Chapter one

Introduction

The diode:

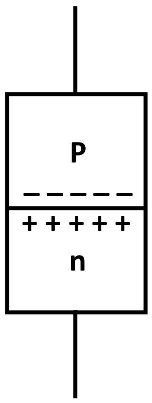
When **p** and **n** types are joined, excess electrons on the **n** side diffuse into the p layer and excess holes on the **p** side diffuse into the **n** layer thus developing a small electrostatic potential across the junction to oppose further flow of charges.

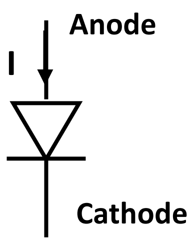
n-layer: Majority charge carrier is the electron.

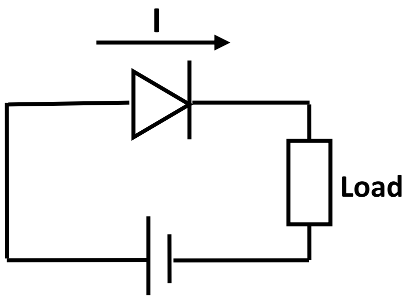
Minority charge carrier is the hole.

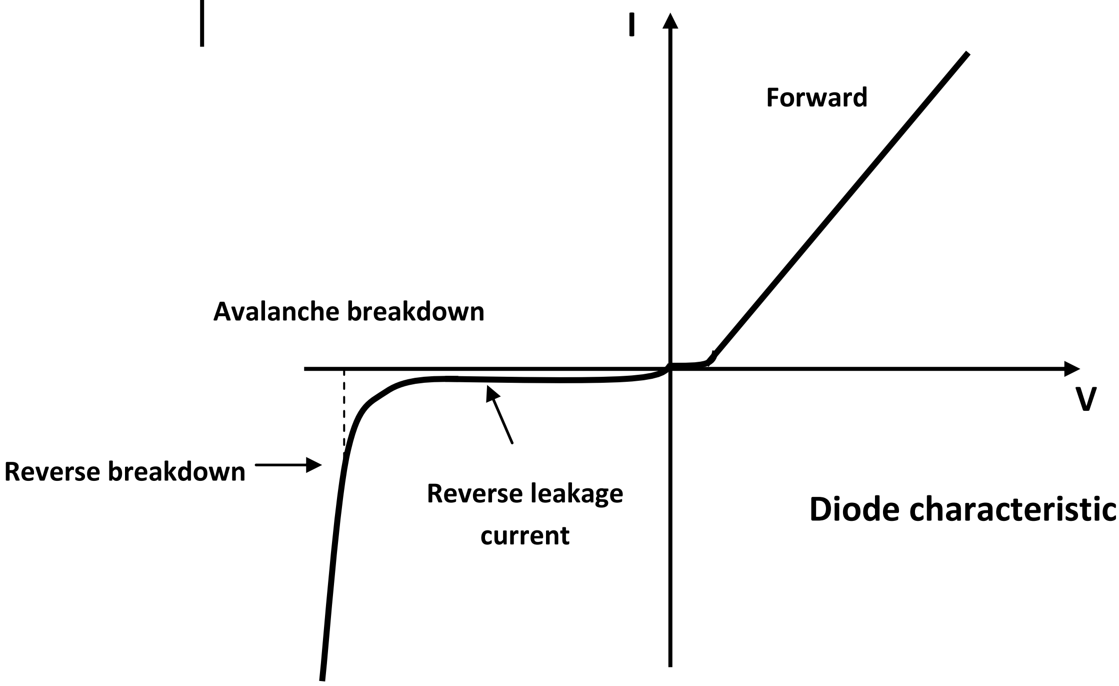
p-layer: Majority charge carrier is the hole.

Minority charge carrier is the electron.



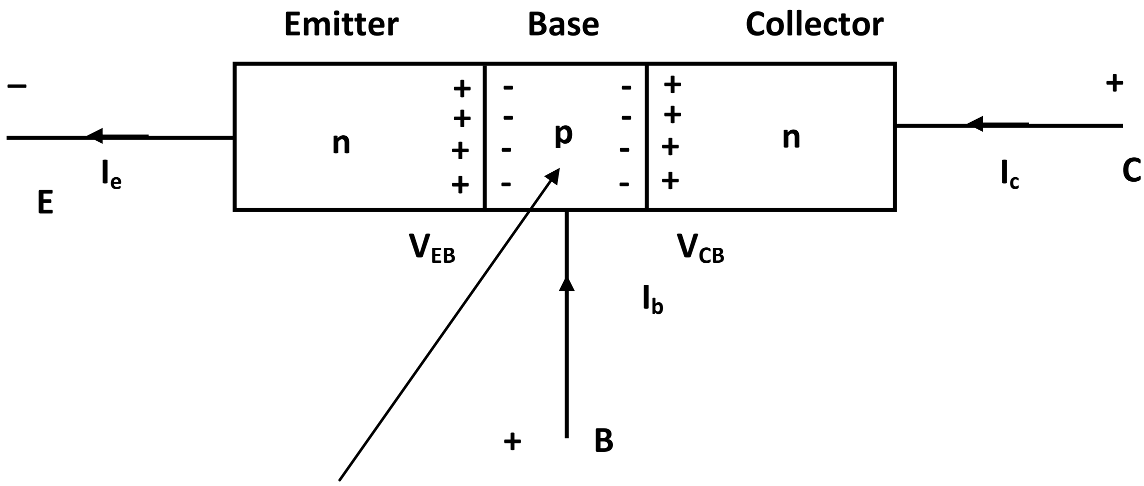




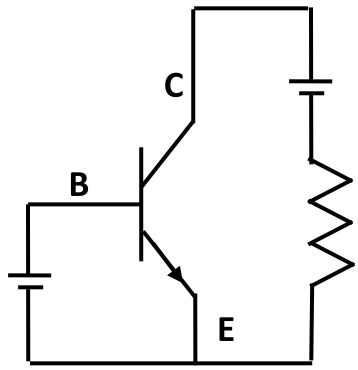


Diode characteristic

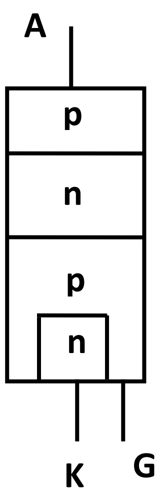
The transistor (n-p-n type):

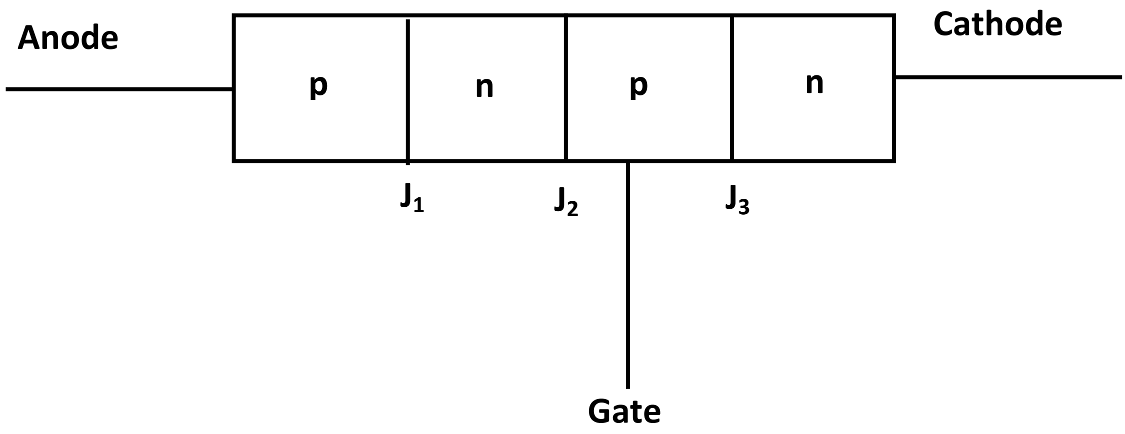


narrow base region so that the recombination of electrons is minimized on their way from the emitter to the collector.

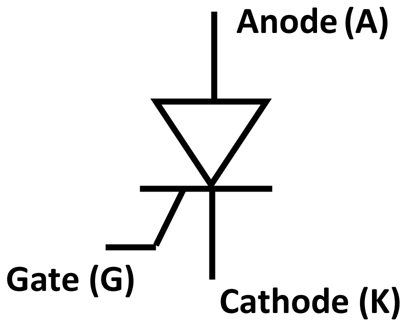


The thyristor (p-n-p-n controlled rectifier):





Four-layer structure

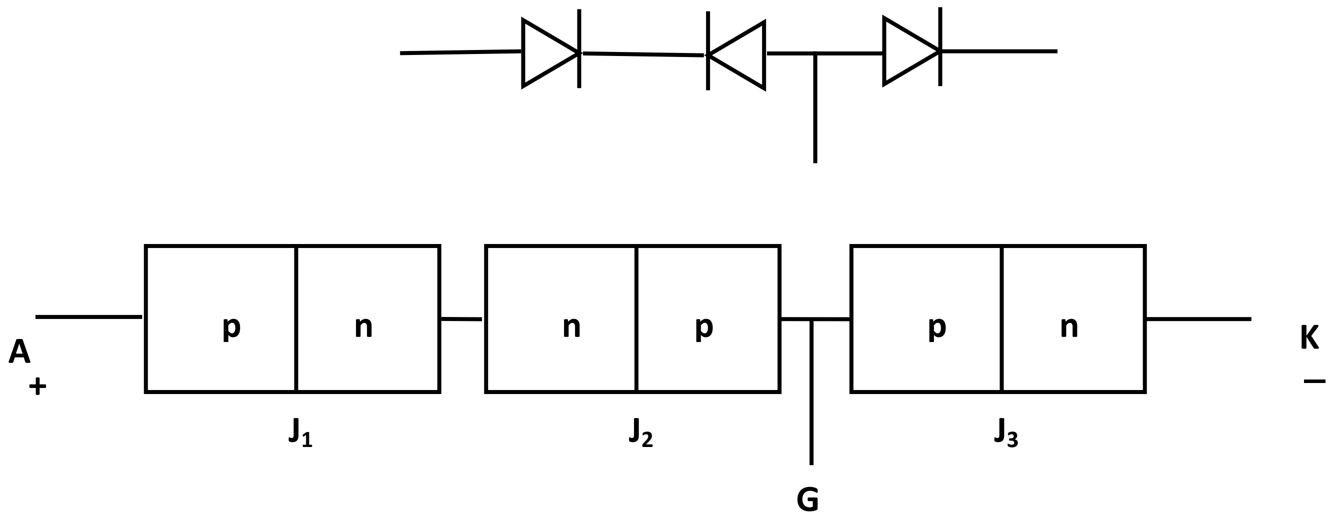


Electrical symbol of SCR (Silicon-Controlled Rectifier)

When (**A**) is position with respect to (**K**), $\mathbf{J_1}$ and $\mathbf{J_3}$ are forward biased but $\mathbf{J_2}$ is reversed biased. Less than 100 mA is sufficient to trigger the **SCR**, which can conduct more than 100A.

The diode model of the thyristor:

The thyristor is similar to three diodes in series

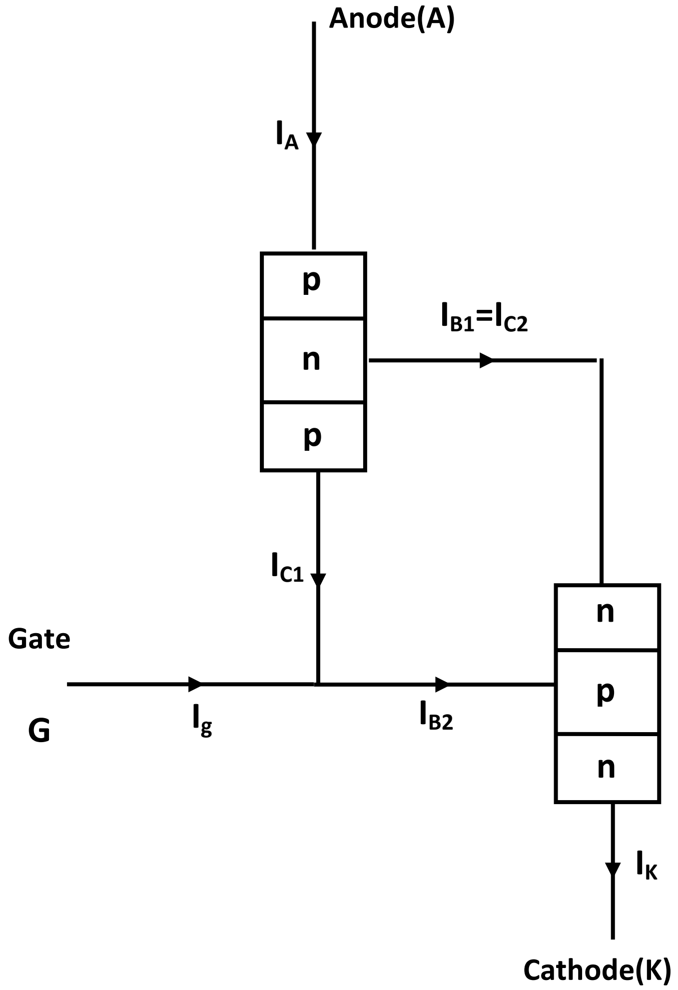


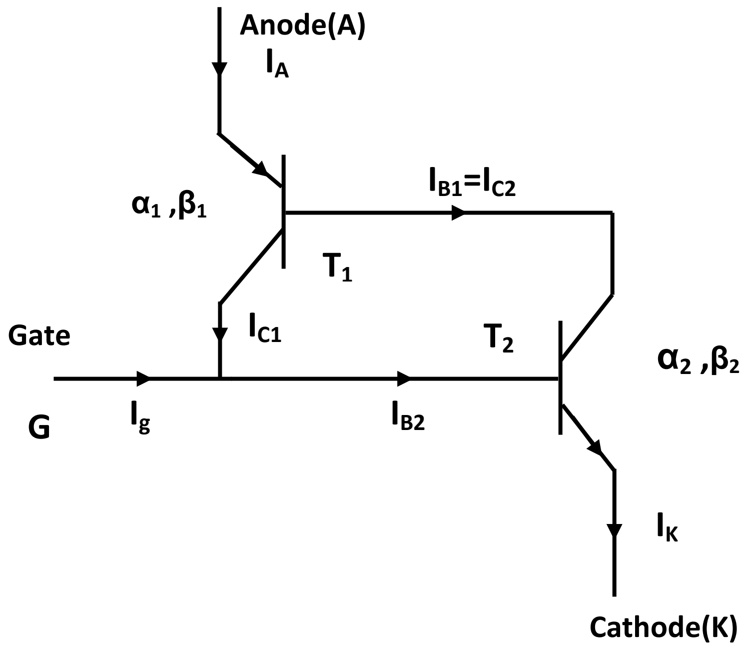
J_1 & J_3 Forward biased.

J_2 Reverse biased.

If a positive voltage is applied to the gate (with respect to the cathode) the **p**-layer of the gate is flooded with electrons from the cathode and will lose its identity as a **p**-layer.

The two-transistor model of the thyristor:





α_1=dc current gain of T_1

$$\propto_1 = \frac{I_{C1} - I_{CBO\,1}}{I_A} \qquad ----------(1)$$

$$I_A = I_{C1} + I_{B1} \qquad \therefore\ I_{C1} = I_A - I_{B1} \quad \text{in}(1)$$

$$\propto_1 I_A = I_A - I_{B1} - I_{CBO\,1}$$

$$\therefore I_{B1} = (1 - \propto_1) I_A - I_{CBO\,1} \qquad ------------(2)$$

$$I_{C2} = \propto_2 I_K + I_{CB\,02} \qquad ------------(3)$$

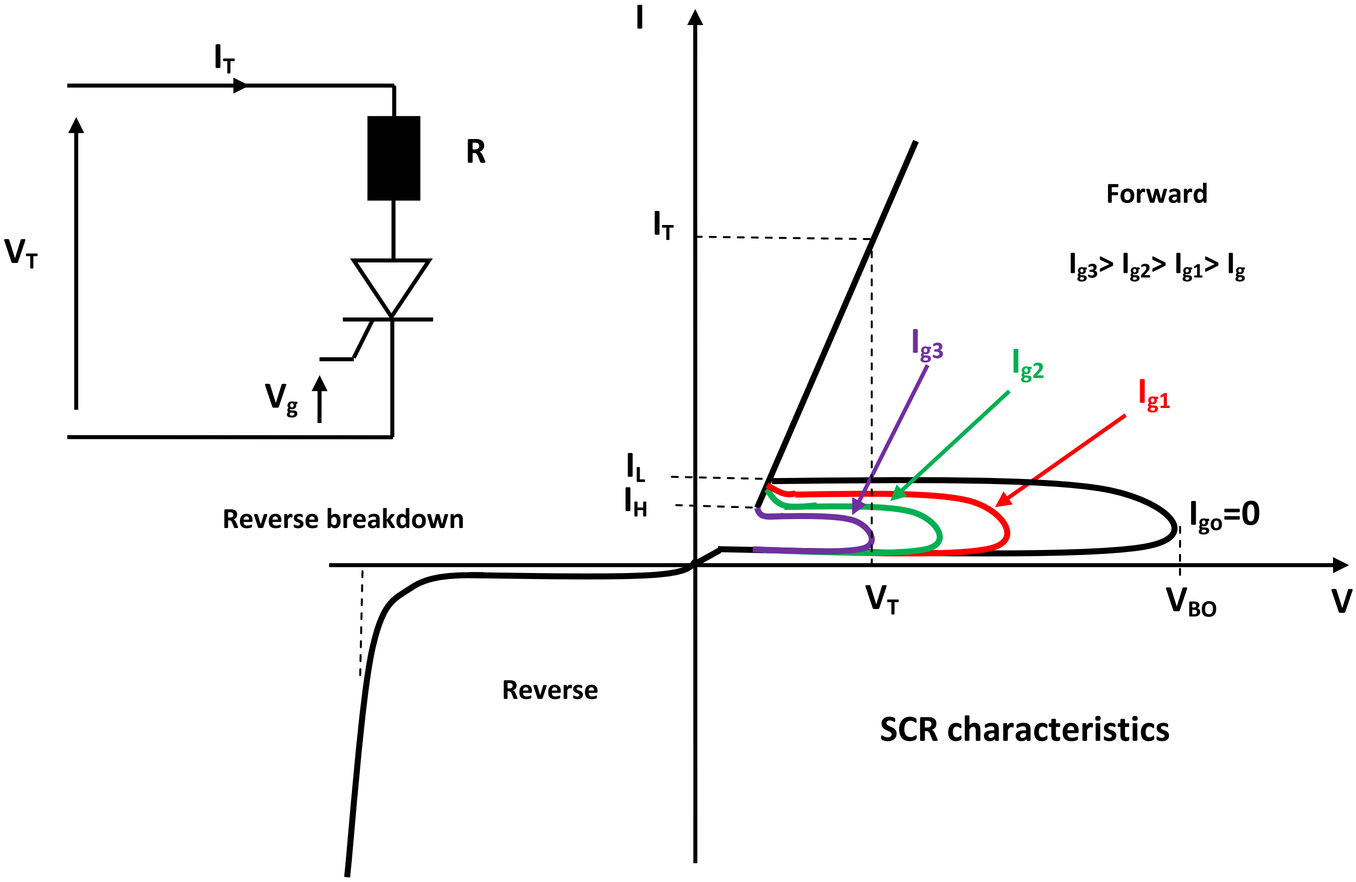
but $\quad I_{B1} = I_{C2} \quad \& \quad I_K = I_g + I_A \qquad ------------(4)$

Solving (2), (3) and (4) gives:

$$\boxed{I_A = \frac{\propto_2 I_g + I_{CBO\,1} + I_{CBO\,2}}{1 - (\propto_1 + \propto_2)}}$$

The current $\mathbf{I_{CBO1}}$ is the collector junction reverse bias leakage current.

Electrical characteristic of SCR:



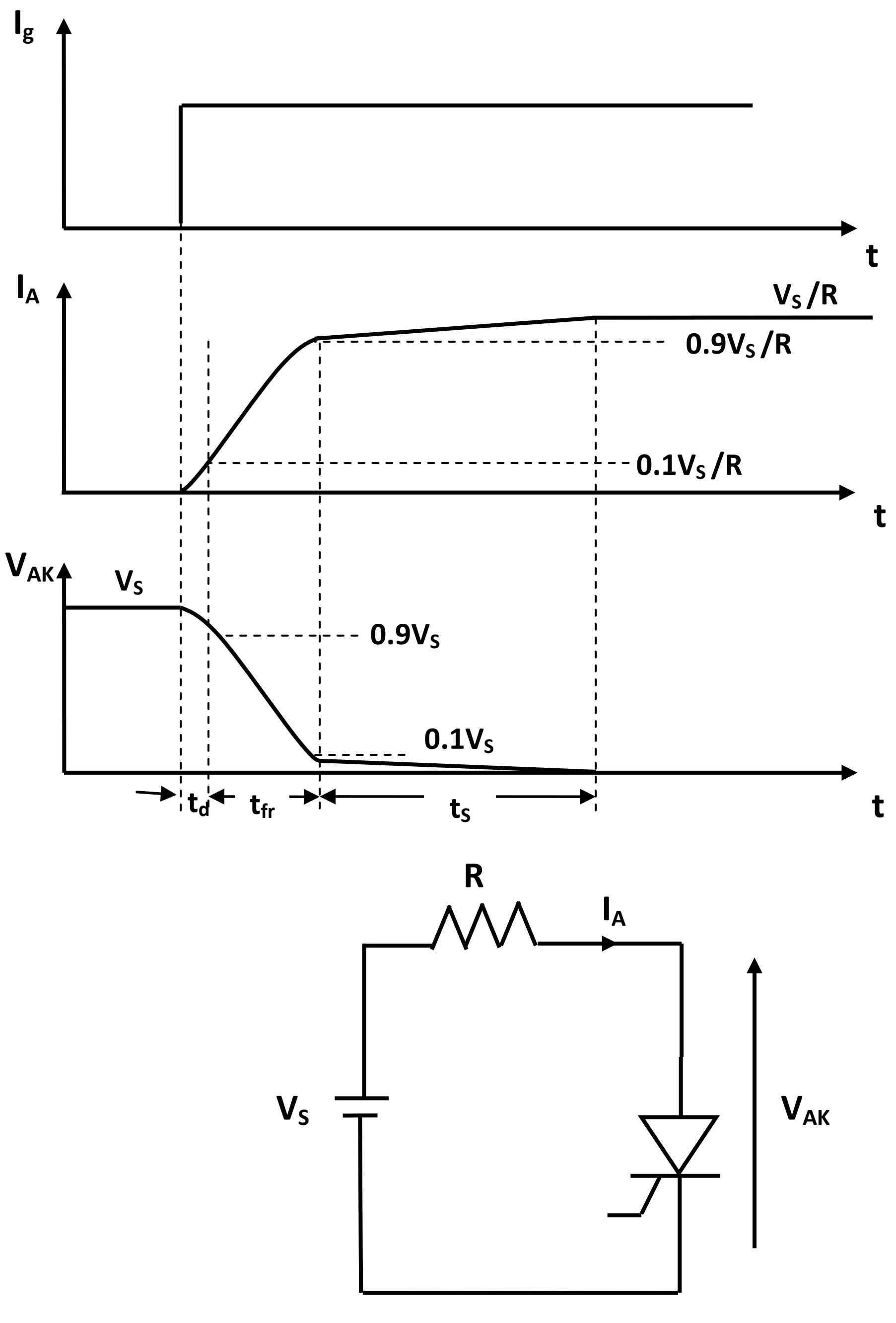
SCR characteristics

I_H(Holding current): It is the least value of anode current to turn-off the thyristor.

I_L(Latching current): It is the least value of anode current to keep the SCR ON after triggering ($I_L > I_H$).

V_{BO}: Forward breaking over voltage.

SCR Transient characteristics (ON):



where,

t_d (delay time): is the 10% point of the anode voltage waveform.

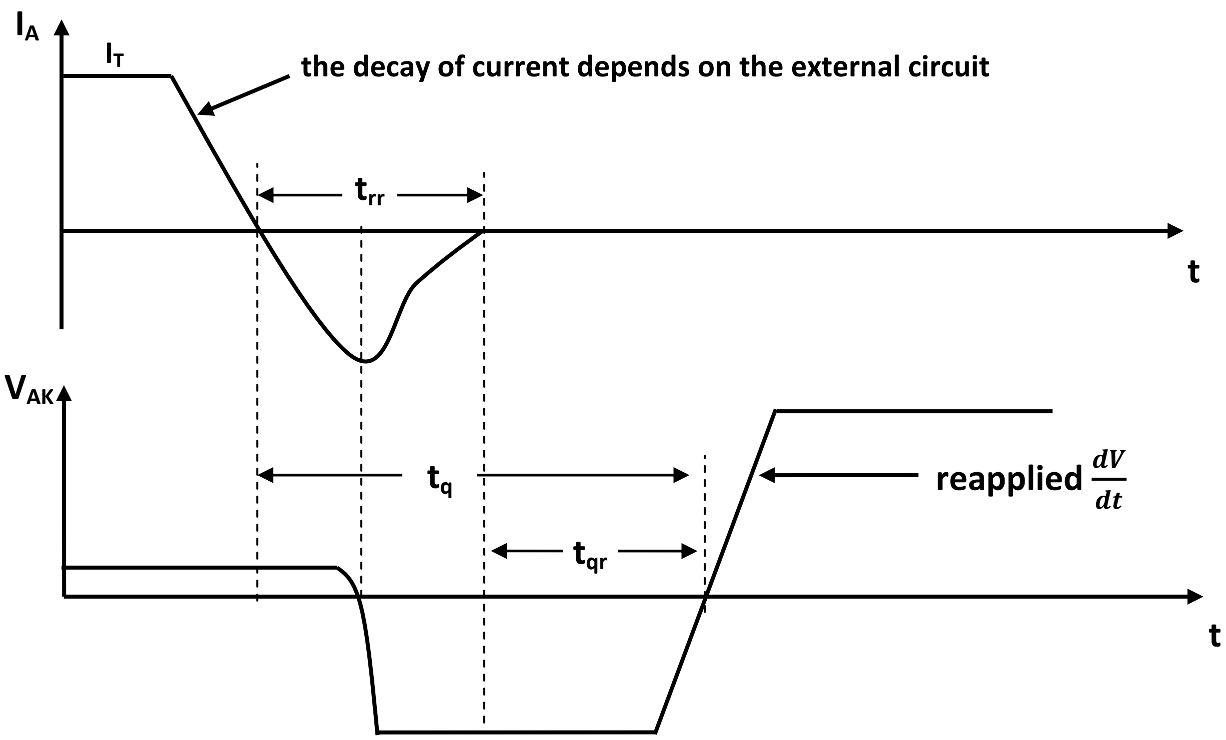
t_{fr} (rise time): is the time required for the anode voltage to drop from 90% of its initial value to 10%.

t_{on} (turn-on time)=(t_d+t_{fr}): it is varying with gate current and it depends on the thyristor type. It is typically equals to several microseconds.

t_S (spread time): It is the time required to change the current from $0.9V_S/R$ to V_S/R.

SCR Transient characteristics (OFF):

In thyristor applications involving DC supplies and resistive / inductive load, the turn-off is accomplished by reverse-biasing the thyristor and reducing the anode current to near zero.

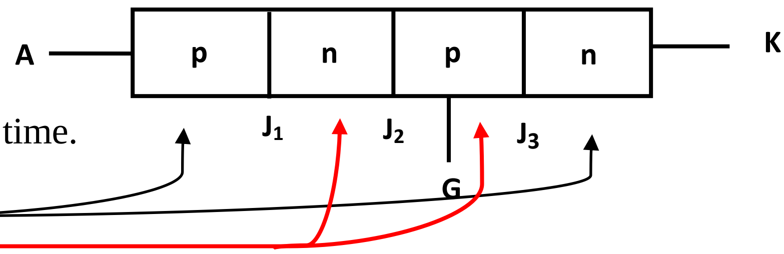


where,

t_{rr}= The reverse recovery period.

t_{qr}= The gate recovery period.

t_q=t_{rr} + t_{qr} = The actual thyristor turn-off time.



t_{rr} [to remove the charges from]

t_{qr} [high concentration of holes and electrons still exists in the central junction which is slightly forward biased. This concentration decreases by the process of natural recombination. When this recombination is completed the junction J_2 will have reverse blocking capability and a forward biasing anode voltage can be reapplied].

If a forward voltage is applied to the thyristor before the time t_q is completed, the thyristor will be ON again. Typical turn-off times are from microseconds to 200 μs.

SCR turn-on methods:

1- Light turn-on:

A beam of light directed at the gate to cathode junction $\mathbf{J_3}$ can produce sufficient energy to break electron bonds in the semiconductor and bring about the necessary additional minority carrier to switch ON the SCR.

2- Gate turn-on:

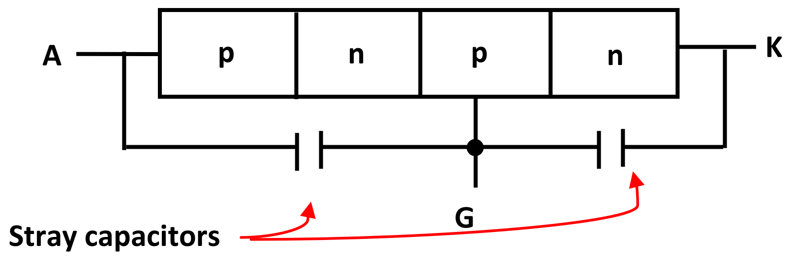
Additional minority carriers can be injected into the gate region through the gate lead to switch the SCR on. The gate current varies between few mA to 250 mA or more.

3- Break over voltage turn-on:

An increase in the anode to cathode voltage increases the width of the depletion layer at $\mathbf{J_2}$ and also increases the accelerating-voltage for minority carrier across $\mathbf{J_2}$. These carrier collide with the fixed atoms and dislodge further minority carriers until there is an avalanche breakdown of the junction.

4- dV/dt turn-on:

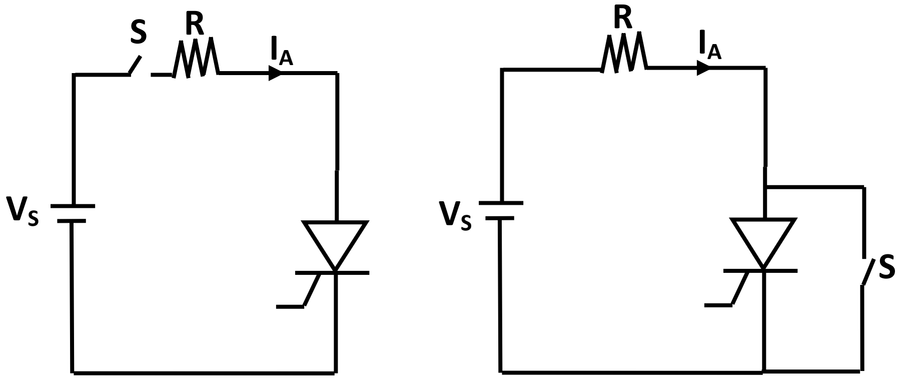
A rapid rate of increase of forward anode to cathode voltage can produce a transient gate current, which is caused by anode to gate and gate to cathode capacitances. This can turn-on the thyristor and is to be avoided.



SCR turn-off methods:

1- Natural commutation:

When the anode current is reduced below the holding current the thyristor turns off.



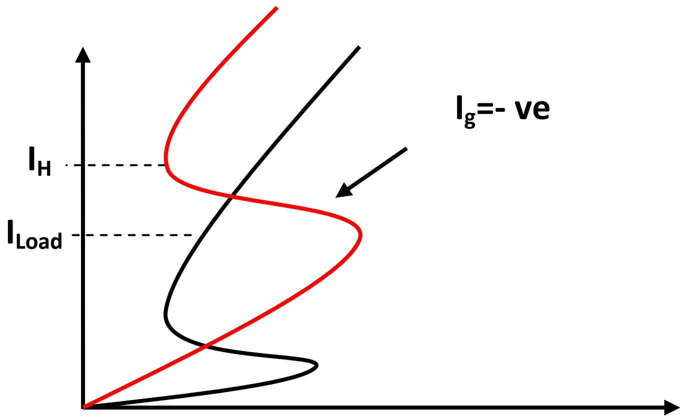
2- Reverse bias turn-off:

A reverse anode to cathode voltage will tend to interrupt the anode current. The voltage reverses every half cycle in an A.C. circuit so that a thyristor in the line would be reverse biased every negative cycle and would turn-off. This is called phase commutation or A.C. line commutation.

To create a reverse biased voltage across a thyristor (in D.C. circuit) capacitors can be used. The method of discharging a capacitor in parallel with a thyristor to turn-off the thyristor is called forced commutation.

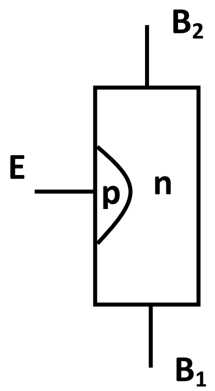
3- Gate turn-off (GTO):

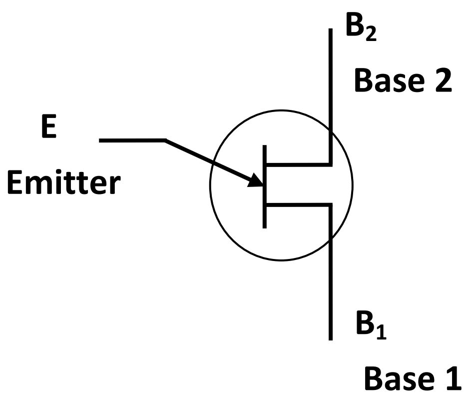
In some specially designed thyristors the characteristics are such that a negative gate current increases the holding current so that it exceeds the load current and the device turns off (below 10 A rating).

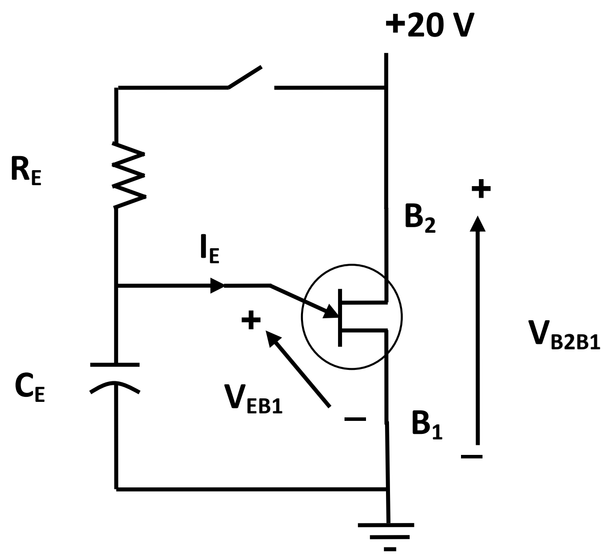


The unijunction transistor (UJT):

It is a break over-type switching device.







when the voltage V_{EB1} is less than a certain value called the peak voltage (V_P), the UJT is turn oFF and I_E=0.

when V_{EB1} exceeds V_P by a small amount, the UJT fires or turn ON, the E to B_1 circuit becomes almost a short circuit and current can surge from E to B_1. The burst of current from E to B_1 is short-lived and the UJT quickly returns back to the OFF condition.

The peak voltage is:

$$V_P=\zeta\, V_{B2B1} + 0.6 \quad V$$

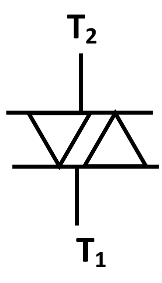
Where ζ is the standoff ratio and is less than 1.

0.6 is voltage drop across p-n junction.

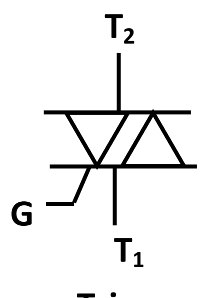
Triacs and Diacs:

Diac: Is a five-layer device without a gate would break over in the first or third quadrant if the voltage exceeds V_{BO}**.**

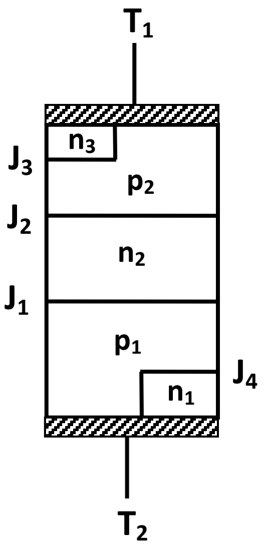
Triac: Is a five-layer device with gate.

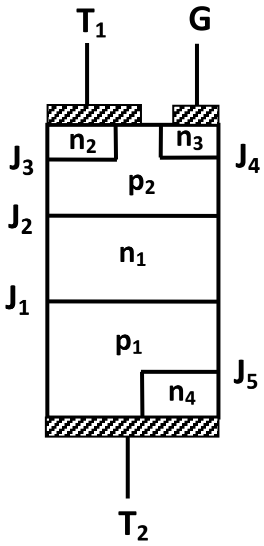


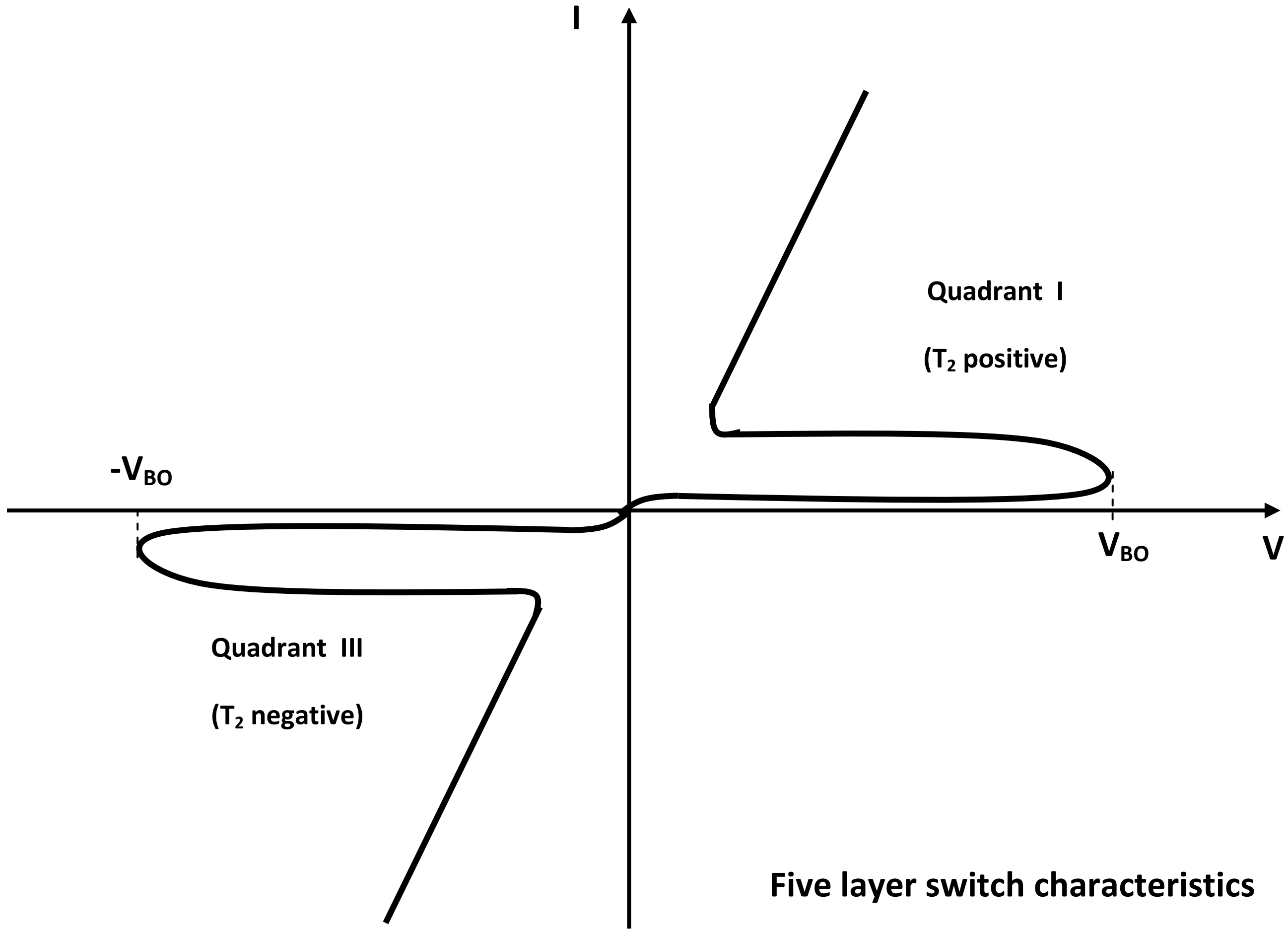
Diac



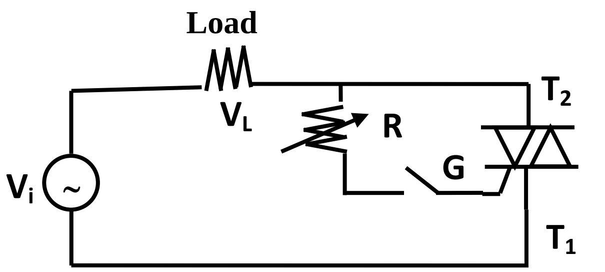
Triac

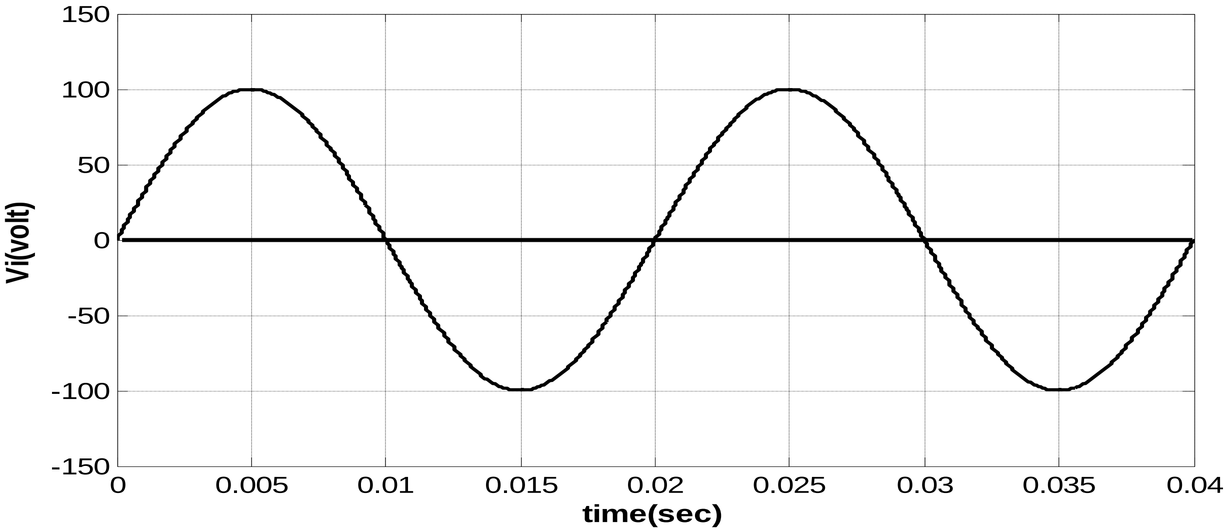


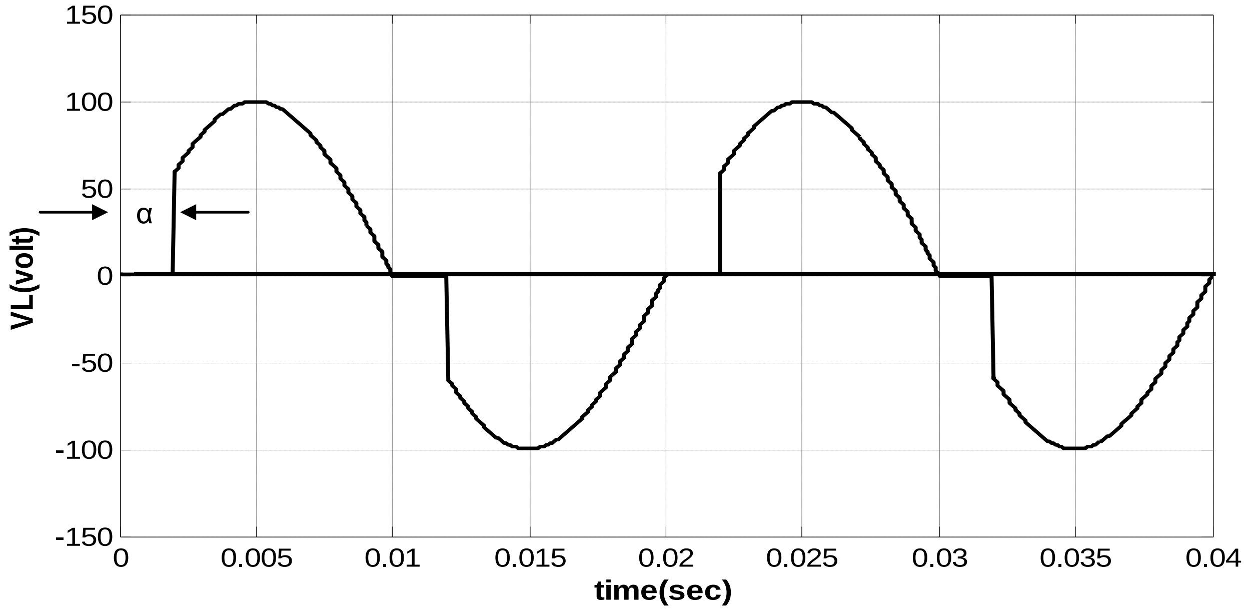




Five layer switch characteristics



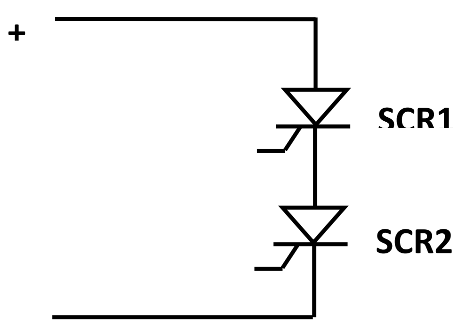


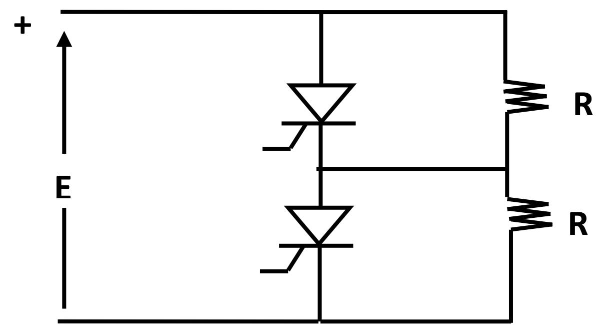


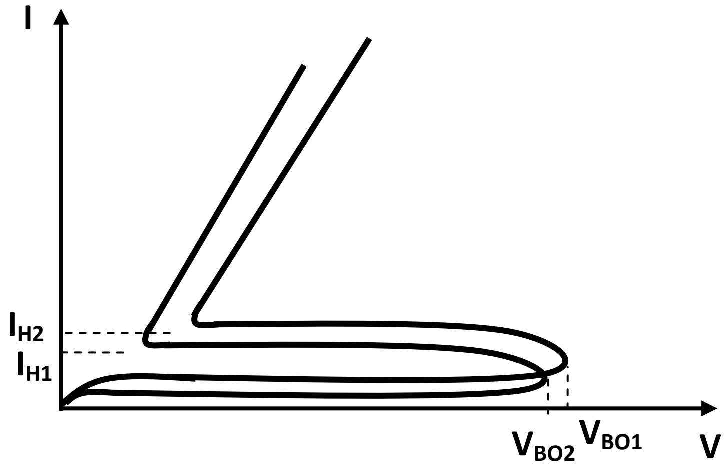
Series and parallel operation of SCRs:

SCRs in series:

When the supply voltage is greater than the thyristor voltage rating, a number of thyristors can be connected in series to share the forward and reverse voltages.







External resistors (R) are to be connected across each SCR in order to force equal sharing of voltages across each SCR if they are not of the same type.

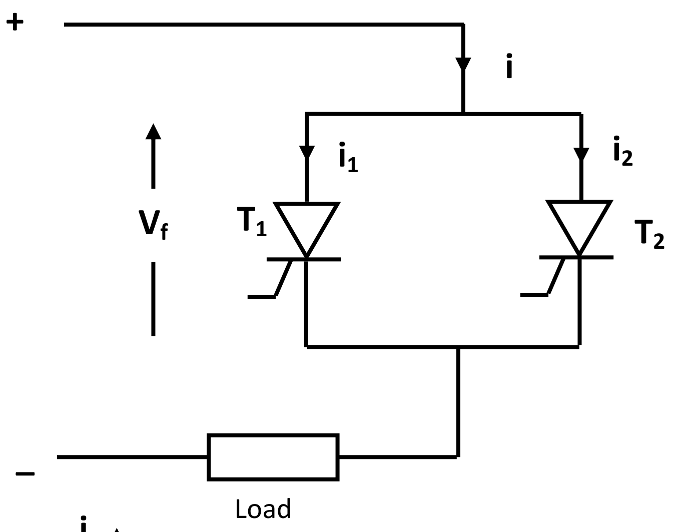
$$R = \frac{2E_{max} - E}{\Delta I_b}$$

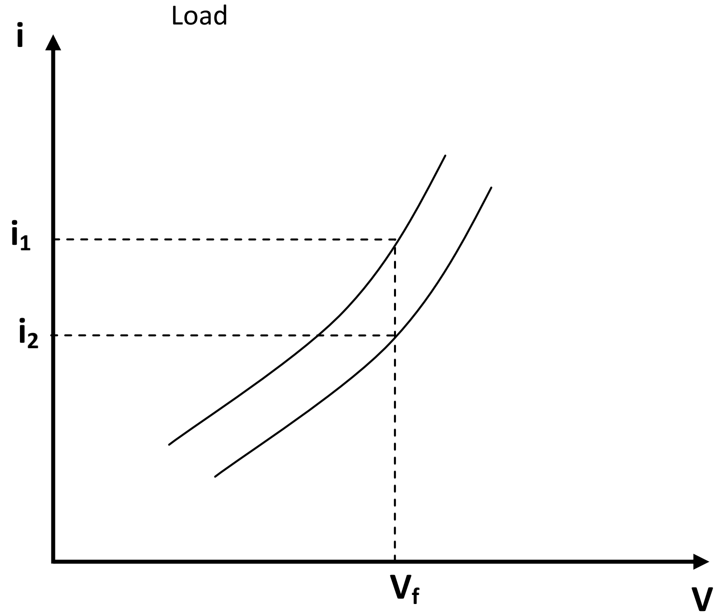
E_{max}=Max. blocking voltage across SCR.

$\Delta I_b = I_{bmax} - I_{bmin}$=range of leakage current variation.

SCRs in parallel:

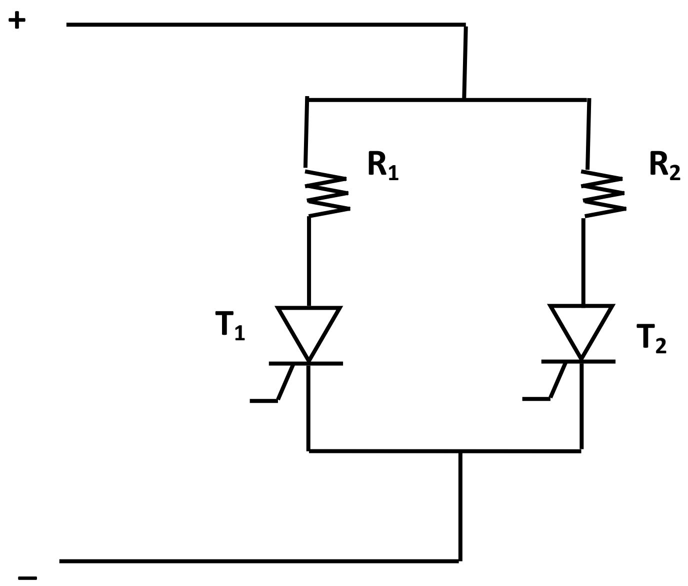
When the load current is greater than the thyristor rating, operation is still possible if a number of thyristors are connected in parallel to share the load current.



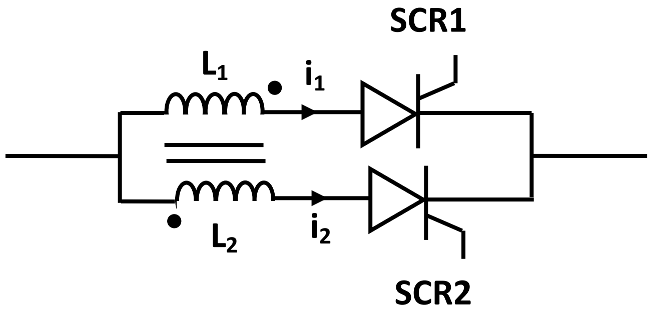


To have equal sharing of current:

1.By using resistors:



2.By using cross-coupled reactors:

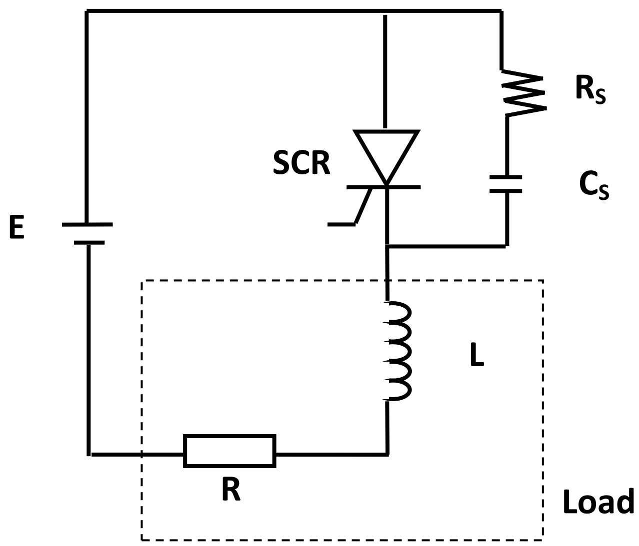


When the current i_1 increases over i_2, an opposing voltage is induced in L_1 which tries to reduce i_1 and increase i_2.

The gate signals must be applied until the latching currents of all thyristors has been exceeded because once one unit conducts, the voltage drop across it reduces to a value just above 1V, and this is then the voltage across the others.

The snubber circuit:

It is an R-C circuit connected across the SCR in order to keep dV/dt below the manufacture's maximum specified value given in the data sheet.



$$\left.\frac{dV_{AK}}{dt}\right|_{max} = \frac{E}{\sqrt{LC_S}}$$

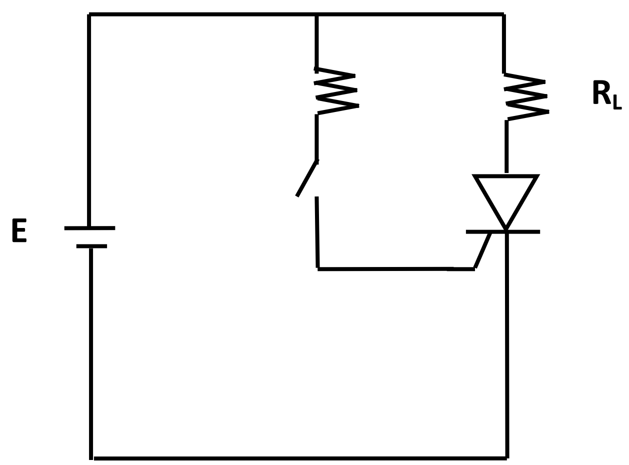
$$R_S = \sqrt{\frac{L}{C_S}}$$

SCR di/dt calculation

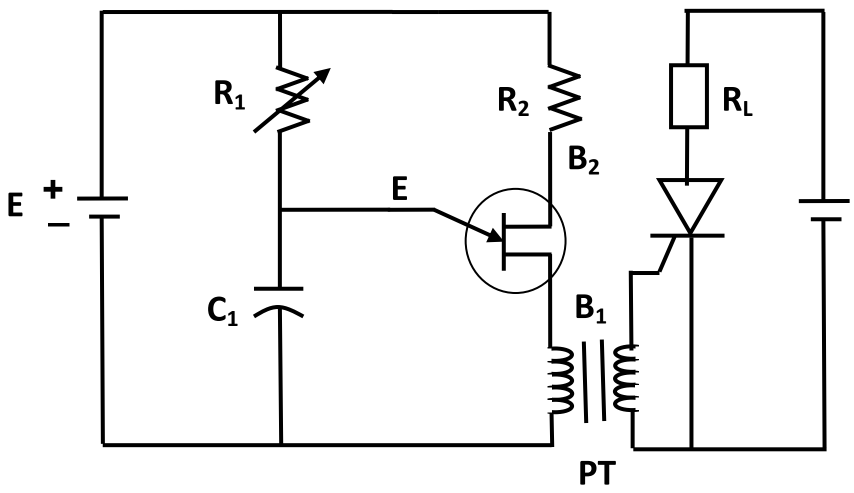
$$\left.\frac{di}{dt}\right|_{max} = \frac{E}{L}$$

Thyristor firing circuits:

1-Using supply voltage:



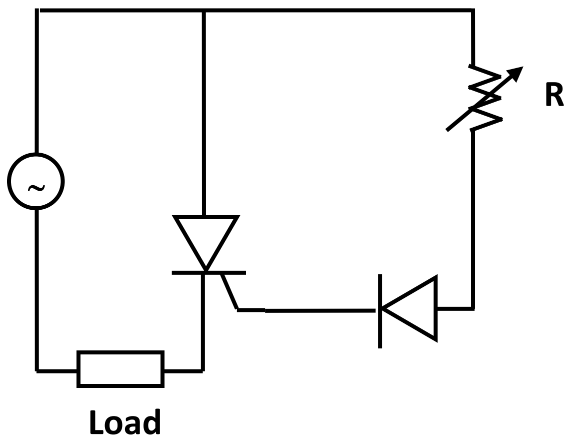
2-Pulse-firing signals:



Unijunction transistor firing.

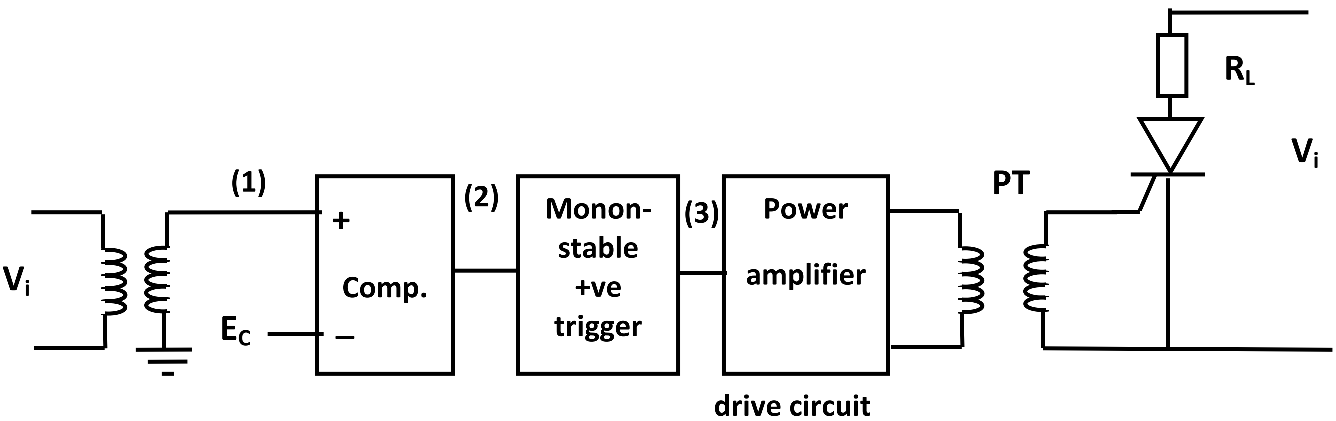
The capacitor C_1 charges up until the UJT breaks down (when $V_{EB1} > V_P$ where $V_P = \zeta\ V_{B2B1} + 0.6$ V) and pulse then appears across the transformer. The time it takes for the pulse to appear depends on the RC time constant.

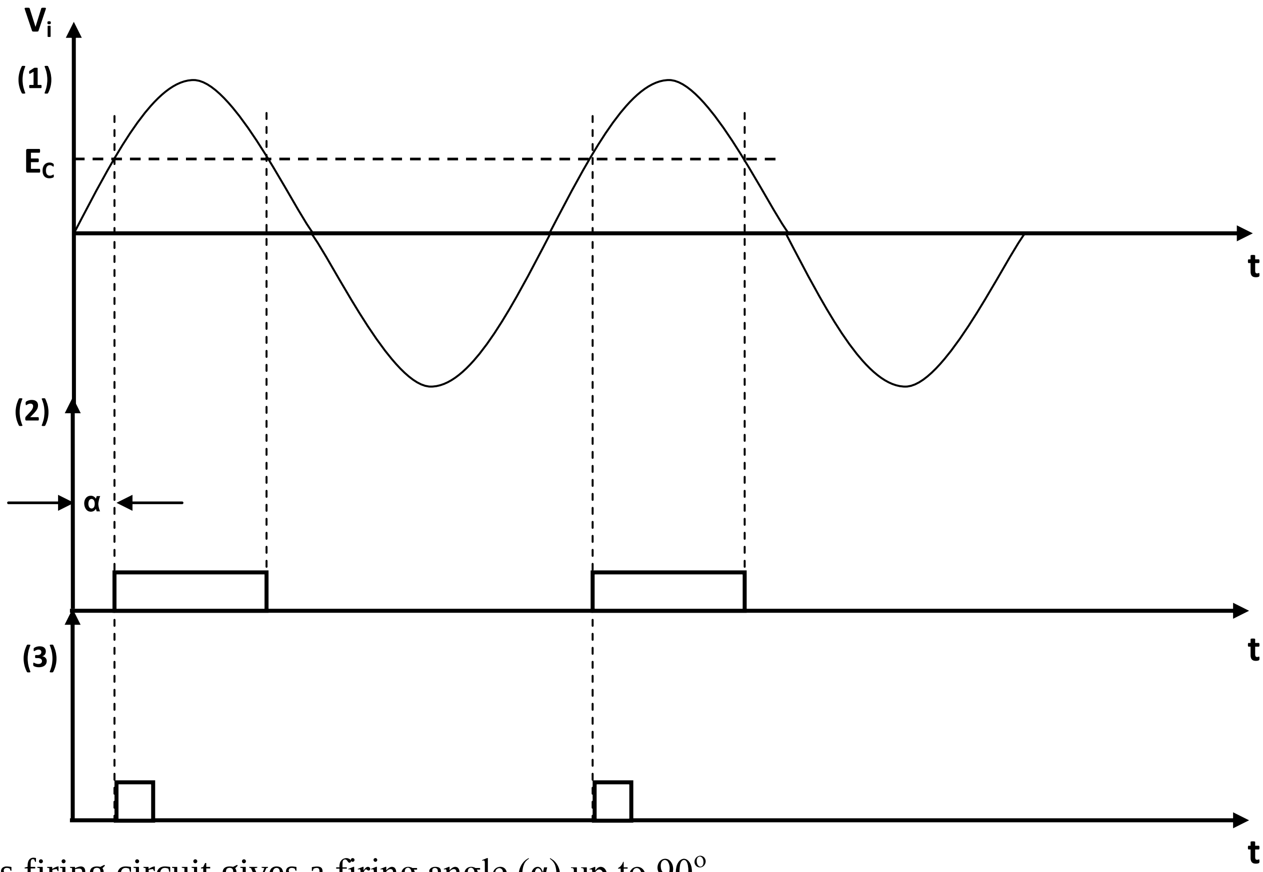
3-Alternating current firing signals:



This is a simple method to give up to a 90^{o} conduction angle.

4-Generating pulses which are synchronized with supply voltage:





This firing circuit gives a firing angle (α) up to 90°.

Circuits to turn off thyristors:

The general methods of turn-off are:

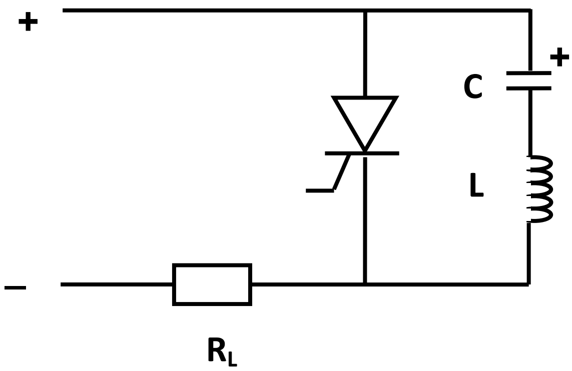
1. Current interruption:

By opening a switch in the load line or closing a switch in parallel with the thyristor.

2. Forced commutation:

For AC operation, the turn off is accomplished by phase commutation when the supply voltage goes negative. For DC operation, capacitors are used for forced commutation.

(a) Self commutation by resonance:



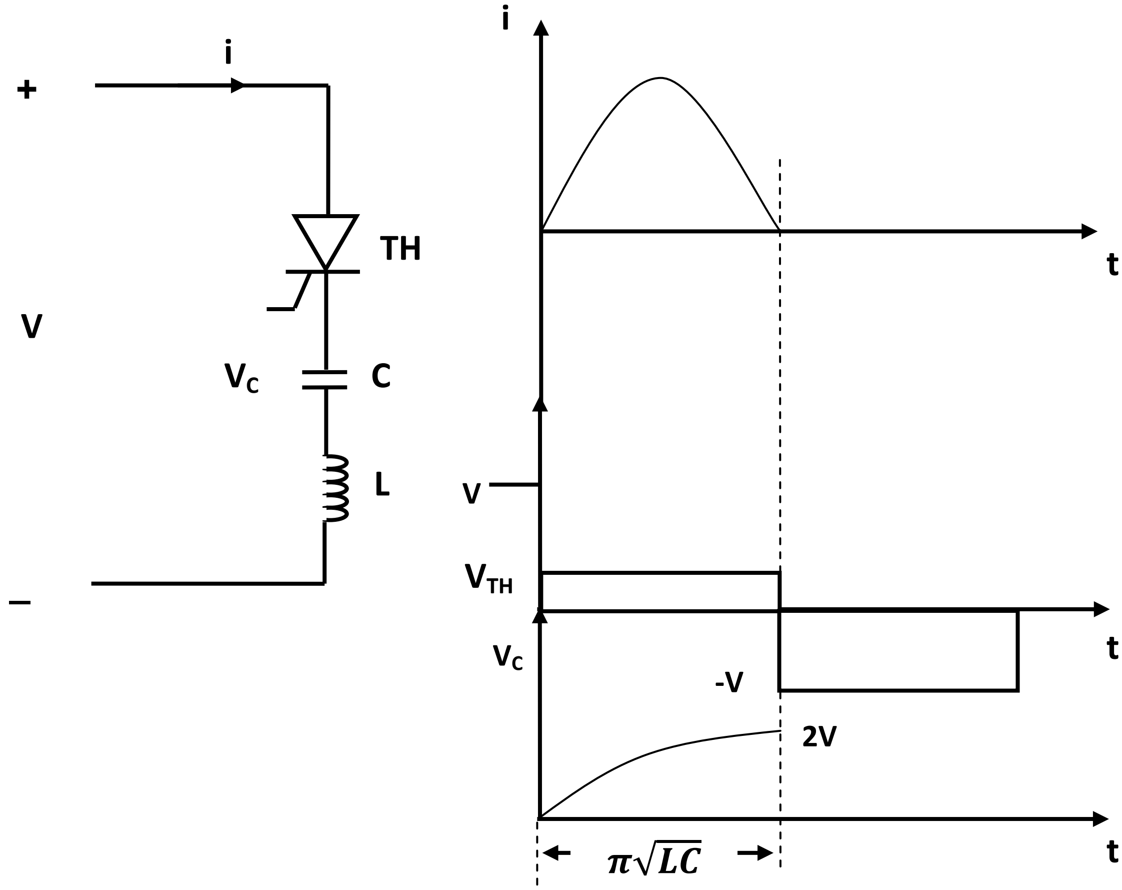
First C is charge from the supply. As the thyristor turns on to conduct load current, C discharges through the resonating circuit of C, thyristor and L so that the capacitor changes polarity. The resonating current will reverse after one half cycle. The thyristor will turn off if the resonating current is greater than the load current.

For all loads:

$$C > t_{off} / R_L \quad \mu F$$

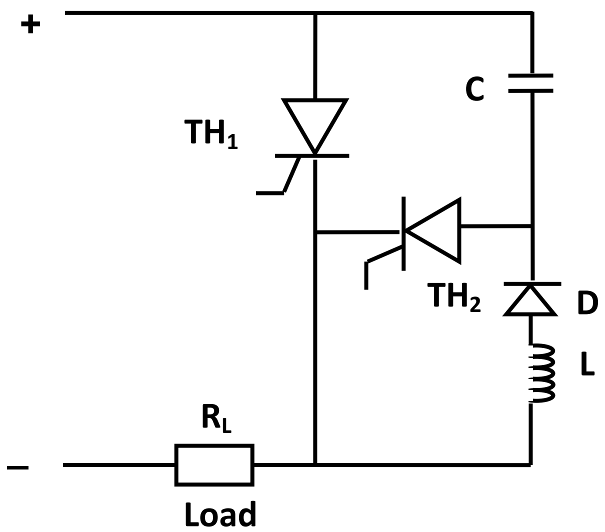
where t_{off} is the commutation time in μs and R_L is the load resistance.

or



When the capacitor has charged up the resonant circuit tries to make the current reverse so that the thyristor turns off.

(b) Auxiliary resonant turn-off:



Controlled resonant turn-off

(1) TH_2 ON ⟹ C charged.

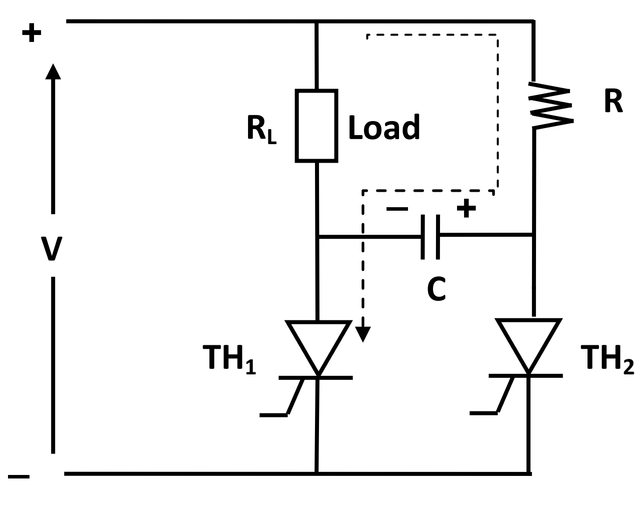
(2) TH_2 OFF ⟹ when the current falls below the holding current of it.

(3) Thyristor TH_1 can be turned on to carry both load current and the resonating current of C and L. The capacitor C changes polarity.

(4) TH_2 ON ⟹ TH_1 OFF.

$$C > t_{off} / R_L \quad \mu F$$

(c) Parallel capacitor turn off:



Parallel capacitance turn-off

(1) TH_1 ON $\Longrightarrow$ C charged.

(2) TH_2 ON $\Longrightarrow$ TH_1 OFF.

$$\boxed{C > t_{off} / 0.7R_L \quad \mu F}$$

Heat sink, thyristors cooling:

During operation of a thyristor, heat can be generated due to several phenomena:

1- Power loss during forward conduction.

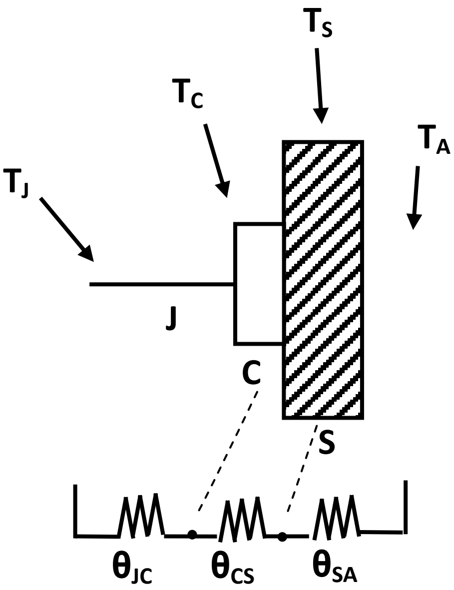
2- Leakage current when the thyristor is blocking in the forward or reverse direction.

3-Switching losses which occurs during turn-on and turn-off.

4-Gate losses, normally small when single-phase firing techniques are adopted, but can be significant for DC or pulse train signals.

The heat arising at the junction due to the forward conduction losses flows to the thyristor case, from then to heat sink, and from the heat sink to the surrounding atmosphere. The difference in temperature between junction and atmosphere under steady-state condition is given by the following equation:

$$\mathbf{T_J - T_A = P_{AVE}(\theta_{JC} + \theta_{CS} + \theta_{SA}) \quad C^o}$$



where, T_A: is the ambient temperature.

T_J : Junction temperature. ($-40 < T_J < 125$ C^o)

θ_{JC} : Thermal impedance, junction to case , C^o/W.

θ_{CS} : Thermal impedance, case to sink , C^o/W.

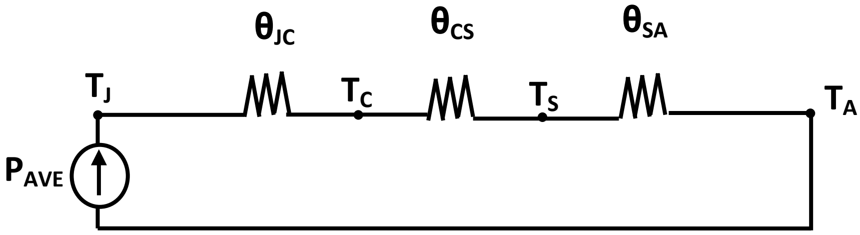
θ_{SA} : Sink to atmosphere thermal impedance, C^o/W.

P_{AVE} : Average rate of heat generation in watts.

$\Delta T = T_S - T_A$ C^o

where, T_S : Sink temperature.

$$\theta_{SA} = \frac{\Delta T}{P_{AVE}} \quad C^{\circ}/W$$

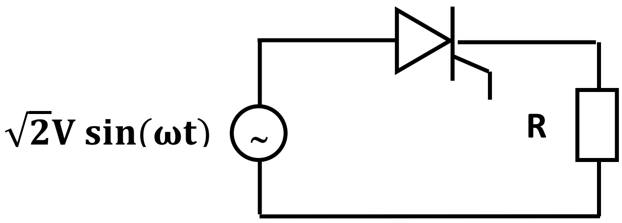


Equivalent thermal circuit.

Example: For the following circuit, V=220 V, R=1 Ω, α=0, T_A=40 C°, T_S=86 C°, T_C=98 C°, T_J=120 C°, and θ_{CS}=0.075 C°/W, calculate:

1- The thermal impedances of the thyristor and heat sink, θ_{SA}, θ_{JC} and P_{AVE}.

2-The circuit efficiency.



Soultion:

1- $\theta_{CS} = \frac{T_C - T_S}{P_{AVE}}$ $\qquad 0.075 = \frac{98-86}{P_{AVE}}$

$$\therefore P_{AVE} = 160 \text{ Watt}$$

$$\therefore \theta_{JC} = \frac{T_{J-T_C}}{P_{AVE}} = \frac{120 - 98}{160} = 0.1375 \text{ °C/W}$$

$$\theta_{SA} = \frac{T_{S-T_A}}{P_{AVE}} = \frac{86 - 40}{160} = 0.2875 \text{ °C/W}$$

2- $\qquad P_o = I_{rms}^2 \, R = \frac{V_{rms}^2}{R}$

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{\pi}\left(\sqrt{2}V\sin(\omega t)\right)^2 d\omega t\right]^{\frac{1}{2}} = \frac{V}{\sqrt{2}}$$

$$P_o = \frac{\left(V/\sqrt{2}\right)^2}{R} = \frac{V^2}{2R} = \frac{(220)^2}{2*1} = 24.2*10^3\ Watt$$

$$\zeta\% = \frac{P_o}{P_o + P_{AVE}} * 100\% = \frac{24.2*10^3}{24.2*10^3 + 160} * 100\% = 99.34\%$$

18. Thyristors rating:

1. Voltage ratings:

These are three voltages to be considered:

i. PFV: Peak Forward Voltage, is the limiting positive anode voltage above which the thyristor may be damaged.

ii. V_{BO}: Forward Break Over voltage, is the minimum anode to cathode voltage to cause turn-on when no gate signal is applied.

iii. PRV: Peak Reverse Voltage, is the maximum reverse repetitive voltage that can be applied to the thyristor. If PRV is exceeded there may be avalanche breakdown and the thyristor will be damaged if the external circuit does not limit the current.

2. Current ratings:

Example of a manufacture's specification for pulse application is:

1000A peak current (30 A average current)

maximum repetitive di/dt=1200 A/µs

current rise time to 300A in 300 ns.

applied voltage 400 V.

gate current 4A with 0.1 µs rise time.

19. Thyristors gating requirements:

Below a certain gate voltage, called the gate non-trigger voltage V_{GD}, no device will trigger. The gate voltage should be between 2 and 10 V to cause current between 100 μA to 1500 mA to flow. High gate currents are needed for thyristors of high power rating.

An increase in anode supporting voltage tends to decrease the gate drive requirements. But if the gate signal is a pulse of less than about 100 μs, the turn-on (I_G, V_G) requirement is increased as the pulse duration is decreased.