MODULE - 3
THYRISTORS

Structure

3.0 Introduction

A thyristor is the most important type of power semiconductor devices. They are extensively used in power electronic circuits. They are operated as bi-stable switches from non-conducting to conducting state.

A thyristor is a four layer, semiconductor of p-n-p-n structure with three p-n junctions. It has three terminals, the anode, cathode and the gate.

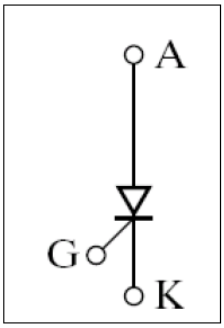
The word thyristor is coined from thyratron and transistor. It was invented in the year 1957 at Bell Labs. The Different types of Thyristors are

- Silicon Controlled Rectifier (SCR).
- TRIAC
- DIAC
- Gate Turn Off Thyristor

3.1Objectives:

- To explain different types of Thyristors, their gate characteristics and gate control requirements.

3.2 Silicon Controlled Rectifier (SCR)



The SCR is a four layer three terminal device with junctions as shown. The construction of SCR shows that the gate terminal is kept nearer the cathode. The approximate thickness of each layer and doping densities are as indicated in the figure. In terms of their lateral dimensions Thyristors are the largest semiconductor devices made. A complete silicon wafer as large as ten centimeter in diameter may be used to make a single high power thyristor.

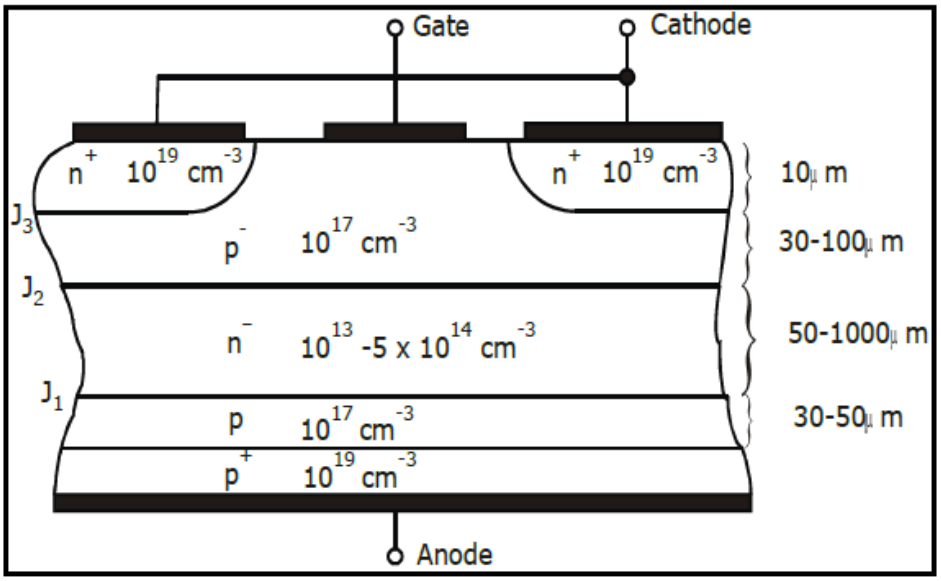


Fig.3.1: Structure of a generic thyristor

Qualitative Analysis

When the anode is made positive with respect the cathode junctions 1 3 *J* & *J* are forward biased and junction 2 *J* is reverse biased. With anode to cathode voltage *AK V* being small, only leakage current flows through the device. The SCR is then said to be in the forward blocking state. If *AK V* is further increased to a large value, the reverse biased junction 2 *J* will breakdown due to avalanche effect resulting in a large current through the device. The voltage at which this phenomenon occurs is called the forward breakdown voltage *BO V* .

Since the other junctions 1 3 *J* & *J* are already forward biased, there will be free movement of carriers across all three junctions resulting in a large forward anode current. Once the SCR is switched on, the voltage drop across it is very small, typically 1 to 1.5V. The anode current is limited only by the external impedance present in the circuit.

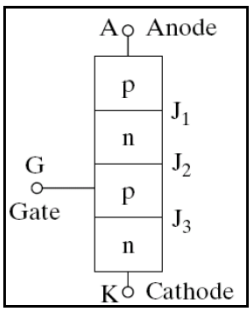
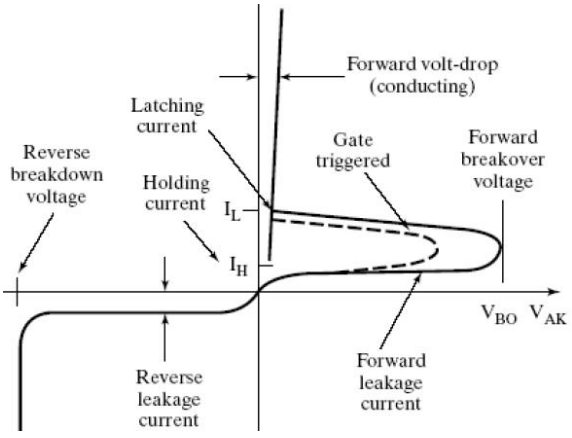


Fig.3.2: Simplified model of a thyristor

Although an SCR can be turned on by increasing the forward voltage beyond *BO V* , in practice, the forward voltage is maintained well below *BO V* and the SCR is turned on by applying a positive voltage between gate and cathode.

With the application of positive gate voltage, theleakage current through the junction 2 *J* is increased. This is because the resulting gate current consists mainly of electron flow from cathode to gate. Since the bottom end layer is heavily doped as compared to the p-layer, due to the applied voltage, some of these electrons reach junction 2 *J* and add to the minority carrier concentration in the p-layer. This raises the reverse leakage current and results in breakdown of junction 2 *J* even though the applied forward voltage is less than the breakdown voltage *BO V* . With increase in gate current
breakdown occurs earlier.

V-I Characteristics



A typical V-I characteristics of a thyristor is shown above. In the reverse direction the thyristor appears similar to a reverse biased diode which conducts very little current until avalanche breakdown occurs. In the forward direction the thyristor has two stable states ormodes of operation that are connected together by an unstable mode that appears as anegative resistance on the V-I characteristics. The low current high voltage region is the 1forward blocking state or the off state and the low voltage high current mode is the on state.

For the forward blocking state the quantity of interest is the forward blocking voltage *BO V* which is defined for zero gate current. If a positive gate current is applied to a thyristor then the transition or break over to the on state will occur at smaller values of anode to cathode voltage as shown. Although not indicated the gate current does not have to be a dc current but instead can be a pulse of current having some minimum time duration. This ability to switch the thyristor by means of a current pulse is the reason for wide spread applications of the device.

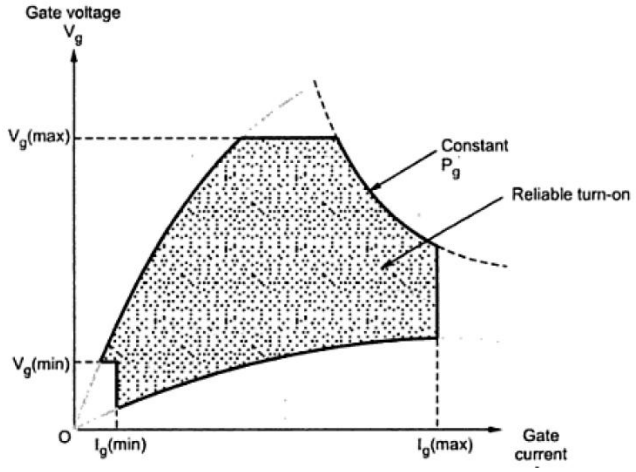
Holding Current *H I*

After an SCR has been switched to the on state a certain minimum value of anode +current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually *I* is associated with turn off the device.

Latching Current *L I*

After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. *L I* associated with turn on and is usually greater than holding current.

3.3 Thyristor Gate Characteristics



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

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

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

The characteristic of Fig. also shows the curve for constant gate power (Pg). Thus for reliable turn-on, the (Vg, Ig) point must lie in the shaded area in Fig. 3.6. It turns-on thyristor successfully. Note that any spurious voltage/current spikes at the gate must be less than Vg (min) and Ig(min) to avoid false triggering of the thyristor. The gate characteristics shown in Fig. 3.6 are for DC values of gate voltage and current.

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 l0 kHz. Hence the width of the pulse can be upto 100 micro seconds. The pulsed gate drive is applied for following reasons (advantages):

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

ii) Once thyristor 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 thyristor. Pulsed gate drive has reduced losses.

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

Requirement of Gate Drive

The gate drive has to satisfy the following requirements

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

. ii) The gate voltage and current should be within the limits specified by gate characteristics (Fig. 3.6) 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 x pulse width) x (Pulse frequency) ≤ Allowable average gate power

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

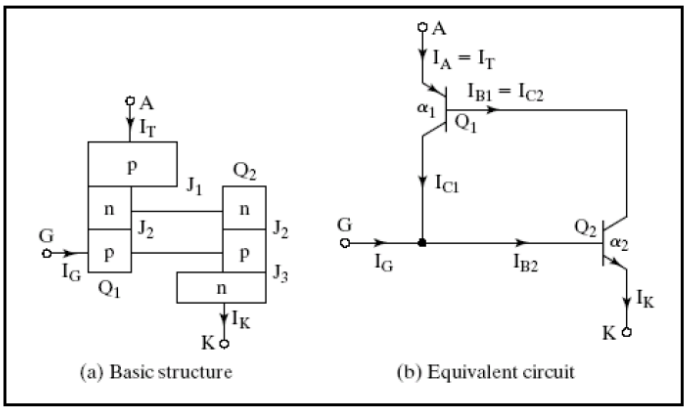
v) The gate drive should be isolated electrically from the thyristor. This avoids any damage to the trigger circuit if in case thyristor is damaged.

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

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

3.4 Quantitative Analysis

Two Transistor Model



The general transistor equations are,

$$I_C = \beta I_B + \ 1+\beta \ \ I_{CBO}$$
$$I_C = \alpha I_E + I_{CBO}$$
$$I_E = I_C + I_B$$
$$I_B = I_E \ \ 1-\alpha \ \ - I_{CBO}$$

The SCR can be considered to be made up of two transistors as shown in above figure. Considering PNP transistor of the equivalent circuit,

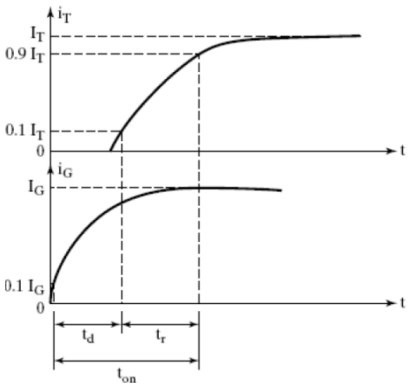
$$I_{E_1} = I_A, I_C = I_{C_1}, \alpha = \alpha_1, I_{CBO} = I_{CBO_1}, I_B = I_{B_1}$$
$$\therefore \qquad I_{B_1} = I_A \ \ 1-\alpha_1 \ \ - I_{CBO_1} \qquad ---$$

From the equivalent circuit, we see that

$$\therefore \qquad I_{C_2} = I_{B_1}$$
$$\Rightarrow \qquad I_A = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1- \ \alpha_1 + \alpha_2}$$

3.5 Switching Characteristics (Dynamic characteristics)

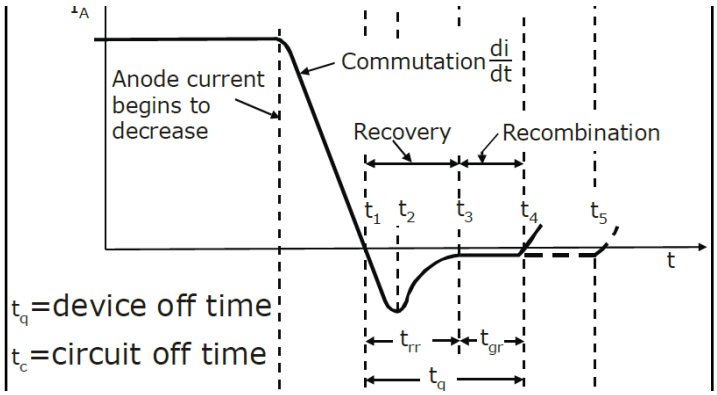
Thyristor Turn-ON Characteristics



When the SCR is turned on with the application of the gate signal, the SCR does not conduct fully at the instant of application of the gate trigger pulse. In the beginning, there is no appreciable increase in the SCR anode current, which is because, only a small portion of the

silicon pellet in the immediate vicinity of the gate electrode starts conducting. The duration between 90% of the peak gate trigger pulse and the instant the forward voltage has fallen to 90% of its initial value is called the gate controlled / trigger delay time *gd t* . It is also defined as the duration between 90% of the gate trigger pulse and the instant at which the anode current rises to 10% of its peak value. *gd t* is usually in the range of 1 sec.

Thyristor Turn OFF Characteristics



When an SCR is turned on by the gate signal, the gate loses control over the device and the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current. In AC circuits, however, the current goes through a natural zero value and the device will automatically switch off. But in DC circuits, where no neutral zero value of current exists, the forward current is reduced by applying a reverse voltage across anode and cathode and thus forcing the current through the SCR to zero.

As in the case of diodes, the SCR has a reverse recovery time *rr t* which is due to charge storage in the junctions of the SCR. These excess carriers take some time for recombination resulting in the gate recovery time or reverse recombination time *gr t* . Thus, the turn-off time *q t* is the sum of the durations for which reverse recovery current flows after the application of reverse voltage and the time required for the recombination of all excess carriers present. At the end of the turn off time, a depletion layer develops across 2 *J* and the junction can now withstand the forward voltage. The turn off time is dependent on the anode current, the magnitude of reverse *g V* applied ad the magnitude and rate of application of the forward voltage. The turn off time for converte grade SCR's is 50 to 100 sec and that for inverter grade SCR's is 10 to 20 sec.

To ensure that SCR has successfully turned off , it is required that the circuit off time $c\ t$ be greater than SCR turn off time $q\ t$.

Thyristor Turn ON

Thermal Turn on: If the temperature of the thyristor is high, there will be an increase in charge carriers which would increase the leakage current. This would cause an increase in 1 & 2 and the thyristor may turn on. This type of turn on many cause thermal run away and is usually avoided.

Light: If light be allowed to fall on the junctions of a thyristor, charge carrier concentration would increase which may turn on the SCR.

LASCR: Light activated SCRs are turned on by allowing light to strike the silicon wafer.

High Voltage Triggering: This is triggering without application of gate voltage with only application of a large voltage across the anode-cathode such that it is greater than the forward breakdown voltage $BO\ V$ **.** This type of turn on is destructive and should be avoided.

Gate Triggering: Gate triggering is the method practically employed to turn-on the thyristor. Gate triggering will be discussed in detail later.

dv

dt

Triggering: Under transient conditions, the capacitances of the p-n junction will influence the characteristics of a thyristor. If the thyristor is in the blocking state, a rapidly rising voltage applied across the device would cause a high current to flow through the device resulting in turn-on. If

$j2\ i$ is the current throught the junction 2 j and

$j2\ C$ is the junction capacitance and

$j2\ V$ is the voltage across 2 j , then

$$i_{j_2} = \frac{dq_2}{dt} = \frac{d}{dt}\ C_{j_2} V_{j_2}\ = \frac{C_{j_2} dV_{J2}}{dt} + V_{j_2} \frac{dC_{j_2}}{dt}$$

Thyristor Ratings

VOLTAGE RATINGS

V_{DWM} : This specifies the peak off state working forward voltage of the device. This specifies the maximum forward off state voltage which the thyristor can withstand during its working.

V_{DRM} : This is the peak repetitive off state forward voltage that the thyristor can block repeatedly in the forward direction (transient).

V_{DSM} : This is the peak off state surge / non-repetitive forward voltage that will occur across the thyristor.

V_{RWM} : This the peak reverse working voltage that the thyristor can withstand in the reverse direction.

V_{RRM} : It is the peak repetitive reverse voltage. It is defined as the maximum permissible instantaneous value of repetitive applied reverse voltage that the thyristor can block in reverse direction.

V_{RSM} : Peak surge reverse voltage. This rating occurs for transient conditions for a specified time duration.

V_T : On state voltage drop and is dependent on junction temperature.

V_{TM} : Peak on state voltage. This is specified for a particular anode current and junction temperature.

$\frac{dv}{dt}$ rating: This is the maximum rate of rise of anode voltage that the SCR has to withstand and which will not trigger the device without gate signal (refer dv

Current Rating

$I_{Taverage}$: This is the on state average current which is specified at a particular temperature.

I_{TRMS} : This is the on-state RMS current.

Latching current, I_L : After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. I_L associated with turn on and is usually greater than holding current

Holding current, I_H : After an SCR has been switched to the on state a certain minimum value of anode current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually I□ is associated with turn off the device.

$\frac{di}{dt}$ rating: This is a non repetitive rate of rise of on-state current. This maximum value of rate of rise of current is which the thyristor can withstand without destruction. When thyristor is switched on, conduction starts at a place near the gate. This small area of conduction spreads rapidly and if rate of rise of anode current di

carriers, local hotspots will be formed near the gate due to high current density

Gate Specifications

I_{GT} : This is the required gate current to trigger the SCR. This is usually specified as a DC value.

V_{GT} : This is the specified value of gate voltage to turn on the SCR (dc value).

V_{GD} : This is the value of gate voltage, to switch from off state to on state. A value below this will keep the SCR in off state.

Q_{RR} : Amount of charge carriers which have to be recovered during the turn off process.

R_{thjc} : Thermal resistance between junction and outer case of the device.

3.6 Gate Triggering Methods

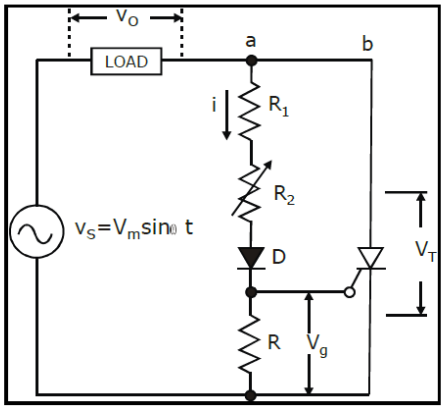
Types

The different methods of gate triggering are the following

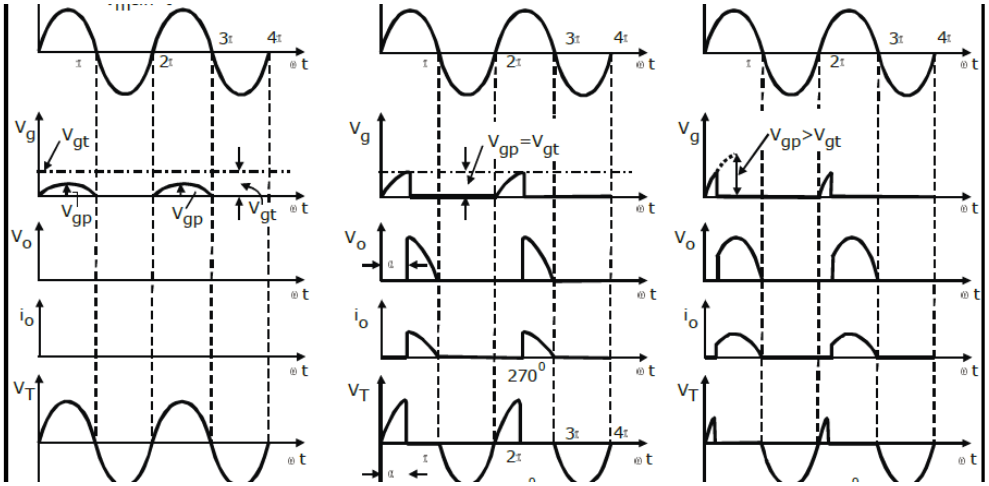
- R-triggering.
- RC triggering.
- UJT triggering

Resistance Triggering

A simple resistance triggering circuit is as shown. The resistor 1 *R* limits the current through the gate of the SCR. 2 *R* is the variable resistance added to the circuit to achieve control over the triggering angle of SCR. Resistor 'R' is a stabilizing resistor. The diode D is required to ensure that no negative voltage reaches the gate of the

SC 

R.



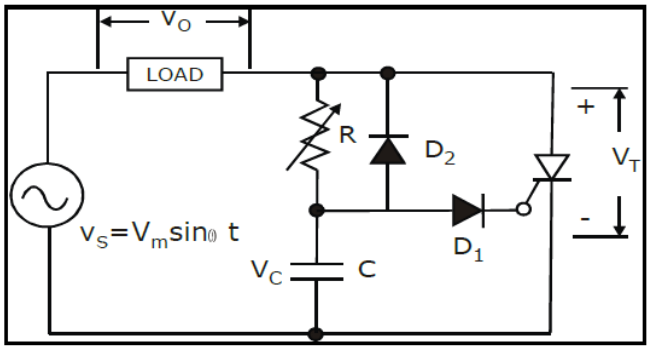
Resistance Capacitance Triggering

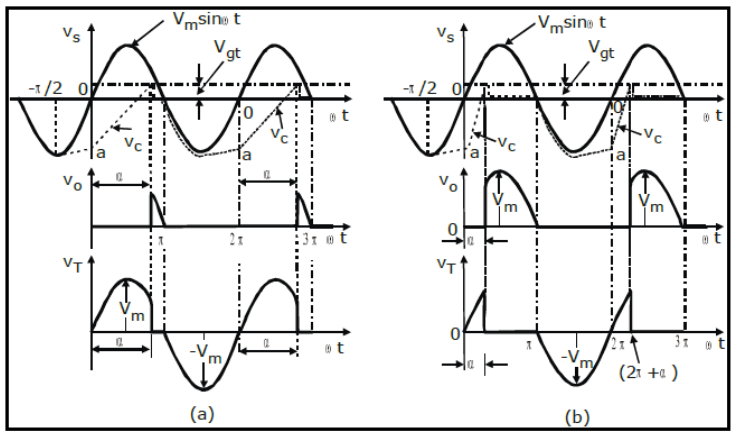
RC Half Wave

Capacitor 'C' in the circuit is connected to shift the phase of the gate voltage. 1 *D* is used to prevent negative voltage from reaching the gate cathode of SCR.

In the negative half cycle, the capacitor charges to the peak negative voltage of the supply *m V* through the diode 2 *D* . The capacitor maintains this voltage across it, till the supply voltage crosses zero. As the supply becomes positive, the capacitor charges through resistor 'R' from initial voltage of *m V* , to a positive value.

When the capacitor voltage is equal to the gate trigger voltage of the SCR, the SCR is fired and the capacitor voltage is clamped to a small positive value.





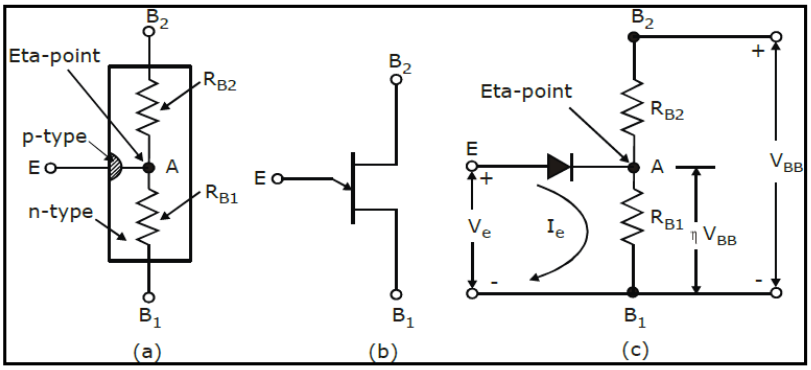
Case 1: R Large.

When the resistor 'R' is large, the time taken for the capacitance to charge from *m V* to *gt V* is large, resulting in larger firing angle and lower load voltage.

Case 2: R Small

When 'R' is set to a smaller value, the capacitor charges at a faster rate towards *gt V* resulting in early triggering of SCR and hence *L V* is more. When the SCR triggers, the voltage drop across it falls to 1 – 1.5V. This in turn lowers, the voltage across R & C. Low voltage across the SCR during conduction period keeps the capacitor discharge during the positive half cycle.

UNI-JUNCTION TRANSISTOR (UJT)



UJT is an n-type silicon bar in which p-type emitter is embedded. It has three terminals base1, base2 and emitter 'E'. Between 1 *B* and 2 *B* UJT behaves like ordinary resistor and the internal resistances are given as *B*1 *R* and *B*2 *R* with emitter open *BB B*1 *B*2 *R R R* . Usually the p-region is heavily doped and n-region is lightly doped. The equivalent circuit of UJT is as shown. When *BB V* is applied across 1 *B* and 2 *B* , we find that potential at A is

Operation

When voltage *BB V* is applied between emitter 'E' with base 1 1 *B* as reference and the emitter voltage *E V* is less than *D BE V V* the UJT does not conduct. *D BB V V* is designated as *P V* which is the value of voltage required to turn on the UJT. Once *E V* is equal to *P BE D V V V* , then UJT is forward biased and it conducts.

The peak point is the point at which peak current *P I* flows and the peak voltage *P V* is across the UJT. After peak point the current increases but voltage across device drops, this is due to the fact that emitter starts to inject holes into the lower doped n-region. Since p-region is heavily doped compared to n-region. Also holes have a longer life time, therefore number of carriers in the base region increases rapidly. Thus potential at 'A' falls but current *E I* increases rapidly. *B*1 *R* acts as a decreasing resistance.

The negative resistance region of UJT is between peak point and valley point. After valley point, the device acts as a normal diode since the base region is saturated and *B*1 *R* does not decrease again.

$$V_{AB1} = \frac{V_{BB}R_{B1}}{R_{B1}+R_{B2}} = \eta V_{BB}\left[\eta = \frac{R_{B1}}{R_{B1}+R_{B2}}\right]$$

(i) Expression for period of oscillation,,t"

The period of oscillation of the UJT can be derived based on the voltage across the capacitor. Here we assume that the period of charging of the capacitor is lot larger than than the discharging time. Using initial and final value theorem for voltage across a capacitor, we get

$$V_C = V_{final} + V_{initial} - V_{final}\ e^{-t/RC}$$

$$t = T, V_C = V_P, V_{initial} = V_V, V_{final} = V_{BB}$$

Therefore $$V_P = V_{BB} + V_V - V_{BB}\ e^{-T/RC}$$

$$\Rightarrow \qquad T = RC\log_e\left(\frac{V_{BB}-V_V}{V_{BB}-V_P}\right)$$

If

$$V_V < V_{BB},$$

$$T = RC\ln\left(\frac{V_{BB}}{V_{BB}-V_P}\right)$$

$$T = RC\ln\left[\frac{1}{1-\eta}\right]$$

3.7 Assignment Questions

1 Distinguish between latching current and holding current.
2. Converter grade and inverter grade thyristors
3. Thyristor turn off and circuit turn off time
4. Peak repetitive forward blocking voltage i^2t rating
5. Explain the turn on and turn of dynamic characteristics of thyristor
6. A string of series connected thyristors is to withstand a DC voltage of 12 KV. The maximum leakage current and recovery charge differences of a thyristors are 12 mA and 120 μC respectively. A de-rating factor of 20% is applied for the steady state and dynamic (transient) voltage sharing of the thyristors. If the maximum steady sate voltage is 1000V, determine 1) the steady voltage sharing resistor R for each thyristor. 2) the transient voltage capacitor C1 for each thryristor
7. A SCR is to operate in a circuit where the supply voltage is 200 VDC. The dv/dt should be limited to 100 V/ μs. Series R and C are connected across the SCR for limiting dv/dt. The maximum discharge current from C into the SCR, if and when it is turned ON is to be limited to 100 A. Using an approximate expression, obtain the values of R and C.
8. With the circuit diagram and relevant waveforms,

3.8 Generic Skills / Outcomes:

- Discuss different types of Thyristors, their operation, gate characteristics and gate control requirements.

3.9 Further Reading

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510