leakage current generated by the internal capacitor.

iv) When a gate cathode junction is exposed to light

When the gate cathode junction is exposed to a beam of light, the current flows in the junction due to photons of light. This current acts as a gate drive to the SCR and it is driven into conduction. This type of triggering is normally used in light activated SCRs (LASCR).

2.3.4 Latching and Holding Currents

Answer following question after reading this topic

1. *Explain the terms latching current and holding current and compare them.*

Most likely and **Important** Question

Now let us briefly discuss the two important currents which flow through the SCR. These currents are : latching current and the holding current.

2.3.4.1 Latching Current (I_L)

Consider that the SCR is in forward blocking state. Then the SCR can be turned-on by applying a gate drive. Then the SCR goes into forward conduction mode (ON state). For the SCR to remain in the 'ON' state, the anode to cathode current (I_{AK}) must be greater than *latching current*. i.e.,

$I_{AK} \geq I_L$; to remain in ON state after triggering. Fig. 2.3.7 shows the V-I characteristics of the SCR showing latching current.

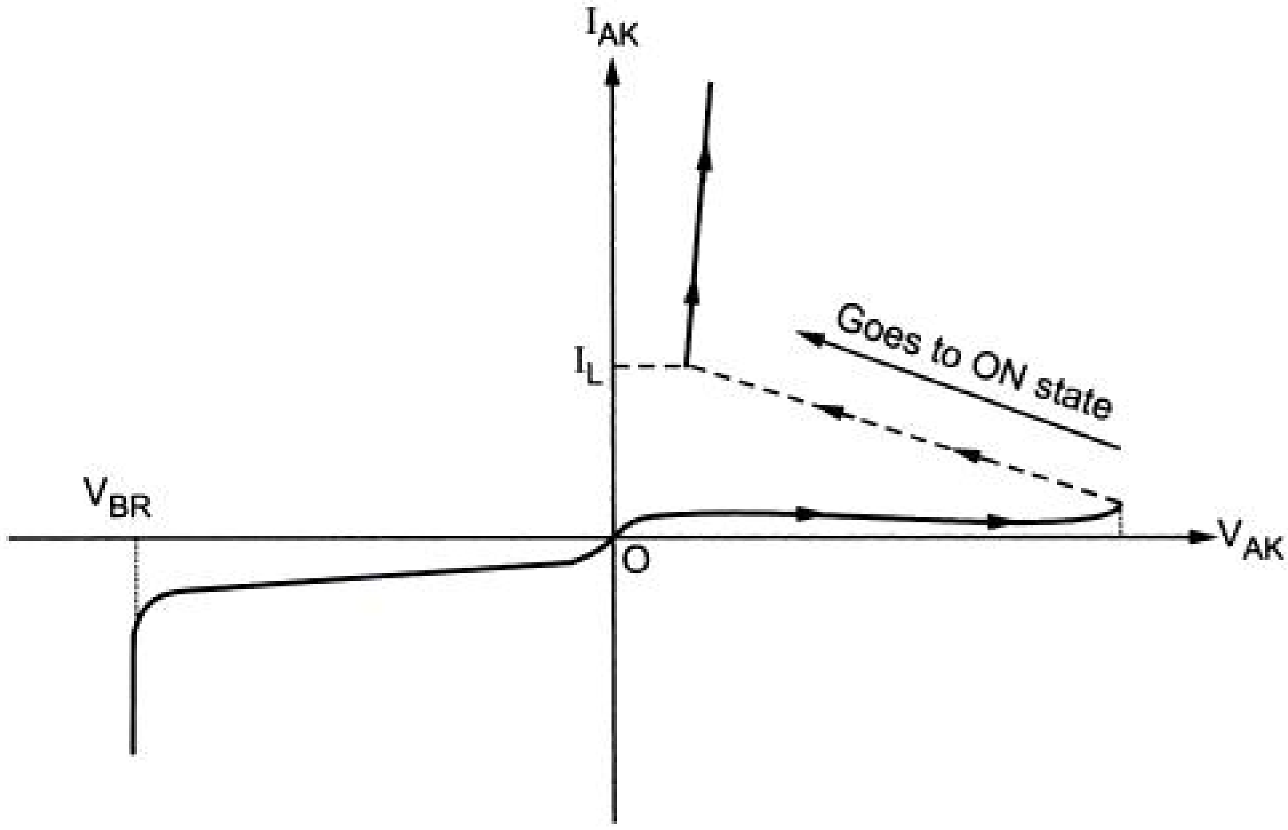


Fig. 2.3.7 V-I characteristics of the SCR showing latching current

Observe that latching current is the lowest current which flows through the SCR to remain in forward conduction (ON state) after triggering. If the current through the SCR is less than latching current, then the SCR goes back into forward blocking state as soon as gate drive is removed. This is said to be SCR is not *latched* (i.e. not turned-on). From the above discussion, the latching current can be defined as follows :

> *Latching current is the minimum forward current that flows through the SCR to keep it in forward conduction mode (i.e. ON state) at the time of triggering. If forward current is less than latching current, SCR doesnot turn-on.*

The latching current is of the order of 10 to 15 milliamperes.

2.3.4.2 Holding Current (I_H)

> ***Answer following question after reading this topic.***
>
> 1. *In SCR latching current is greater than holding current. State true or false and justify.* **Marks [15], Dec.-2002**

Most likely and **asked in** previous University Exam

Consider that the SCR is in forward conduction state (i.e. ON state). The SCR goes into forward blocking state when current through it falls below *holding current* (I_H). i.e., if $I_{AK} < I_H$; SCR turns-off. Fig. 2.3.8 shows the V-I characteristics of the SCR showing holding current.

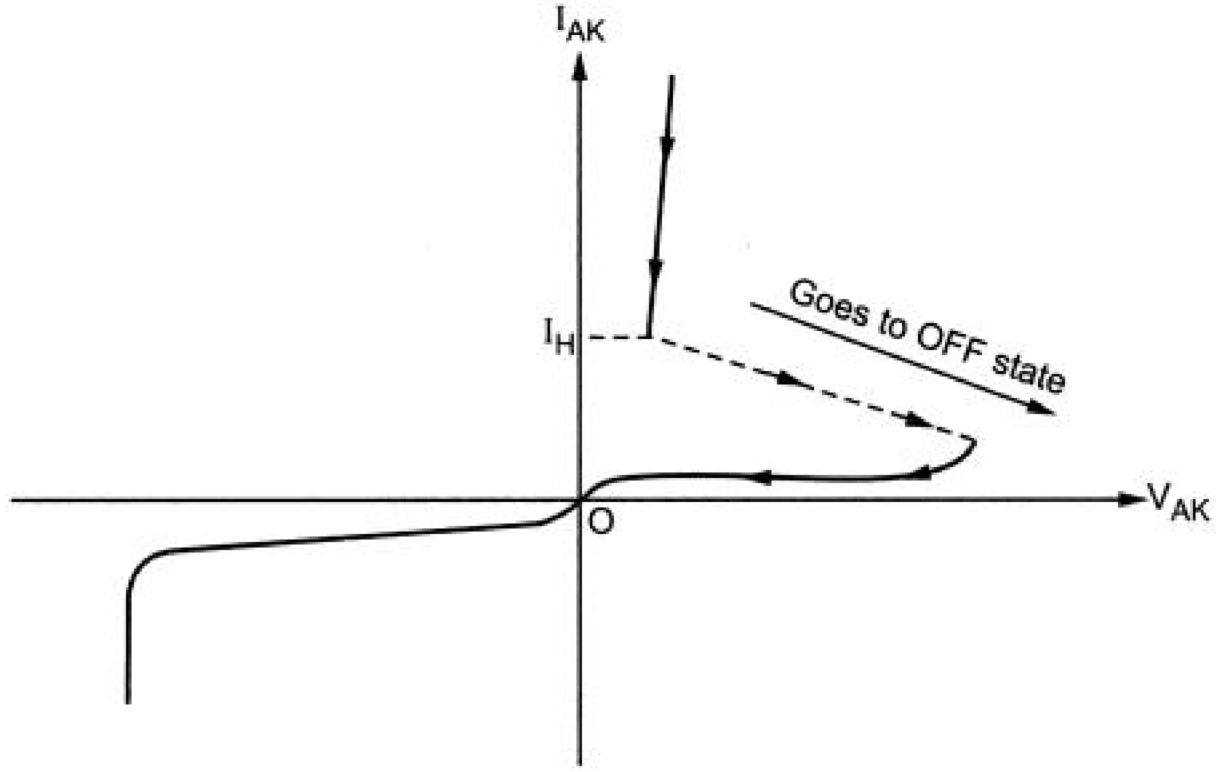


Fig. 2.3.8 V-I characteristics of the SCR showing holding current

Observe that the holding current is the lowest current below which SCR turns-off. In other words we can say that, for the SCR to remain in ON-state, its forward current should not reduce below holding current. From the above discussion, the holding current can be defined as follows :

> *Holding current is the minimum forward current that flows through the SCR to keep it in forward conduction mode. When forward current reduces below holding current, SCR turns-off.*

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

Latching current is always greater than holding current since it is the current that is required at the time of turning on the thyristor. But holding current is the current that is required to keep the thyristor in 'on' condition. Unless the SCR is turned on (latched) it cannot be turned-off. Hence latching current must be higher than holding current.

2.3.4.3 Comparison (Difference) between Holding and Latching Currents

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

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

Example 2.3.1 : *The SCR shown in Fig. 2.3.9 has the latching current of 20 mA and is fired by the pulse of width 50 μsec. Determine whether the SCR triggers or not.*

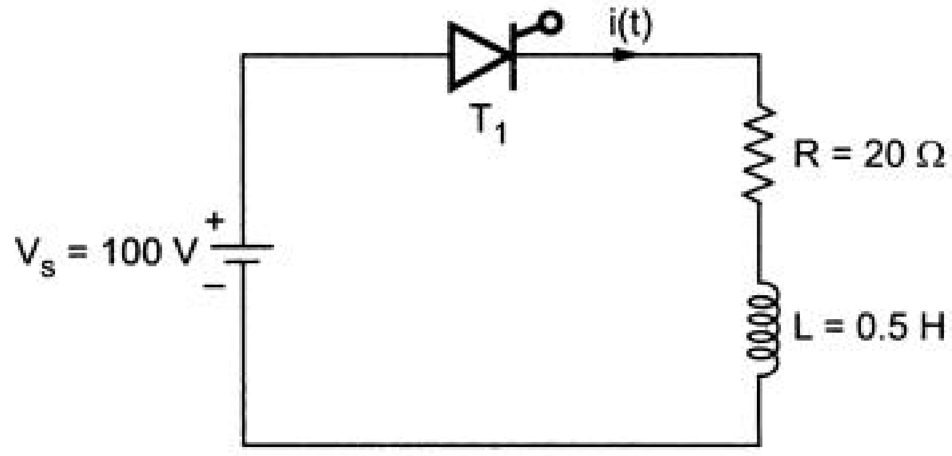


Fig. 2.3.9 Circuit of example 2.3.1

Solution : A step of voltage is applied to the RL load when SCR turns on. The current through the RL circuit for step input is given as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right) \quad \text{... (2.3.2)}$$

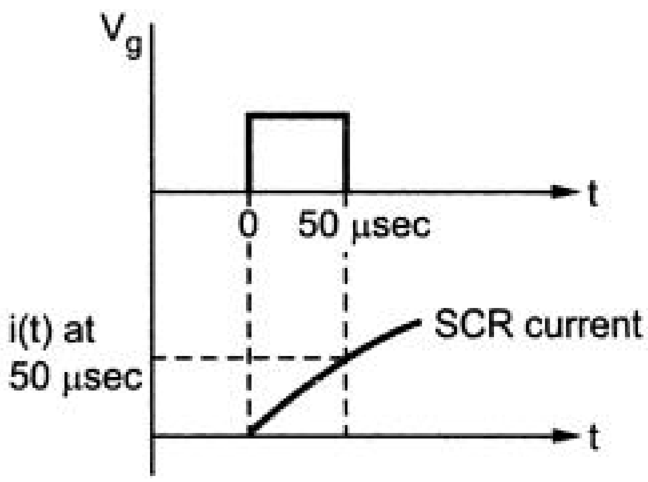


Fig. 2.3.10 After 50 μ sec, $i(t) > I_L$ to trigger the SCR properly (triggered)

Fig. 2.3.10 shows the gate pulse and current waveform. Here observe that the SCR will be latched (triggered) if $i(t)$ is greater than latching current when gate triggering pulse is removed after 50 μsec. Hence let us calculate current $i(t)$ through the SCR at 50 μ*sec,*

$$i(t) = \frac{100}{20}\left(1-e^{-50\times10^{-6}\times\frac{20}{0.5}}\right) = 10 \text{ mA}$$

Here note that current through the SCR is 10 mA. It is not reached to the latching current level and trigger pulse is removed at 50 μ*sec*. Hence the SCR will not be triggered.

Example 2.3.2 : *A SCR is connected in series with a 0.5 H inductor and 20 Ω resistance. A 100 V DC voltage is applied to this circuit. If the latching current of the SCR is 4 mA, find the minimum width of the gate trigger pulse required to properly turn-on the SCR.*

Solution : Fig. 2.3.11 shows the circuit diagram.

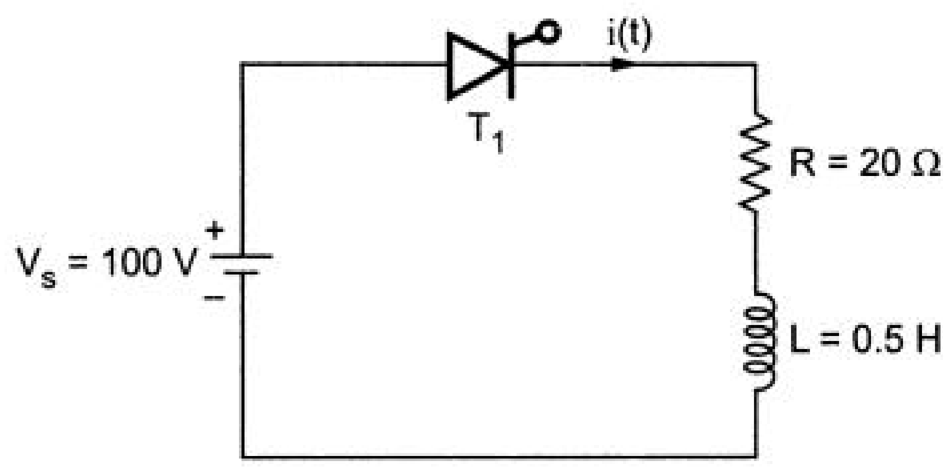


Fig. 2.3.11 Circuit of example 2.3.2

Latching current, $I_L = 4\ mA$ (Given). The current through the RL circuit is given by equation 2.3.2 as,

$$i(t) = \frac{V_s}{R}\left(1 - e^{-t\frac{R}{L}}\right)$$

In the above equation when $i(t)$ is equal to latching current, SCR turns on. Hence with $i(t) = I_L$, above equation becomes,

$$I_L = \frac{V_s}{R}\left(1 - e^{-t\frac{R}{L}}\right)$$

Now we have to determine the time 't' in above equation. Putting other values,

$$4 \times 10^{-3} = \frac{100}{20}\left(1 - e^{-t\frac{20}{0.5}}\right)$$

Solving above equation for t,

$$t = 20\ \mu sec$$

Thus the width of the gate trigger pulse must be 20 μsec to turn-on the SCR.

Example 2.3.3 : *The latching current of an SCR used in a phase controlled circuit, comprising an inductive load of R = 10 Ω and L = 0.1 H is 15 mA. The input voltage is 325 sin 314 t. Obtain the minimum gate pulse width required for reliable triggering of the SCR if gated at $\frac{\pi}{3}$ angle in every positive half cycle.*

Solution : Fig. 2.3.12 shows the circuit diagram of this example.

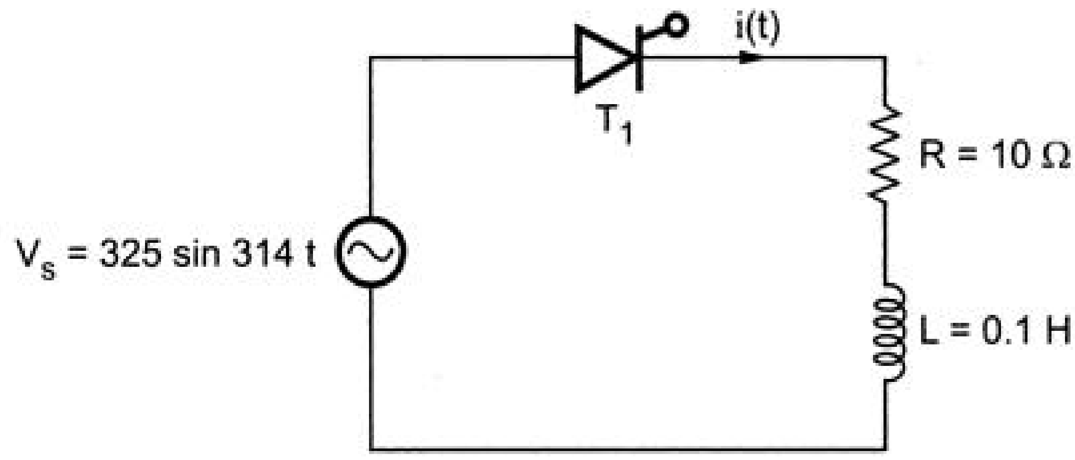


Fig. 2.3.12 Circuit of example 2.3.3

Thus SCR is triggered at $\frac{\pi}{3}$. Hence applied voltage at this angle will be,

$$V_s = 325 \sin \frac{\pi}{3} = 281.458 \text{ volts.}$$

Thus 281.458 volts is applied at the time when SCR is triggered. For short duration (till SCR turns on) this voltage can be considered constant. The current through load is then given by equation 2.3.2 as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right)$$

In this equation we have to determine the pulse width when SCR triggers successfully. SCR will be triggered successfully when $i(t) = I_L$ = 15 mA. Putting other values in above equation.

$$15 \times 10^{-3} = \frac{281.458}{10}\left(1-e^{-t\frac{10}{0.1}}\right)$$

Solving the above equation,

$$t = 5.33 \ \mu\text{sec}$$

Thus, the minimum gate pulse should be 5.33 μsec to reliably turn-on the SCR

Example 2.3.4 : *A SCR has a forward breakover voltage of 175 volts when a gate pulse of 2 mA is made to flow. Find the conduction angle if a sinusoidal voltage of 350 V peak is applied.*

Solution : When the gate pulse is applied, the SCR turns on at 175 volts. The applied voltage is,

$$v_s = 350 \sin \omega t$$

when v_s reaches to 175 SCR will turn on. i.e.

$$175 = 350 \sin \omega t$$

Hence the value of conduction angle (ωt) will be,

$$\therefore \quad \omega t = 30°$$

Thus, at 30°, SCR will turn-on.

➠ **Example 2.3.5 :** *In the SCR circuit shown in Fig. 2.3.13 below, the SCR has a latching current of 50 mA and is fired by a pulse of length 50 μsec. Show that without resistance R, the SCR will fail to remian on, when the firing pulse ends and then find the maximum value of R to ensure firing.*

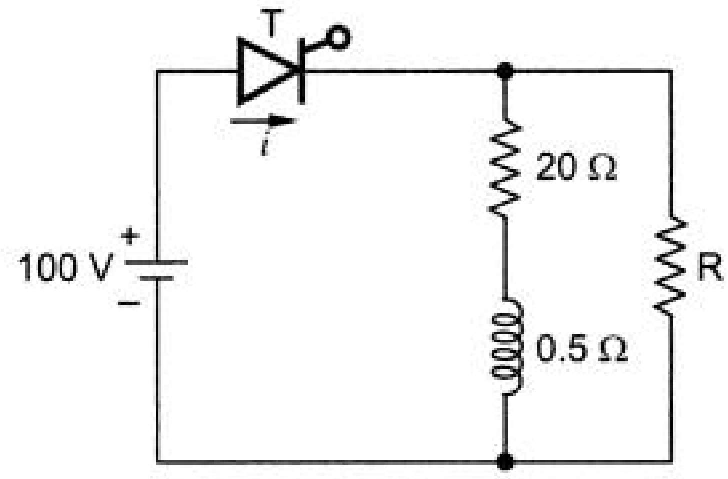


Fig. 2.3.13 SCR circuit of example 2.3.5

Solution : To show that SCR does not latch

Here first consider the SCR circuit without resistance R. This circuit is shown in Fig. 2.3.14.

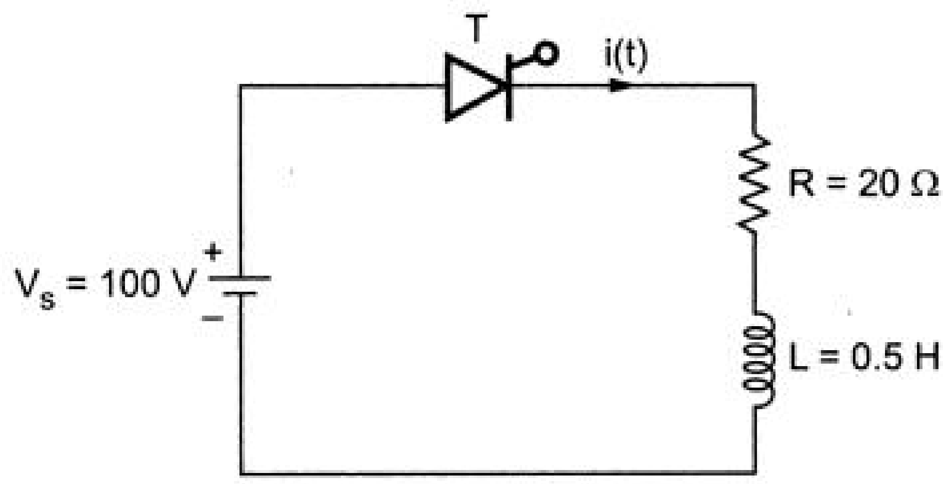


Fig. 2.3.14 SCR circuit of example 2.3.5 without R

For this circuit the given data is,

$$V_s = 100$$

$$R = 20\ \Omega$$

$$L = 0.5\ \text{H}$$

$$I_L = 50\ \text{mA}$$

$$\text{Pulse width} = 50\ \mu s$$

Now let us check whether the SCR current rises above latching current in the firing pulse duration of 50 μs. The current in the RL circuit is given by equation (2.3.2) as,

$$i(t) = \frac{V_s}{R}\left(1-e^{-t\frac{R}{L}}\right)$$

Putting the value of R, L and V_s

$$i(t) = \frac{100}{20}\left(1-e^{-t\frac{20}{0.5}}\right)$$

$$= 5(1-e^{-40t})$$

The current after t = 50 μs will be,

$$i(t=50\,\mu s) = 5(1-e^{-40\times 50\times 10^{-6}})$$

$$= 9.99\times 10^{-3} \approx 10 \text{ mA}$$

Thus during the firing pulse width of 50 μs, the SCR current rises upto 10 mA. Since this current is less than latching current of 50 mA. SCR will fail to remain on when firing pulse ends.

To determine value of R

The additional resistance connected in parallel with RL circuit increases the current through SCR. SCR takes 10 mA current when firing pulse of width 50 μs ends. To latch the SCR, 50 mA current should be passed through it. Hence additional 40 mA current can be passed through 'R' as shown in Fig. 2.3.15.

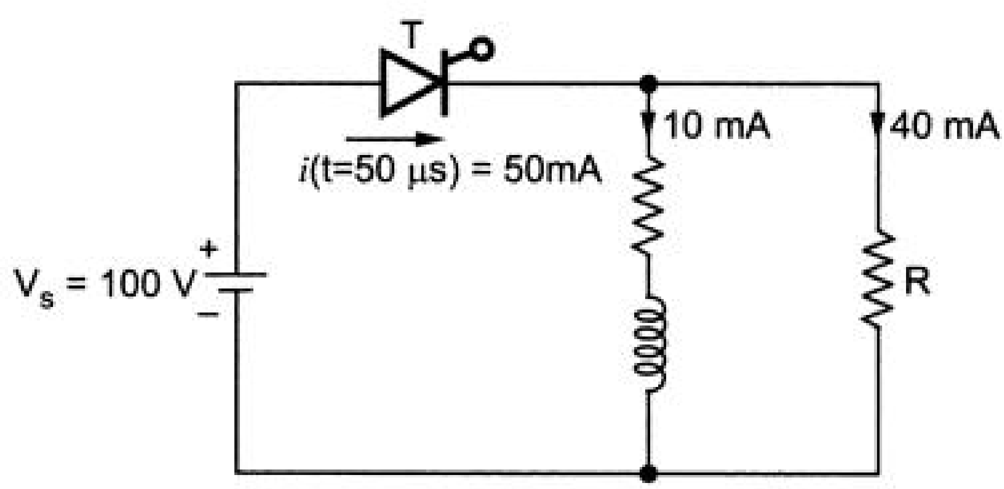


Fig. 2.3.15 Currents at t = 50 μs

If we neglect the voltage drop in the SCR, full V_s will appear across R. Hence,

$$V_s = 40\,mA \times R$$

$$\therefore \quad R = \frac{V_s}{40mA} = \frac{100}{40\times 10^{-3}}$$

$$= 2500\ \Omega$$

Thus a maximum R = 2.5 kΩ will ensure firing of the SCR.

Example 2.3.6 : *A SCR is connected in series with a RL load and is fed from a 115 V, 60 Hz AC supply. The load resistance is 25 Ω and load inductance is 0.25 H. If a firing pulse of 60 μs is applied at a firing angle of 45°, what is the maximum permissible latching current of the SCR to ensure turn-on.* **[May-2003, 6 Marks]**

Solution : Fig. 2.3.16 shows the circuit diagram. The input voltage is,

$$V_s = V_m \sin \omega t$$

$$= 115\sqrt{2} \sin 45°$$

$$= 115 \text{ V}$$

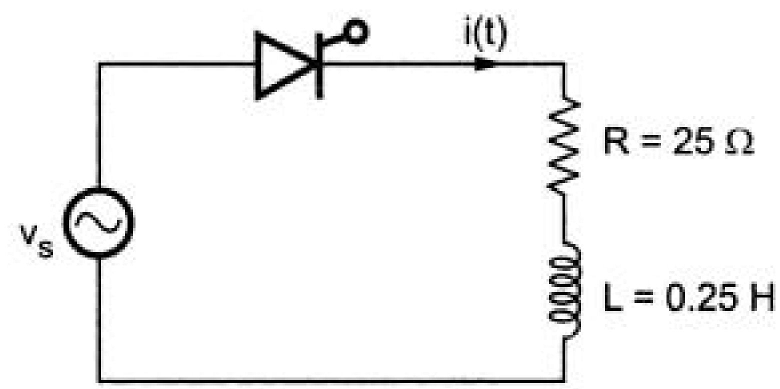


Fig. 2.3.16 RL circuit

Thus the input voltage at the time of turning on is 115 V.

Current through RL circuit is given as,

$$i(t) = \frac{V_s}{R}(1 - e^{-t\frac{R}{L}}) = \frac{115}{25}(1 - e^{-t\frac{25}{0.25}})$$

$$= 4.6\,(1 - e^{-100t})$$

Since the firing pulse is of 60 μsec, the current at the end of firing pulse is,

$$i(t) = 4.6(1 - e^{-100 \times 60 \times 10^{-6}}) \quad \text{with t = 60 μsec}$$

$$= 27.5 \text{ mA}$$

Thus the maximum latching current must be 27.5 mA to ensure turn-on.

Example 2.3.7 : *A SCR is connected in series with RL load and is fed from a 120 V, 60 Hz AC supply. The load resistance is 15 Ω and load is 0.75 H. What is the maximum allowable latching current of the SCR if the gate trigger circuit output pulse is of 100 μs duration at a delay angle of 45°.* **[May-2006, 8 Marks]**

Solution : Fig. 2.3.17 show the circuit diagram.

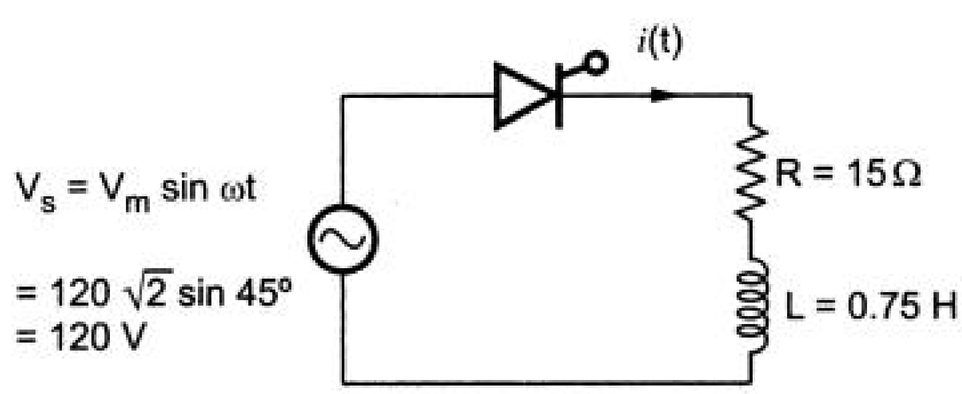


Fig. 2.3.17

Current through RL circuit is given as,

$$i(t) = \frac{V_s}{R}\left(1 - e^{-t\frac{R}{L}}\right)$$

$$\therefore \quad i(t = 100\ \mu s) = \frac{120}{15}\left(1 - e^{-100\times10^{-6}\times15/0.75}\right)$$

$$= 16\ \text{mA.}$$

Thus at end of 100 μs trigger pulse, SCR current will reach to 16 mA. Hence latching current must bt at least 16 mA to keep the device in ON condition. Thus,

$$I_L = 16\ \text{mA.}$$

2.3.5 Two Transistor Model of SCR

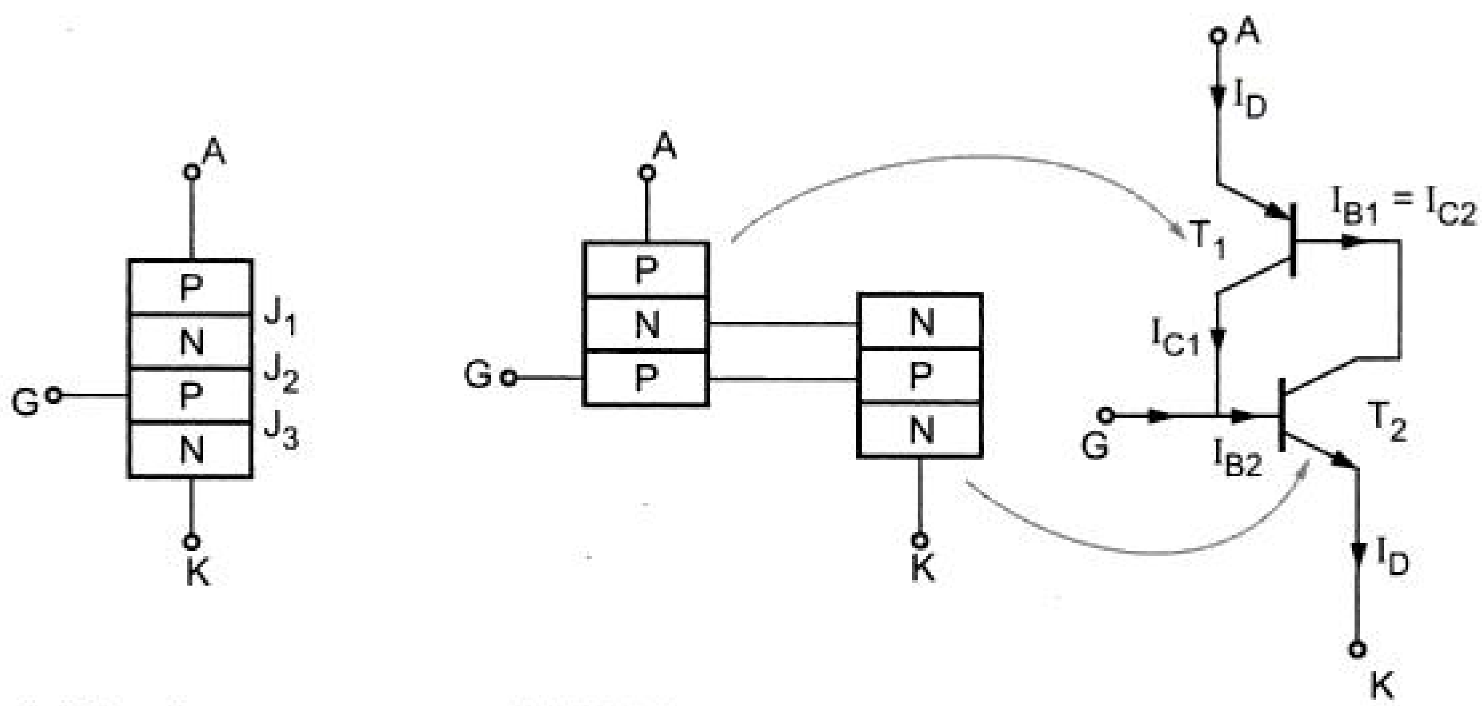
Answer following questions after reading this topic.

1. *Explain the operation of the SCR with the help of two transistor analogy.*
2. *Explain the two transistor analogy for an SCR and derive an expression for the anode current in terms of the current gains and leakage currents of the transistors.*

Marks[6], May-2000, 2002, 2003, 2006, 2008; Marks[8], May-2001, Dec.-2001, 2003, 2006; Marks[6], Dec.-2004, 2008

Most likely and **asked in** previous University Exam

The operation of the SCR can be explained with the help of two transistor model. Fig. 2.3.18 shows how the two transistor model of the SCR is formed.



(a) Four layer structure of SCR **(b) Middle two layers split into two separate parts** **(c) Two transistor mode of the SCR from Fig. (b)**

Fig. 2.3.18 A two transistor model of the SCR

As shown in Fig. 2.3.18(b), the middle two layers are split into two separate parts. Because of this, the two transistors are formed. These transistors are shown in Fig. 2.3.18(c). The transistor T_1 is pnp, whereas T_2 is npn. The base of T_1 is connected to collector of T_2. Similarly base of T_2 is connected to collector of T_1. These transistors are in common base configuration. When the SCR is forward biased and gate is open, various currents flow as shown in Fig. 2.3.18(c). As shown in this figure, the anode to cathode current is I_D. The collector current, emitter current and leakage currents of T_1 are related as,

$$I_{C_1} = \alpha_1 I_{E_1} + I_{CO_1} \qquad \text{... (2.3.3)}$$

Here $I_{E_1} = I_D$ and I_{CO_1} is leakage current of T_1. Similarly for T_2,

$$I_{C_2} = \alpha_2 I_{E_2} + I_{CO_2} \qquad \text{... (2.3.4)}$$

Here $I_{E_2} = I_D$ and I_{CO_2} is leakage current of T_2.

Therefore equation (2.3.3) and (2.3.4) can be written as,

$$\left.\begin{aligned} I_{C_1} &= \alpha_1 I_D + I_{CO_1} \\ I_{C_2} &= \alpha_2 I_D + I_{CO_2} \end{aligned}\right\} \qquad \text{... (2.3.5)}$$

In Fig. 2.3.18(c), observe that the current I_D flows through the collectors of T_1 and T_2. Hence we can write,

$$I_D = I_{C_1} + I_{C_2}$$

Putting the values from equation 2.3.5 in above equation,

$$I_D = \alpha_1 I_D + I_{CO_1} + \alpha_2 I_D + I_{CO_2}$$

$$\therefore \quad I_D = (\alpha_1 + \alpha_2) I_D + I_{CO_1} + I_{CO_2}$$

$$\therefore \quad I_D = \frac{I_{CO_1} + I_{CO_2}}{1-(\alpha_1 + \alpha_2)} \qquad \text{... (2.3.6)}$$

$I_{CO_1} + I_{CO_2}$ can be considered as total reverse leakage current of junction J_2. This current can be denoted by the I_{CO}. Then above equation can be written as,

$$\boxed{I_D = \frac{I_{CO}}{1-(\alpha_1 + \alpha_2)}} \qquad \text{... (2.3.7)}$$

Here I_{CO} is the reverse leakage current of the reverse biased junction J_2. And α_1 is the common base current gain of T_1 and α_2 is common base current gain of T_2. Initially when forward voltage is small, $(\alpha_1 + \alpha_2)$ is very small and less than 1. Hence forward blocking current as given by equation (2.3.7) is also small. As forward voltage applied across the SCR increases, the values of α_1 and α_2 also increase. When $(\alpha_1 + \alpha_2)$ tends unity, then $I_D$approaches infinity as given by equation (2.3.7.) At this instant, internal regeneration starts and the SCR goes into forward conduction (ON-state) mode. The current through the SCR is only limited by the external load.

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

When the gate current I_g is applied, then equation (2.3.7) will be written as,

$$I_D = \frac{I_{CO} + I_g}{1-(\alpha_1 + \alpha_2)} \qquad \text{... (2.3.8)}$$

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

2.4 SCR Turn-on and Turn-off

Answer following question after reading this topic.

1. *Explain the turn-on and turn-off dynamic characteristics of the SCR.*

Most likely and **Important** Question

2.4.1 Different Ways to Turn-on the SCR

We know that SCR can be turned-on if the anode current is above latching current. There is regenerative action in the SCR. SCR can be turned-on by following ways:

1. **Gate drive**

   SCR can be turned on by applying positive gate-cathode voltage. Injected gate carriers increase the anode current and regenerative action starts. As shown in equation (2.3.7) $(\alpha_1 + \alpha_2)$ approaches unit and anode current (I_D) becomes large. It is limited only by external load. Once the SCR is turned-on, there is no need of gate drive. Hence it can be removed. Normally pulsed gate drive is applied to reduce losses in the SCR gate.

2. **High forward voltage**

   SCR turns on when its anode-cathode voltage exceeds forward break over voltage, i.e. $V_{AK} > V_{BO}$. This is shown in Fig. 2.3.1. At these voltages, the leakage current is so high, that internal regenerative starts in the device.

3. $\frac{dv}{dt}$

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

4. **Light**

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

5. **High temperature**

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

2.4.2 Turn-on Dynamic Characteristics

Answer following question after reading this topic.

1. *Define turn-on time.*

Most likely and **Important** Question

Fig. 2.4.1 shows the current and voltage of the SCR during turn-on. The gate pulse is applied at $t = 0$. During the *delay time* (t_d), the anode current rises very slowly and flows only near the narrow region of the gate. Observe that anode to cathode doesnot reduce during t_d. It remains to the forward blocking value. During the *rise time* (t_r), the anode current increases rapidly and anode to cathode voltage falls rapidly. The high voltage and current are present in the SCR. Hence large dissipation takes place in the SCR.

This power dissipation is called switching loss of the SCR. The current starts spreading in the remaining area of the SCR. During the *spread time* (t_p), the conduction spreads over the complete cross-section of the SCR. The anode current reaches to its maximum value. And the anode to cathode voltage falls to lowest value (i.e. less than 2 V). The dissipation

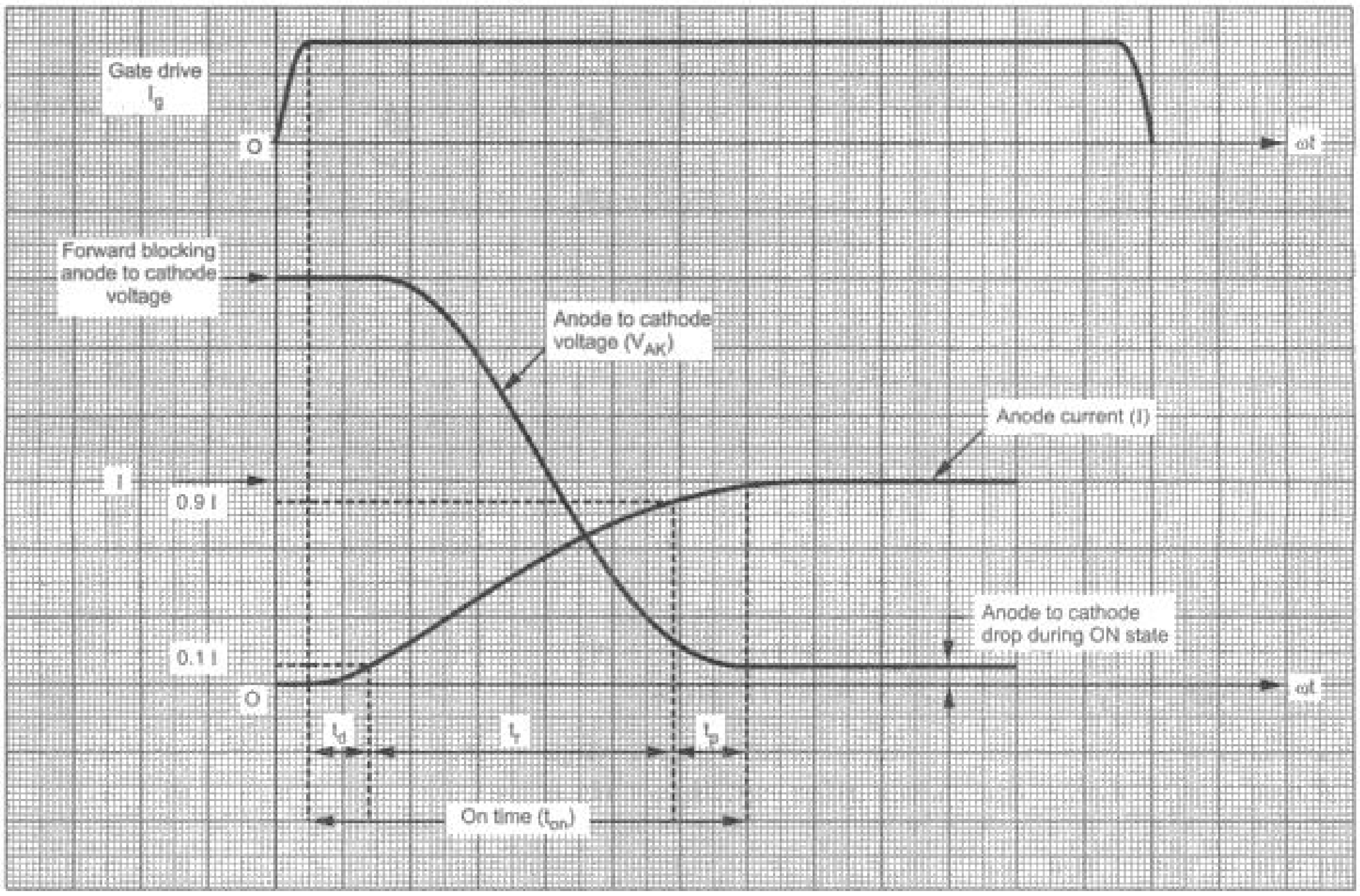


Fig. 2.4.1 Dynamic characteristics of SCR during turn-on

in the SCR is also reduced. *The turn on time* (t_{on}) of the SCR is given as total of t_d, t_r and t_p. Thus,

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

The turn on time can be defined as,

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

The turn-on time of the SCRs is about 1 to 3 microseconds. The turn-on time can be effectively reduced by applying higher values of gate currents. Because of high gate currents, more electron-holes are injected near junction J_2. Hence avalanche break-down of J_2 takes place fast. Therefore anode current rises fast. Thus effective turn-on time is reduced. To turn-on the SCR, the gate pulse is thus sufficient.

2.4.3 SCR Turn-off

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

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

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

2.4.4 Turn-off Dynamic Characteristics

Answer following questions after reading this topic.

1. *Define turn-off time.*
2. *Forward voltage is reapplied across an outgoing SCR, immediately after reducing its forward current to zero - Explain with technical reason.* **Marks [2], Dec.-2002**

Most likely and **Important** Question

Fig. 2.4.2 shows the SCR current and voltage during turn-off. The SCRs are not turned off by gate. They need external circuit for turn-off. These circuits are called commutation circuits. These commutation circuits has to hold negative voltage across the SCR during turn-off period. The SCR is said to be turned-off when it regains forward blocking

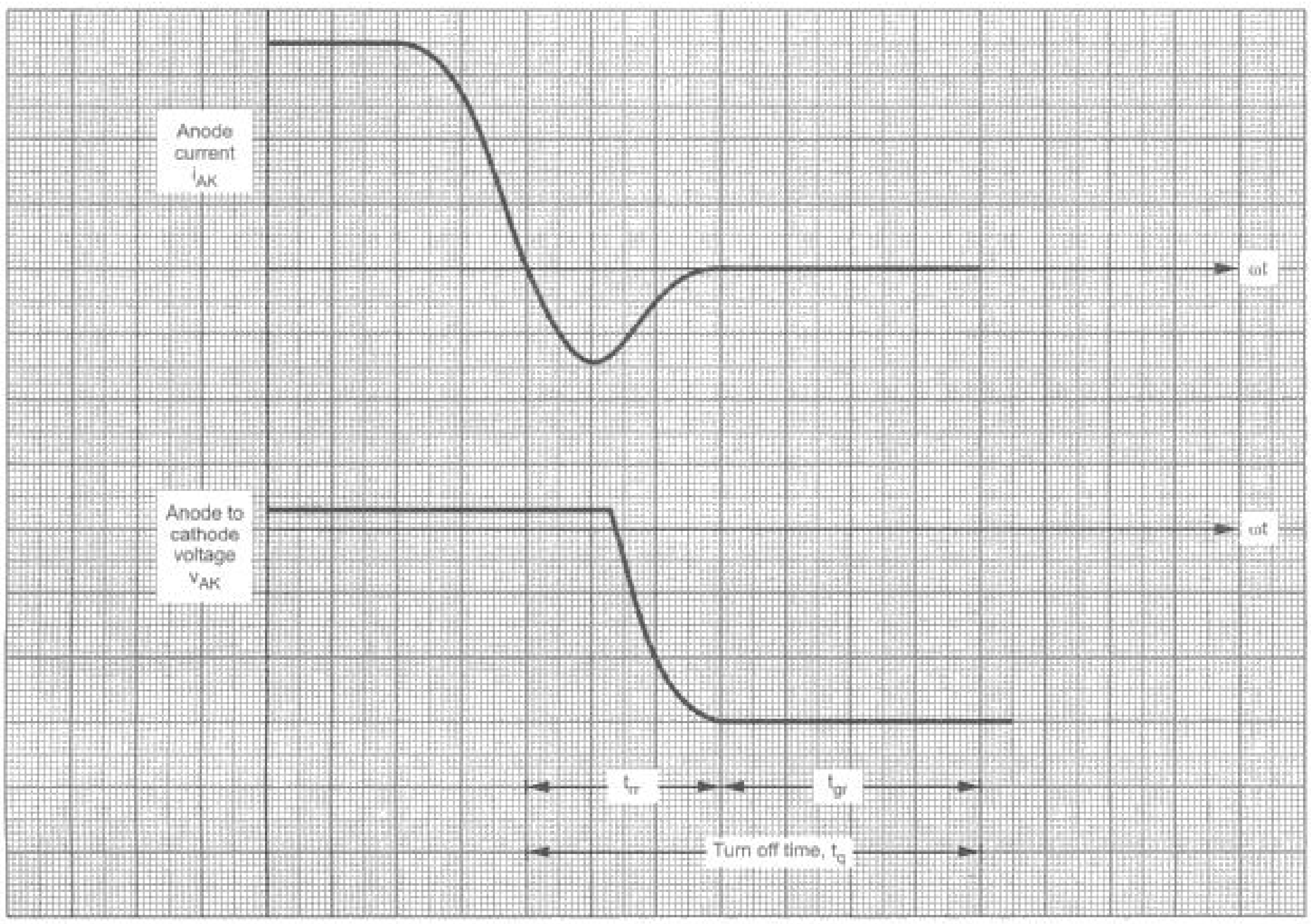


Fig. 2.4.2 Dynamic characteristics of SCR during turn-off

capability after forward conduction. In the above figure observe that anode current falls and then it becomes negative. The negative pulse of current flows through the SCR for short period. During the conducting state, the SCR is flooded with carriers and it acts as short circuit. The negative anode current flows through the SCR till all these carriers are removed. Then junctions J_1 and J_3 achieve their forward blocking state. The time required for this is called *reverse recovery time* (t_{rr}). At the end of t_{rr}, reverse voltage appears across the SCR and anode current becomes zero. This is shown in Fig. 2.4.2. But still, the SCR is not turned-on. The commutation circuit has to hold negative voltage across the SCR for *gate recovery time* (t_{gr}). During this time, the excess carriers near junction J_2 are recombined. If negative voltage is removed by commutation circuit before t_{gr}, then SCR may turn-on again due to these excess carrier near junction J_2. Because they act like gate drive to the SCR. Hence the turn-off is complete at the end of gate recovery time. The SCR regains its forward blocking capability. The negative voltage imposed by commutation circuit can be removed at the end of t_{gr}. *The turn-off time* (t_q) of the SCR is the total time required by reverse recovery and gate recovery. i.e.,

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

The turn-off time can be defined as follows :

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

The turn-off time of the SCR varies from 5 to 200 microseconds. The turn-off time of the commutation circuit is called *circuit turn-off time* (t_c). And hence circuit turn-off time must be greater than the turn-off time of the SCR $(t_c > t_q)$.

2.4.5 Inverter Grade and Converter Grade SCRs

Answer following question after reading this topic.

1. *Define converter grade SCR and inverter grade SCR.*

Most likely and **Important** Question

Inverter grade SCRs

The SCRs which have turn-off time less than 25 μs are called inverter grade SCRs. Such SCRs are used in inverters, choppers etc.

Converter grade SCRs

The SCRs having larger turn-off times $\left(t_q > 25\ \mu s\right)$ are called converter grade SCRs. Such SCRs are used in controlled rectifiers, AC voltage controllers etc.

2.5 SCR Gate Characteristics

Answer following question after reading this topic.

1. *Explain the SCR gate characteristics.*

Most likely and **Important** Question

In the previous section we studied V-I characteristics of SCR. Now we will have a closer look towards gate characteristics of the SCR. Fig. 2.5.1 shows the gate trigger characteristics.

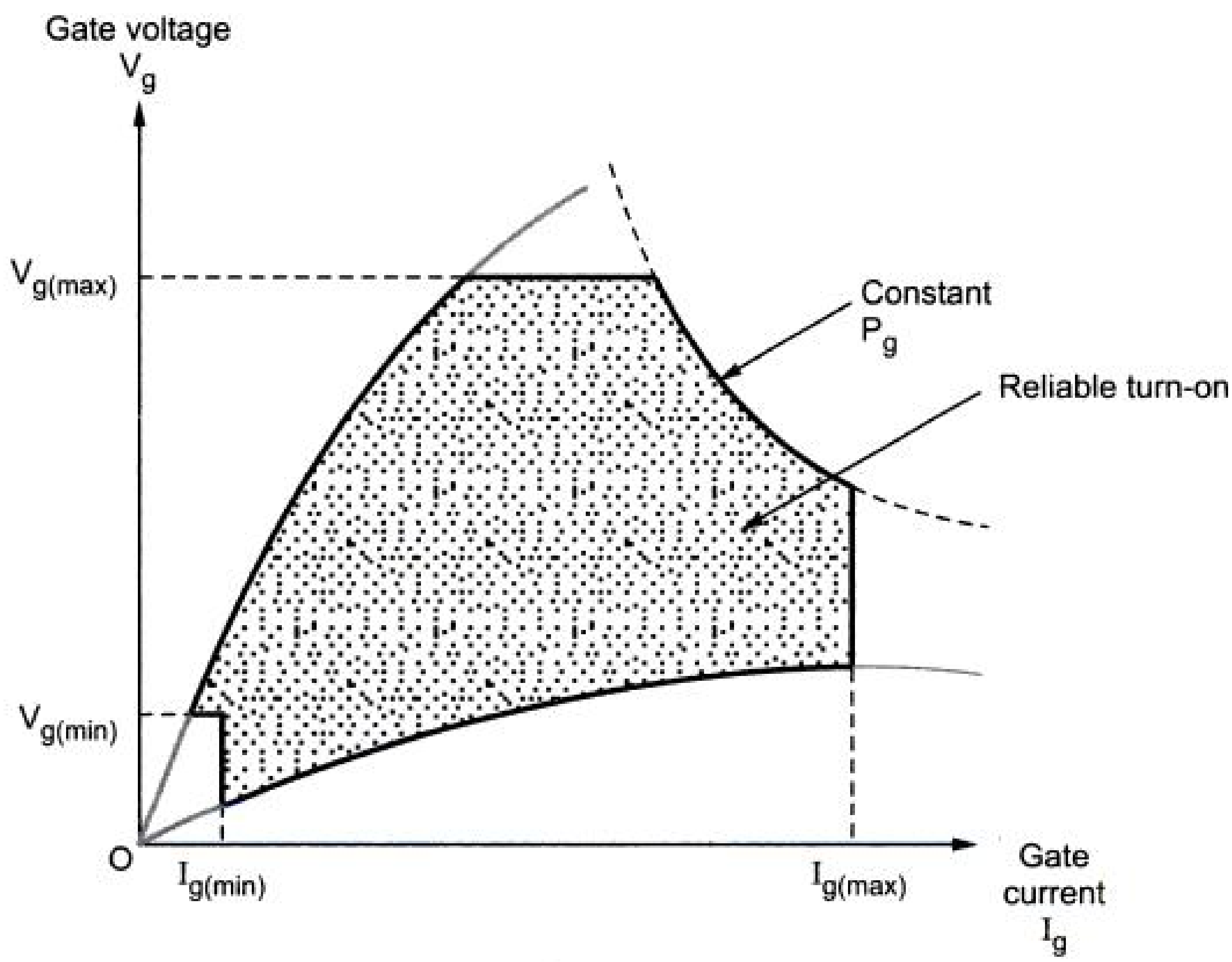


Fig. 2.5.1 Gate trigger characteristics

The gate voltage is plotted with respect to gate current in the above characteristics. $I_{g(\max)}$ is the maximum gate current that can flow through the SCR without damaging it. Similarly $V_{g(\max)}$ is the maximum gate voltage to be applied. Similarly $V_{g(\min)}$ and $I_{g(\min)}$ are minimum gate voltage and current, below which SCR will not be turned-on. Hence to turn-on the SCR successfully the gate current and voltage should be,

$$I_{g(\min)} < I_g < I_{g(\max)}$$

and $$V_{g(\min)} < V_g < V_{g(\max)}$$

The characteristic of Fig. 2.5.1 also shows the curve for constant gate power (P_g). Thus for reliable turn-on, the (V_g, I_g) point must lie in the shaded area in Fig. 2.5.1. It turns-on SCR successfully. Note that any spurious voltage/current spikes at the gate must be less than $V_{g(\min)}$ and $I_{g(\min)}$ to avoid false triggering of the SCR. The gate characteristics shown in Fig. 2.5.1 are for DC values of gate voltage and current.

2.5.1 Pulsed Gate Drive

Answer following questions after reading this topic.

1. *What is pulse gate drive ?*
2. *Why is a high-frequency pulse train preferred for gating SCRs as compared to DC triggering.* **Marks[4], May-2006**

Most likely and **asked in** previous University Exam

Instead of applying a continuous (DC) gate drive, the pulsed gate drive is used. The gate voltage and current are applied in the form of high frequency pulses. The frequency of these pulses is upto 10 kHz. Hence the width of the pulse can be upto 100 microseconds. The pulsed gate drive is applied for following reasons (advantages) :

i) The SCR has small turn-on time i.e. upto 5 microseconds. Hence a pulse of gate drive is sufficient to turn-on the SCR.

ii) Once SCR turns-on, there is no need of gate drive. Hence gate drive in the form of pulses is suitable.

iii) The DC gate voltage and current increases losses in the SCR. Pulsed gate drive has reduced losses.

iv) The pulsed gate drive can be easily passed through isolation transformers to isolate SCR and trigger circuit.

2.5.2 Requirement of Gate Drive

Answer following question after reading this topic.

1. *What are the requirements of gate drive ?*

Most likely and **Important** Question

The gate drive has to satisfy the following requirements :

i) The maximum gate power should not be exceeded by gate drive, otherwise SCR will be damaged.

ii) The gate voltage and current should be within the limits specified by gate characteristics (Fig. 2.5.1) for successful turn-on.

iii) The gate drive should be preferably pulsed. In case of pulsed drive the following relation must be satisfied :

(Maximum gate power × pulse width) × (Pulse frequency) ≤ Allowable average gate power

iv) The width of the pulse should be sufficient to turn-on the SCR successfully.

v) The gate drive should be isolated electrically from the SCR. This avoids any damage to the trigger circuit if in case SCR is damaged.

vi) The gate drive should not exceed permissible negative gate to cathode voltage, otherwise the SCR is damaged.

vii) The gate drive circuit should not sink current out of the SCR after turn-on.

2.6 SCR Ratings

Answer following questions after reading this topic.

1. *Write short notes on repeatitive and non-repeatitive ratings of SCR.* **Marks[6], Dec.-2004**
2. *What are different stress demands on power devices ?* **Marks[3], May-2002, May-2008**

Most likely and **asked in** previous University Exam

Every SCR is manufactured for particular voltage, current and switching frequencies. If these values are exceeded, then the SCR can be damaged. These are called ratings. The SCRs are to be protected when any of the voltage or current rating tries to exceed.

The ratings of SCR can be repetitive and non-repetitive.

Repetitive ratings : These ratings are the voltage, current and power that the SCR has to withstand repetitively. Repetitive ratings can be reached in the normal functioning of the device many times.

Non-repetitive ratings : These ratings will not load the SCR more than a limited number of times over the operating life of an equipment in which SCR is used. These ratings are used only to accomodate the unusal circuit conditions, which are not part of regular operation. These ratings normally reached for a very short interval so that the SCR is protected by fuses, circuit breakers etc. The SCR can be possibly damaged if non-repetitive ratings are exceeded under the conditions that violet above conditions.

Stress demands

The power devices are expected to satisfy following stress demands. These stress demands are related to different ratings :

i) They should have higher blocking voltages.

ii) They should have very high switching frequencies.

iii) They should have very small power dissipation.

iv) The dv/dt and di/dt capabilities should be very high.

2.6.1 Current Ratings

Answer following question after reading this topic.

1. *Describe following ratings as applicable to SCR.*
   i) Surge current rating ii) i^2t rating iii) $\frac{di}{dt}$ rating

   Marks[6], Dec.-2000, 2001, 2006, 2007; Marks[5], May-2007

Most likely and **asked in** previous University Exam

The current flow through the SCR increase the junction temperature. The excess current flow may exceed the permissible junction temperature and damage the device. Hence the current should not exceed the rated value. The various current ratings are discussed next :

i) Average current rating (I_T)

The average current rating is the maximum repetitive average current that can flow through the SCR. The power loss in the SCR depends upon average current flowing through it. If the SCR is operating at sufficiently high frequency, then switching loss will also be significant. Hence switching losses may be added to losses due to average current.

ii) RMS current rating (I_{TR})

The RMS current rating is the maximum repetitive rms current that can flow through the SCR. The RMS current rating is same as average current rating for DC current. This rating is required to prevent excessive heating in metallic joints, leads and interfaces of SCRs.

iii) Surge current rating (I_{TSM})

The surge current rating is the peak amplitude of the surge current that the SCR can withstand only limited number of times in its life cycle. The surge current is normally specified as number of cycles and peak amplitude. The SCR may be damaged when surge current rating and its number of cycles are exceeded.

iv) $i^2 t$ rating

The i^2t rating is the measure of thermal energy that the device can abosrb for a short period of time. Whenever fault occurs, the fast acting fuse clears such fault. Due to the fault, thermal energy is generated in the device also. The fuse should clear the fault and device should be protected. Hence $i^2 t$ rating is used to determine about how long the device can absorb the thermal energy. The fuse must clear the fault before the device is damaged due to exceeding $i^2 t$ rating.

v) $\frac{di}{dt}$ rating

The $\frac{di}{dt}$ rating specifies maximum allowable rate of change of current through the device. Due to rapid variations in anode current, the carriers doesnot spread across the junctions at the turn-on time. Hence they are concentrated in a small area of the device, creating local heating. This is called *hot-spot* created due to high current density in the restricted area of the junctions. Because of this, the junction temperature increases and the device may be damaged. The $\frac{di}{dt}$ rating specifies maximum allowable variations in anode current, so that the device will not be damaged. Normally it is specified in Amperes/microseconds and typical values are from 50 A/μs to 800 A/μsec.

2.6.2 Voltage Ratings

Answer following question after reading this topic.

1. *Describe the $\frac{dv}{dt}$ rating of SCR*

Marks[2], Dec.-2000, 2006, 2007

Most likely and **asked in** previous University Exam

The SCR blocks the forward and reverse voltages. The voltage ratings mainly specify the maximum allowable voltages those the device can withstand without damaging the junctions.

i) Peak repetitive forward blocking voltage (V_{DRM})

This is the maximum voltage that the SCR can block in the forward direction. It is specified with maximum allowable junction temperature and gate open circuited. If this rating is exceeded, the device turns on. Note that device is not damaged.

ii) Peak repetitive reverse voltage (V_{RRM}) or Peak Inverse Voltage (PIV)

This is the maximum voltage that the device can withstand repetitively in the reverse blocking state. It is also specified at maximum allowable junction temperature. The device is damaged, when this rating is exceeded.

iii) Non-repetitive peak reverse voltage (V_{RSM})

This the maximum transient voltage that the device can safely withstand in the reverse direction. This transient is not repetitive. The device is damaged if transient is exceeded or it occurs repetitively. This transient voltage can be increased by putting a diode of same current rating in series with the SCR. The total transient voltage capacity becomes due to SCR and diode.

iv) $\frac{dv}{dt}$ rating

The $\frac{dv}{dt}$ rating specifies maximum allowable rate of change of forward voltage that the device can withstand in forward direction. If the forward voltage variations exceed $\frac{dv}{dt}$ rating, then the device turns on. Such turn-on is false triggering and disturbs the operation of the controller.

The other ratings are : turn-on time (t_{on}), turn-off time (t_q), gate voltage (v_g), gate current (I_g), latching current (I_L) and holding current (I_H). These ratings we have discussed earlier in section 2.3, 2.4 and 2.5.

2.6.3 Improving the Blocking Voltage and $\frac{dv}{dt}$ Capabilities

Answer following question after reading this topic

1. *How we can achieve higher blocking voltage and higher dv/dt capability for SCRs.* **Marks[3], May-2002, 2008**

Most likely and **asked in** previous University Exam