R.N.G.P.I.T, Bardoli
Electrical Engineering Department

Subject: Power Electronics

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Power Electronics

- This Lecture contains

- Introduction & Turning On Methods for SCR
- Static VI characteristics of SCR
- Protection of SCR
- Firing circuit of SCR

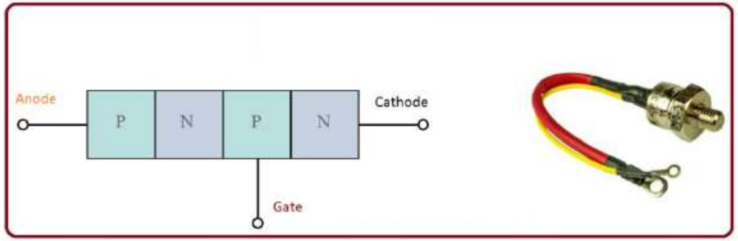
- *Syllabus:*

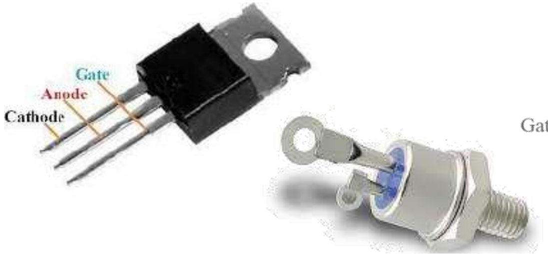
1	Power switching devices Diode, Thyristor, MOSFET, IGBT; Static characteristics of these devices; Operation of power devices as switches and switching losses, Single-quadrant switches, two-quadrant and bidirectional switches; Firing circuit for thyristors; Gate drive circuits for MOSFET and IGBT.	06

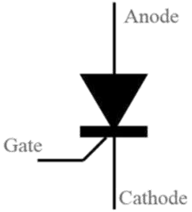
Reference Books:

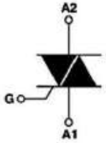
1. M. H. Rashid, "Power electronics: circuits, devices, and applications", Pearson Education India, 2009.
2. N. Mohan, T. M. Undeland, W.M. Robbins, "Power Electronics: Converters, Applications and Design", Wiley India Edition, 2007.
3. R. W. Erickson and D. Maksimovic, "Fundamentals of Power Electronics", Springer Science & Business Media, 2007.
4. P.S. Bimbhra, "Power Electronics", Khanna Publishers, New Delhi, 2012..
5. L. Umanand, "Power Electronics: Essentials and Applications", Wiley India, 2009.

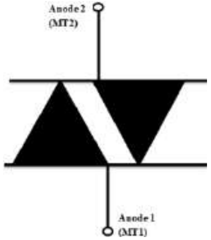
- Thyrsitor
- Combination of THYRatron+transISTOR
- The definition of thyristor was given by IEC (International Electro technical Commission) in 1963 as
- (1) It consist of 3 or more pn junctions
- (2)Has two stable states (ON & OFF)
- Example:- SCR, Triac, diac, SCS (silicon controlled switch), PUT, GTO, RCT etc



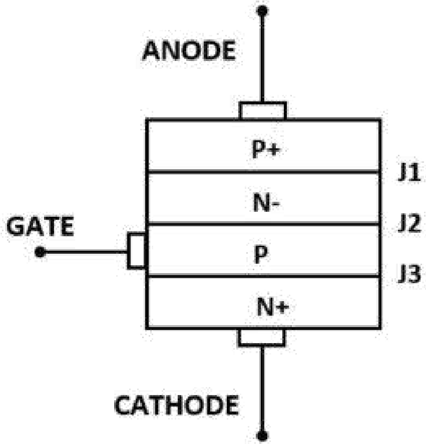


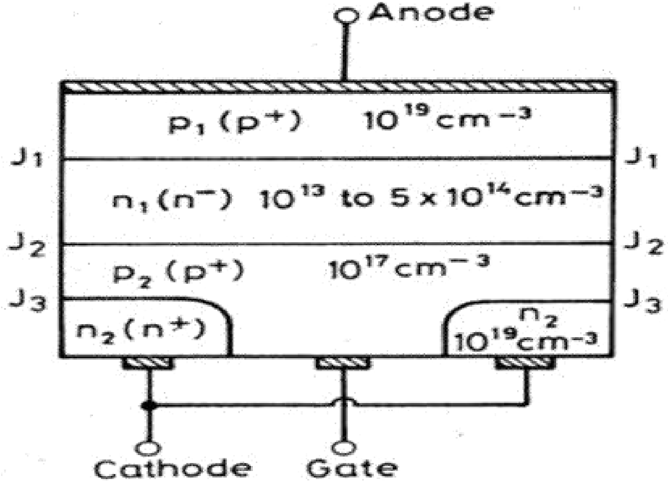




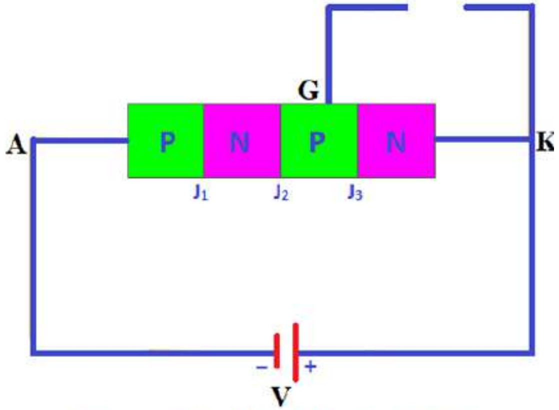


- Silicon Controlled Rectifier (SCR) is made up of silicon and hence called SCR.
- It is unidirectional, Bipolar device
- SCR is widely used for high power (10kV,3000A, 30MW) applications.
- It is a 4 layer, 3 junction, PNPN semiconductor device

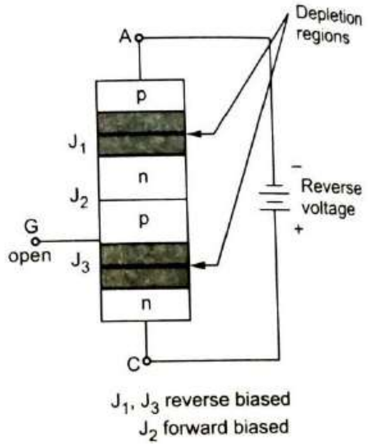




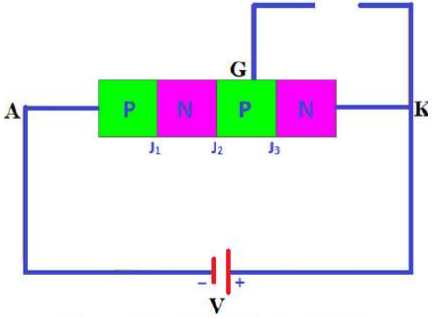
- Static I-V characteristics of SCR
- (1) Reverse blocking mode
- (2)Forward blocking Mode
- (3)Forward Conduction mode
- Reverse Blocking mode:
- J_1 & J_3 are Reverse biased and J_2 is Forward biased
- Small reverse Leakage current (I_{RL}) of the order of few uA to mA flows.



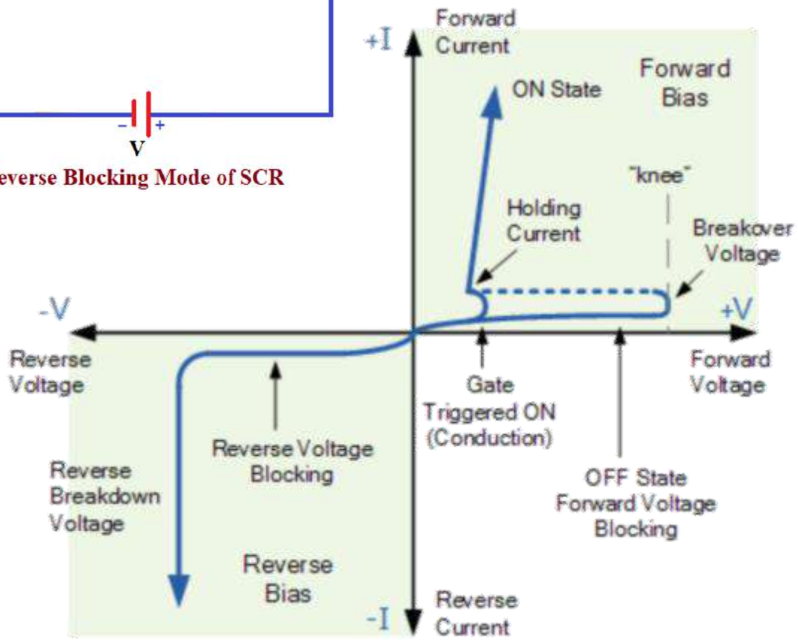
Reverse Blocking Mode of SCR



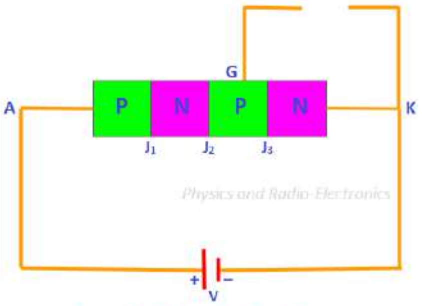
- *As Va increses barrier width of J_1 and J_3 increases. A point will reach where this junction will have avalanche break down at V_{BR} and hence Ia increses raidly=> heat increses=> temp=> and SCR may damage*
- *So applied voltage should be less than VBR to avoid damage of SCR.*
- *After breakdown of J_1 & J_3 current is limited only by the load resistance*



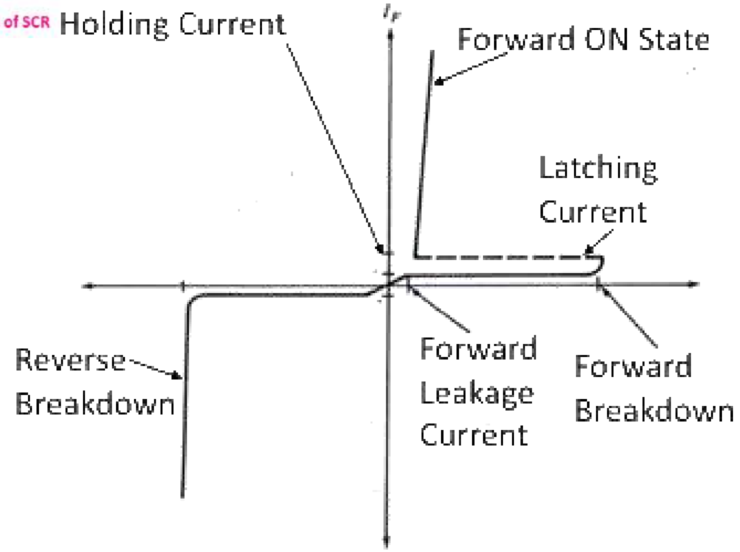
Reverse Blocking Mode of SCR



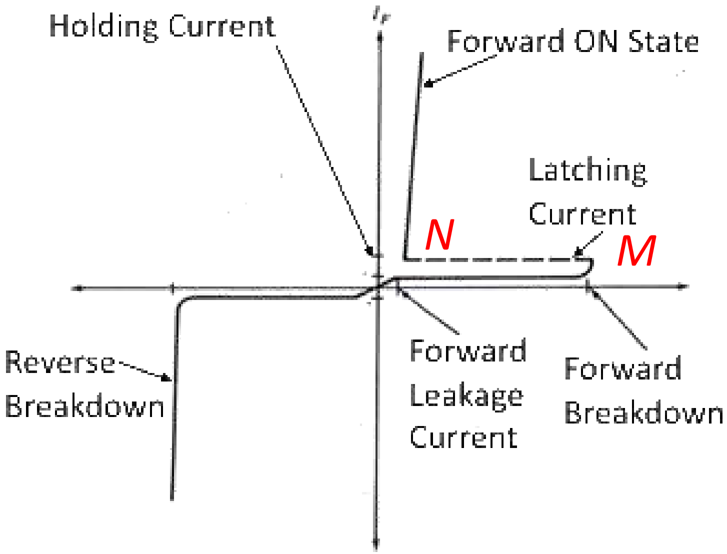
- Forward Blocking mode:
- J_1 and J_3 are forward biased and J_2 is reverse biased.
- So entire voltage will be drop across J_2
- Small forward leakage current (I_{FL}) will flows.
- As Va increases a point is reached where avalanche break down happens in J_2 and SCR starts conducting. This voltage is called V_{bo} (Forward break over voltage)



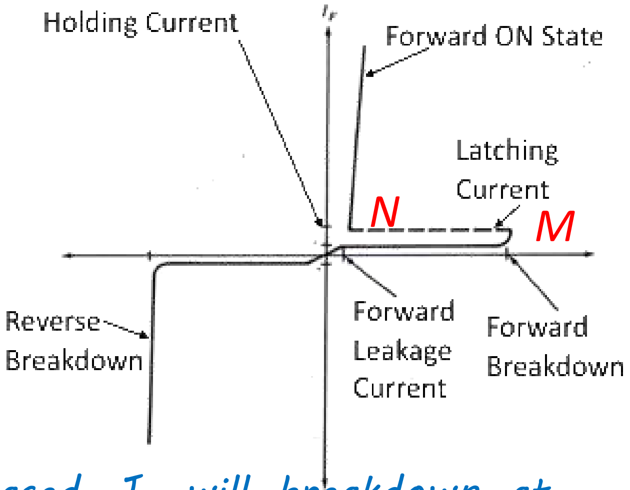
Forward Blocking Mode of SCR



- (III)Forward conduction mode:
- As only J2 needs to be break down in this case
- $V_{Bo} < V_{BR}$
- After reaching V_{Bo} thyristor turns ON & shifts from point M to N and then to a point any where between N & K.
- After breakdown voltage drop across SCR drops to a very less value and current is limited onlly by the load.
- After breakdown Ia increases=> heat increase=> temp increases=> SCR may damage
- This method is not used in practice

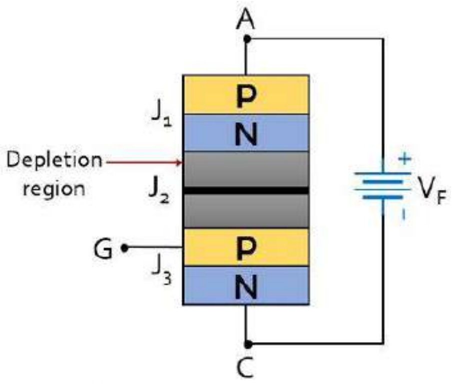


- Thyristor turn-on method:
- (1) Forward voltage triggering
- (2) Gate triggering
- (3)dV/dT triggering
- (4) Thermal triggering
- (5) Light triggering
- (1) Forward voltage triggering:



- Without applying gate pulse if voltage Va is increased J_2 will breakdown at V_{bo}.
- At forward breakover voltage the characteristics curve break over and shifts to its on-state position with breakover current I_{bo} to point N
- This method is never employed in practice as they may destroyed the device due to avalanche breakdown is huge temp produced.
- As $V_{BO}<V_{BR}$
- V_{Bo} represents rating of SCR as applied voltage should be less than this
- SCR can now be turned off only by reducing the anode current bellows a certain value called holding current (I_h)

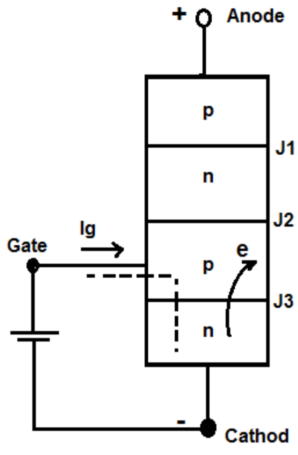
- (2) Thermal Triggering
- During forward blocking moode entire voltage appears across J_2 and small leakage current flows.
- If temp of J_2 increases=> no of (thermal) carriers increases=> IL increses=> losses increses=> temp increases=> no of carriers increases=> width of depletion region decreases=> Il increses=> losses increases=> temp increses=> carrires increses
- This is cumulative process and finally reverse biased junction J_2 vanishes and SCR will turn On.
- This method is not used in practice

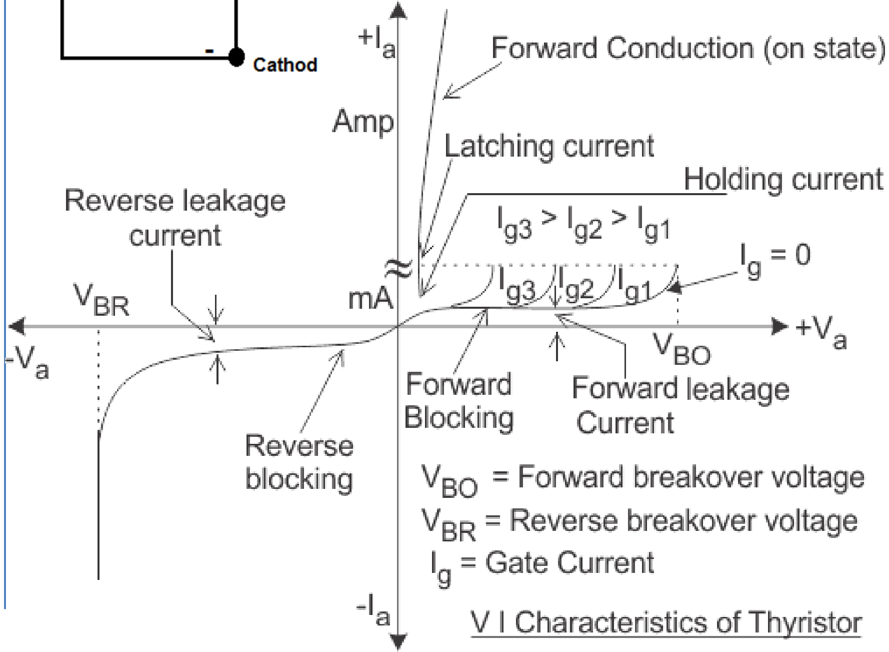


SCR with no any voltage applied at the gate

Circuit Globe

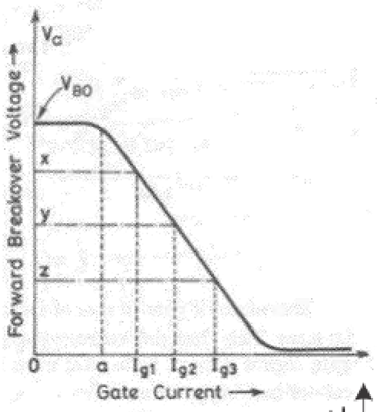
- *(3) Gate triggering*
- *It is most usual method of firing the forward biased SCR.*
- *When a positive gate pulse is applied, a significant number of electrons from n2 layer crosses J3 as N2 is heavily doped as compared to P2.*
- *After crossing junction J3 these electrons diffuse through P2 Layer. The electrons are then swept across junction J2 into the n1 layer.*
- *The electrons in n1 layer reduce the positive space charge in the n1 side of J2 as a result barrier width (J2) decreases and breakdown happens at a lower voltage.*
- *Higher the gate current lower the forward break over voltage*

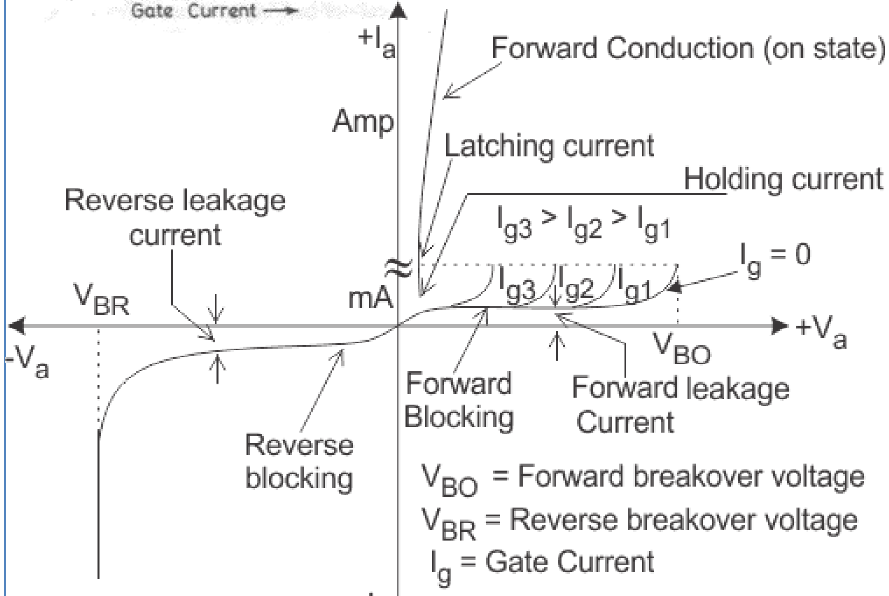




V I Characteristics of Thyristor

- Once the breakdown happens Ig is not required to keep it on and device remains in ON state.
- Latching Current is the minimum value of anode current which must be attained during the turn On process to maintain conduction even when the GATE signal is removed.
- So, Gate pulse should have sufficient width so that Ia reaches to I_L otherwise thyristor will not turn ON.
- Once the thyristor Turns ON Gate loses its control
- Holding current (I_h) is defined as the minimum value of anode current below which thyristor will turn off from off state





V I Characteristics of Thyristor

- **(4) dv/dt triggering:**
- Due to space charge existing in the depletion region J_2, it behaves as a capacitor.

$$i_c = \frac{dQ}{dt} = \frac{d}{dt}(C_j \cdot V_a)$$

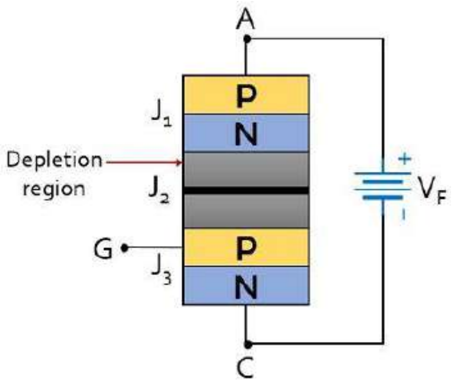
$$i_c = C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt}$$

- As the junction capacitor is nearly constant,, $dc_j/dt=0$

$$i_c = C_j \frac{dV_a}{dt}$$

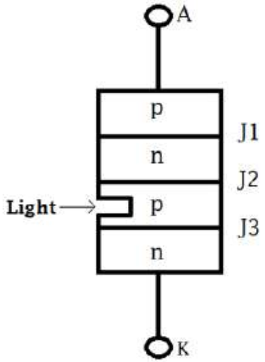
$$i_c \propto \frac{dV_a}{dt}$$

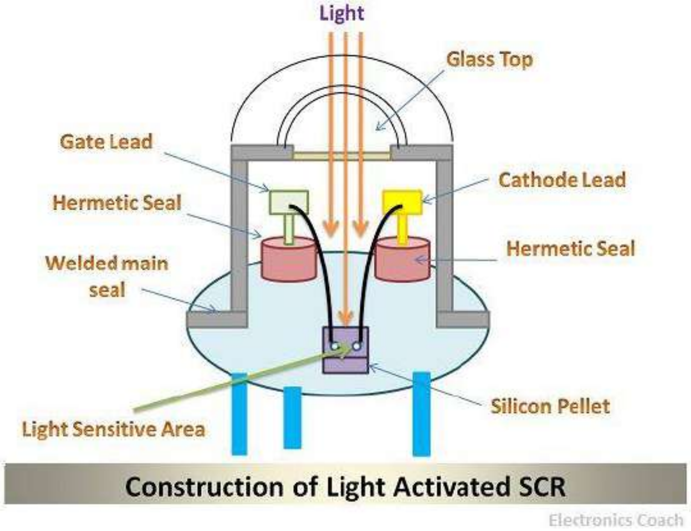
- Ic can play the role of gate current and hence can turn on SCR



SCR with no any voltage applied at the gate

- (5) Light triggering
- A niche is made in the inner P-Layer
- When the niche is irradiated, free charge carriers (Pairs of holes and electros) are generated just like when gate signal is applied.
- A pulse of light of appropriate wave length is guided by optical fibers for irradiation
- Such a thyristor is called LASCR (Light Activated SCR)
- Light triggering Thyristor has an advantage of electrical isolation between power and control circuit.
- Widely used in HVDC transmission system





Construction of Light Activated SCR

- Two Transistor model of SCR
- The regenerative or latching action due to positive feedback can be explained using a 2 transistor model of sCR
- SCR is equivalent to PNP & NPN transistor connected in regenerative or +ve feedback

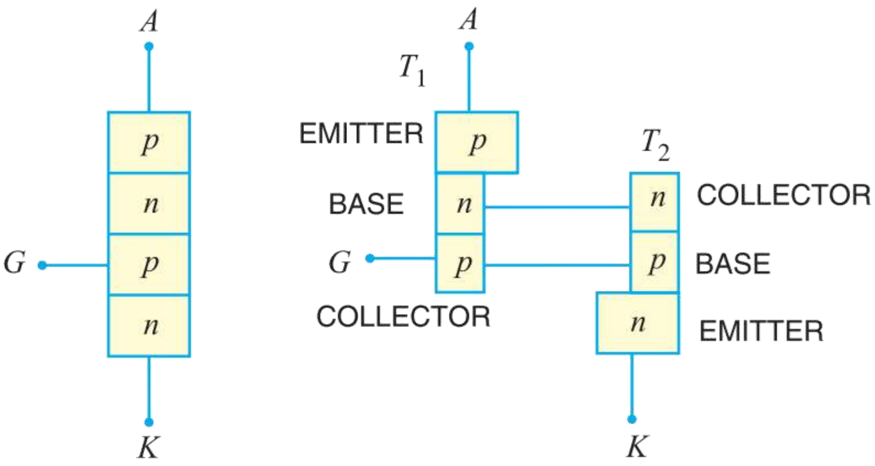
$$I_c = \alpha I_E + I_{CB0}$$

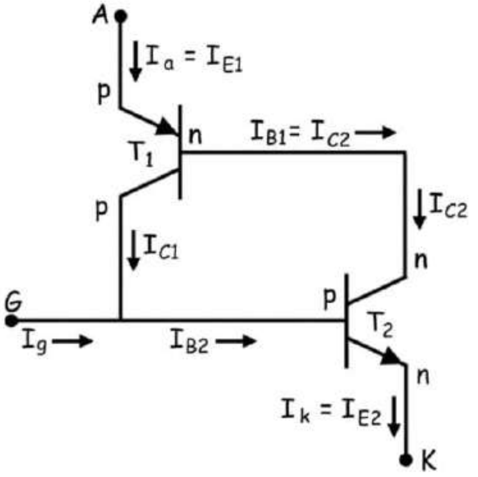
$$I_c = \beta I_B$$

Cut-off=> $I_c = I_{CB0}$

Active=> $I_c = \alpha I_E + I_{CB0}$

Saturation=> $I_c = I_E$



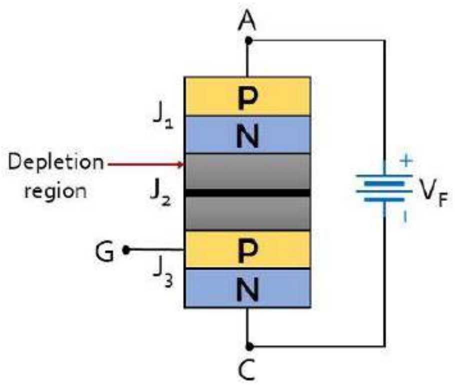


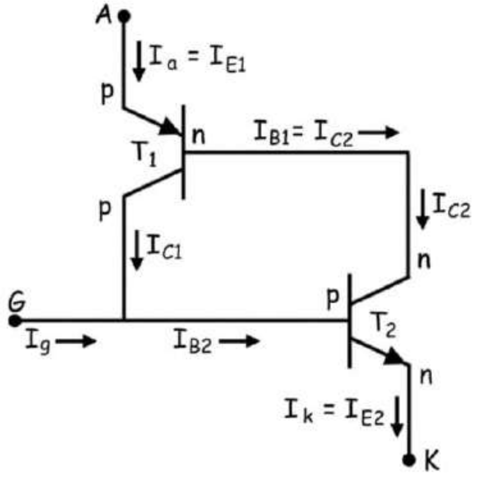
- Two Transistor model of SCR
- As $V_b\uparrow \Rightarrow I_b\uparrow \Rightarrow$ Barrier width$\downarrow \Rightarrow I_E\uparrow$

$$I_c = \alpha I_E$$

$$I_c = \beta I_B$$

- If I_b increase gradually => barrier width decreases and alpha increases





- Two Transistor model of SCR

$$I_c = \alpha I_E + I_{CB0}$$

$$I_{c1} = \alpha_1 I_A + I_{CB01}$$

$$I_{c2} = \alpha_2 I_K + I_{CB02}$$

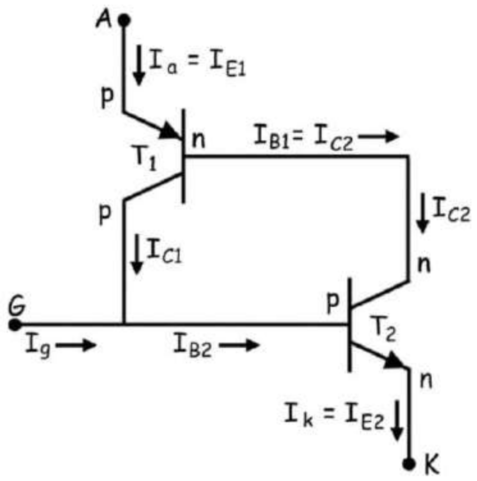
$$I_k = I_G + I_A \qquad I_A = I_{C1} + I_{b1}$$

$$I_A = \alpha_1 I_A + I_{CB01} + \alpha_2 I_K + I_{CB02}$$

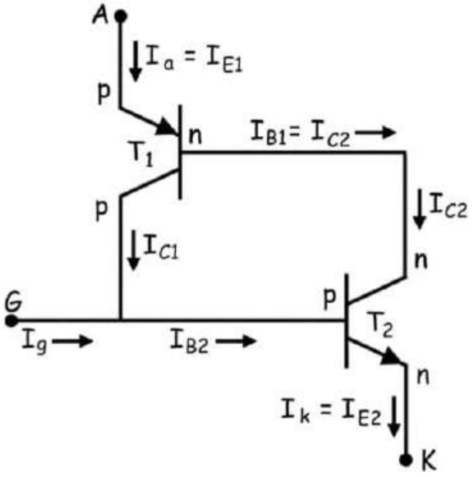
$$I_A = \alpha_1 I_A + I_{CB01} + \alpha_2 (I_G + I_A) + I_{CB02}$$

$$I_A = \frac{\alpha_2 I_G + I_{CB01} + I_{CB02}}{1 - (\alpha_1 + \alpha_2)}$$

- If $(\alpha_1+\alpha_2)=0$ => I_A=infinite => Thyristor act as a close switch
- Current is limited by load only

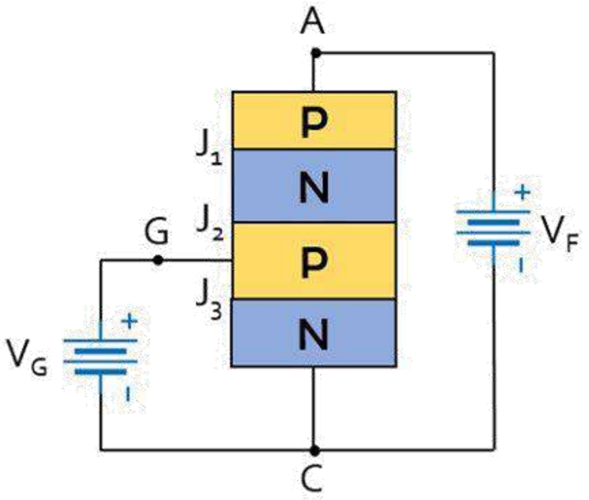


- Two Transistor model of SCR
- When Ig is suddenly applied say 0 to 1mA:
- I_{E2} or I_k => α_2 => I_{c2} => I_b => I_{E1} => α_1 => I_{c2}
- α_1 varies with $I_A = I_{E1}$
- α_2 varies with $I_K = I_A + I_G$

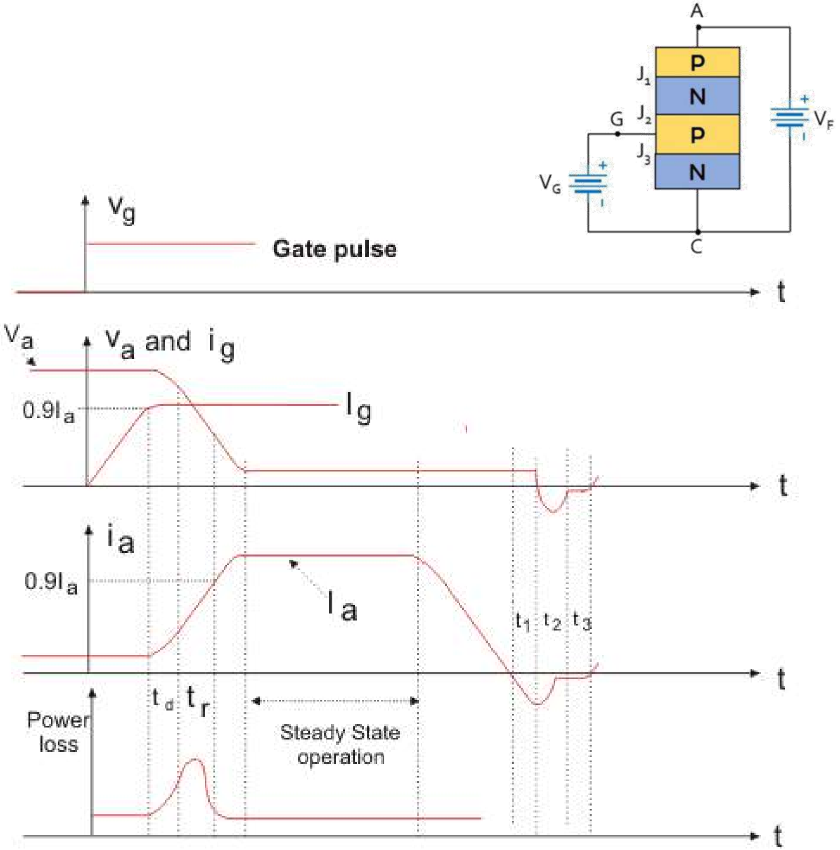


- **Switching characteristics of SCR:**
- Time variation of current through & Voltage across the SCR with time during turn-on and turn-off process is given by dynamic or switching characteristics of SCR.
- **(a)Switching characteristics during turn-on:**
- When a forward biased thyristor is turn-on, thyristor takes some time to change from blocking state to final On state

$$t_{on} = \text{Delay time}(t_d) + \text{Rise time}(t_r) + \text{spread time}(t_p)$$



- Switching characteristics of SCR:
- Delay time (td): It is measured from the instant gate current reaches 90% of Ia to the instant at which anode current reaches 0.1Ia
- Also defined as time during which anode voltage falls from Va to 0.9 Va
- Delay time may be reduced by applying high magnitude gate current and high forward voltage between anode and cathode.



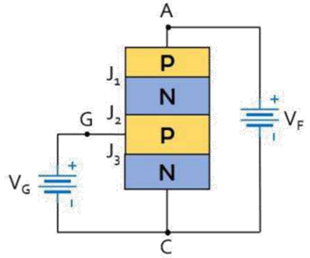
- Switching characteristics of SCR:
- Rise time (tr): Anode current reaches from 0·1Ia to 0·9 Ia·
- Va drops from 0·9Va to 0·1Va
- Delay time may be reduced by applying high magnitude gate current and high forward voltage between anode and cathode·

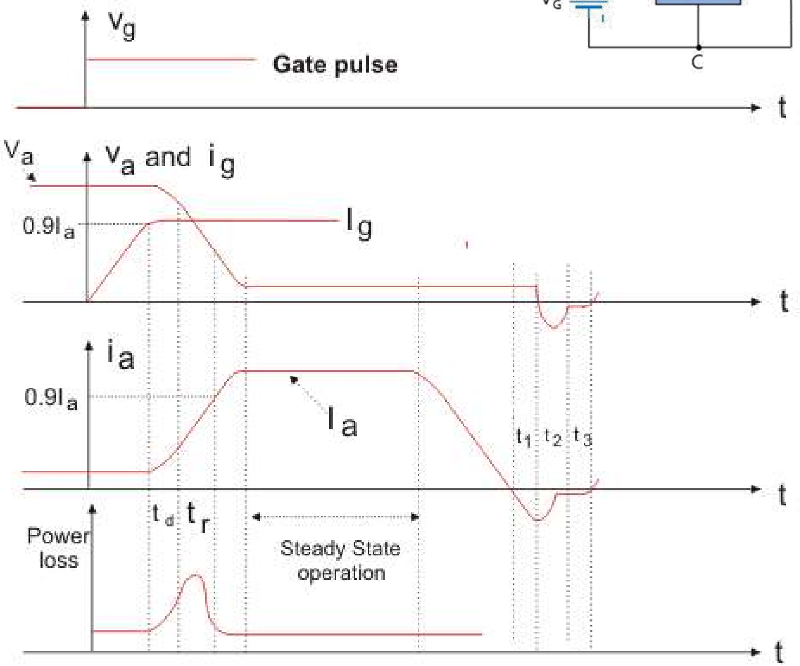
→ $t_r \propto \frac{1}{I_g} \propto \frac{1}{\text{build up rate of } I_g}$

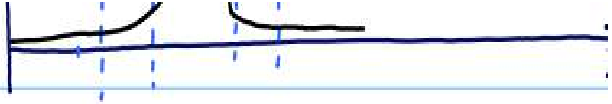
→ t_r mainly depends on the nature of anode ckt

→ t_r ↑ for RL ckt

t_r ↓ for RC ckt







(iii) <u>spread time</u> (t_p):-

$i_a \rightarrow 0.9 I_a$ to I_a

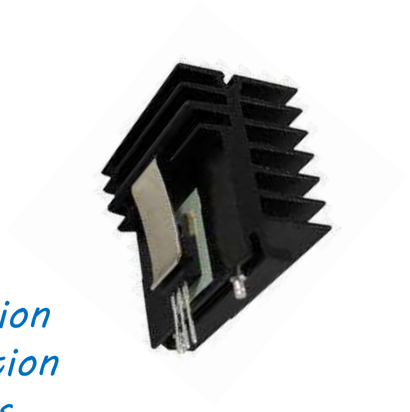
$v_a \rightarrow 0.1 V_a$ to on-state voltage drop (1 to 1.5V)

→ During this time the conduction spreads over the entire cross-section of the cathode of SCR

→ t_p depends on area of cathode & structure of the gate

→ I_g is generally 3 to 5 times the minimum gate current to turn on SCR.

- Protection of SCR:
- (a) Over current Protection
- Varistor (Voltage dependent resistor)
- (b) Over current protection
- Circuit breaker=> overload protection
- Fast acting current limiting fuse=> Short circuit protection
- (c) Thermal protection
- Heat sinks (Aluminum)
- (d)dv/dt protection
- Snubber circuit
- di/dt protection
- Series inductor
- Gate protection:
- R_2-> Over current protection
- ZD-> Over voltage protection
- C_1-> To bypass noise signals
- R_2-> To bypass thermally generated leakage current across junction J_2 ;Improves thermal stability



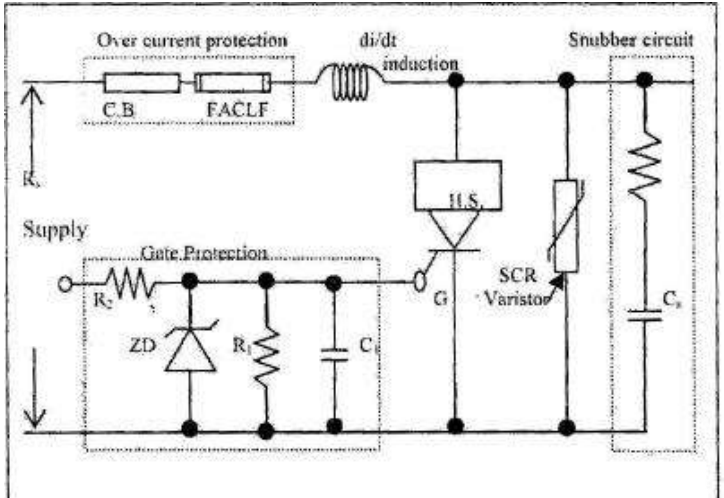


Figure: Circuit components showing the thyristor protection

- **Protection of SCR:**
- Over voltages are due to inductance of the line i.e., $V=L\cdot di/dt$ when suddenly open circuited.
- By increasing the rising time of V, dv/dt can be decreased. This can be done by using a capacitor across SCR.
- When the SCR is turned on, capacitor will discharge through SCR at a faster rate (di/dt) and may spoil the thyristor.
- So a resistor is connected in series with capacitor to limit this current.

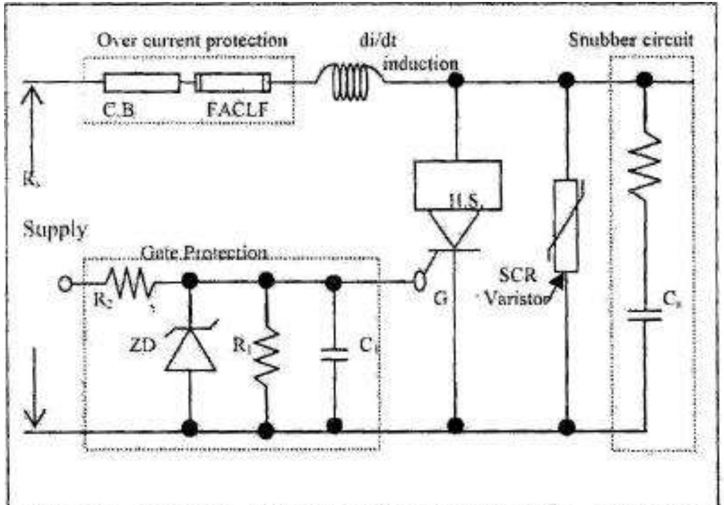
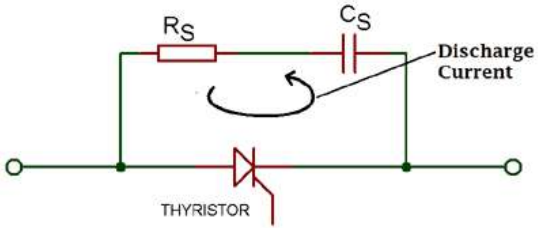


Figure: Circuit components showing the thyristor protection



- Snubber design:
- If the voltage build up across capacitor is assumed zero at the time of connecting supply, then capacitor is short circuited.

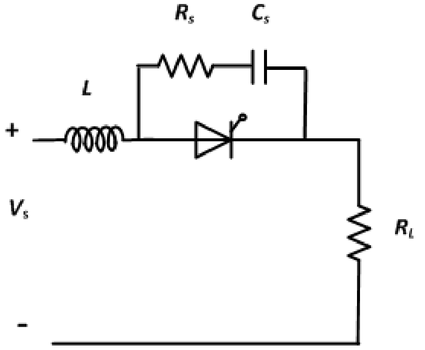
$$L\frac{di}{dt}+(R_S+R_L)i=V_s$$

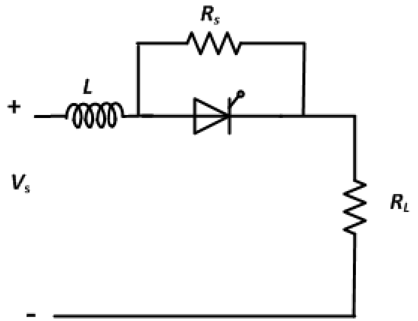
$$i=\frac{V_S}{(R_S+R_L)}\left[1-e^{\frac{-t}{\tau}}\right] \text{where } \tau=\frac{L}{(R_S+R_L)}$$

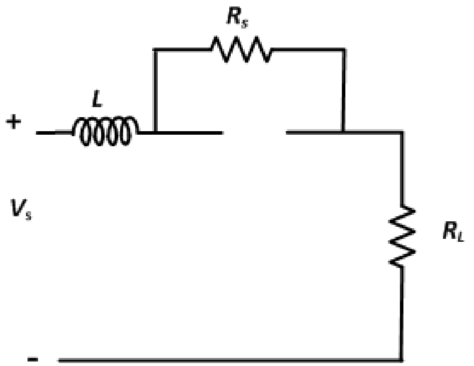
$$i=\frac{V_S}{(R_S+R_L)}\left[1-e^{\frac{-t(R_S+R_L)}{L}}\right]$$

$$\frac{di}{dt}=\frac{V_S}{(R_S+R_L)}\left[e^{\frac{-t(R_S+R_L)}{L}}\right]\times\frac{(R_S+R_L)}{L}$$

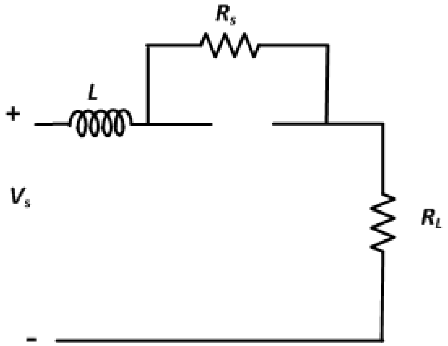
$$\frac{di}{dt}=\frac{V_S}{L}\cdot e^{\frac{-t(R_S+R_L)}{L}}$$

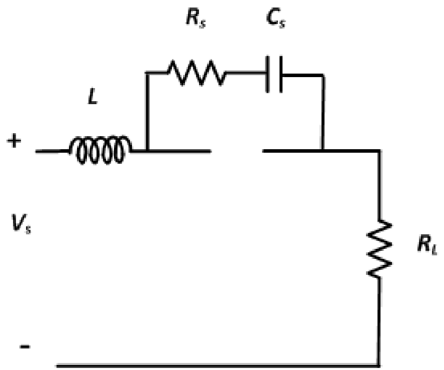






- *Snubber design:*





$$\frac{di}{dt}=\frac{V_S}{L}\cdot e^{\frac{-t(R_S+R_L)}{L}}$$

$$\text{at } t=0 \left.\frac{di}{dt}\right|_{t=0}=\frac{V_S}{L}$$

$$\text{So, } L=\frac{V_S}{di/dt}$$

$$V=i\cdot R_s$$

$$\frac{dV}{dt}=R_s\cdot\frac{di}{dt}$$

$$R_s=\frac{(dv/dt)}{(di/dt)}$$

$$Ri+L\frac{di}{dt}+\frac{1}{c}\int i\cdot dt=V_S$$

$$L\frac{d^2i}{dt^2}+R\frac{di}{dt}+\frac{i}{c}=0$$

$$\frac{d^2i}{dt^2}+\frac{R}{L}\frac{di}{dt}+\frac{i}{Lc}=0$$

$$S^2+2\xi\omega_n s+\omega_n^2=0$$

$$R=2\xi\sqrt{\frac{L}{C}}$$

- Firing circuit of SCR:
- Resistance and resistance capacitance firing circuit

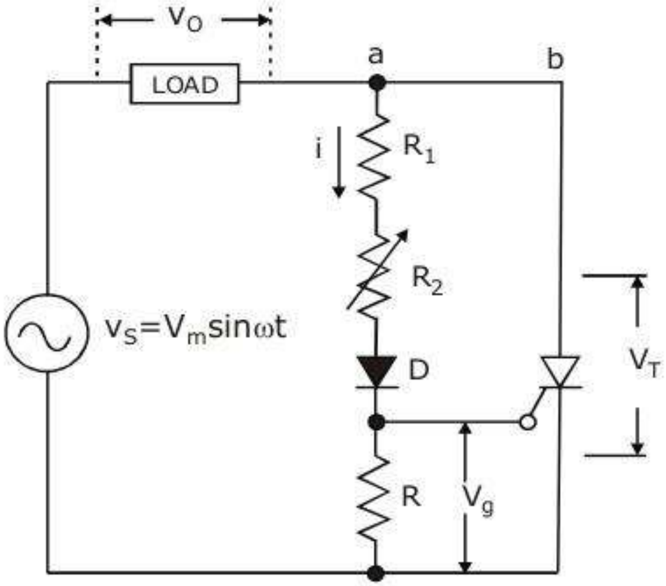
- Simplest and economical
- Limited range of firing angle (0 to 90°)

- R1 is used to limit the gate current $I_{gm} \geq Vm/R_1$

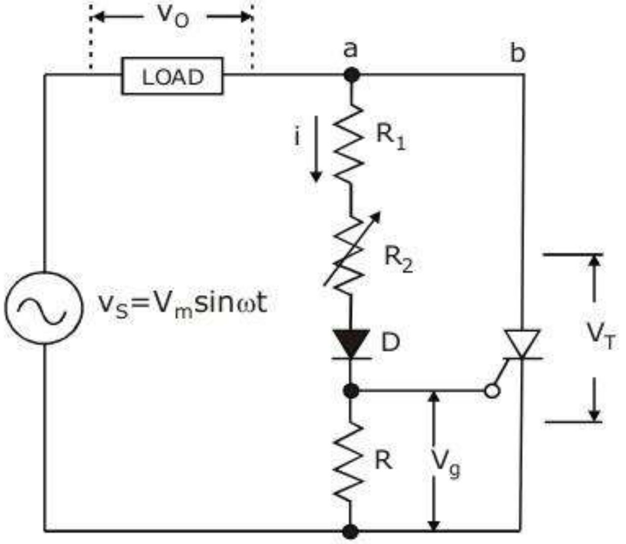
- Resistance R should have such a value that maximum voltage drop across it does not exceed maximum permissible gate voltage.

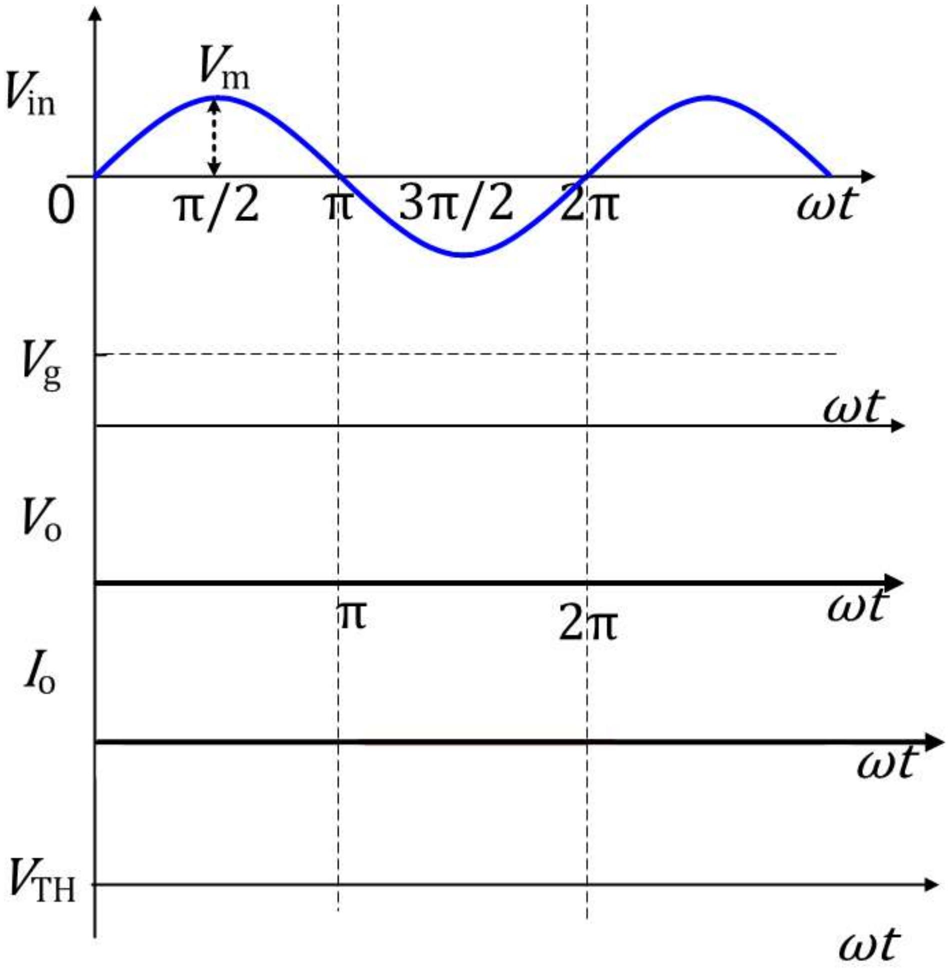
- Firing angle is controlled using Resistance R_2.

R Triggering Circuit

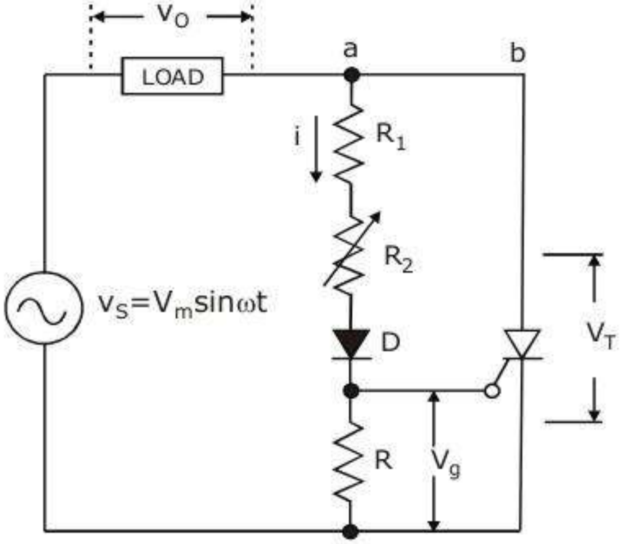


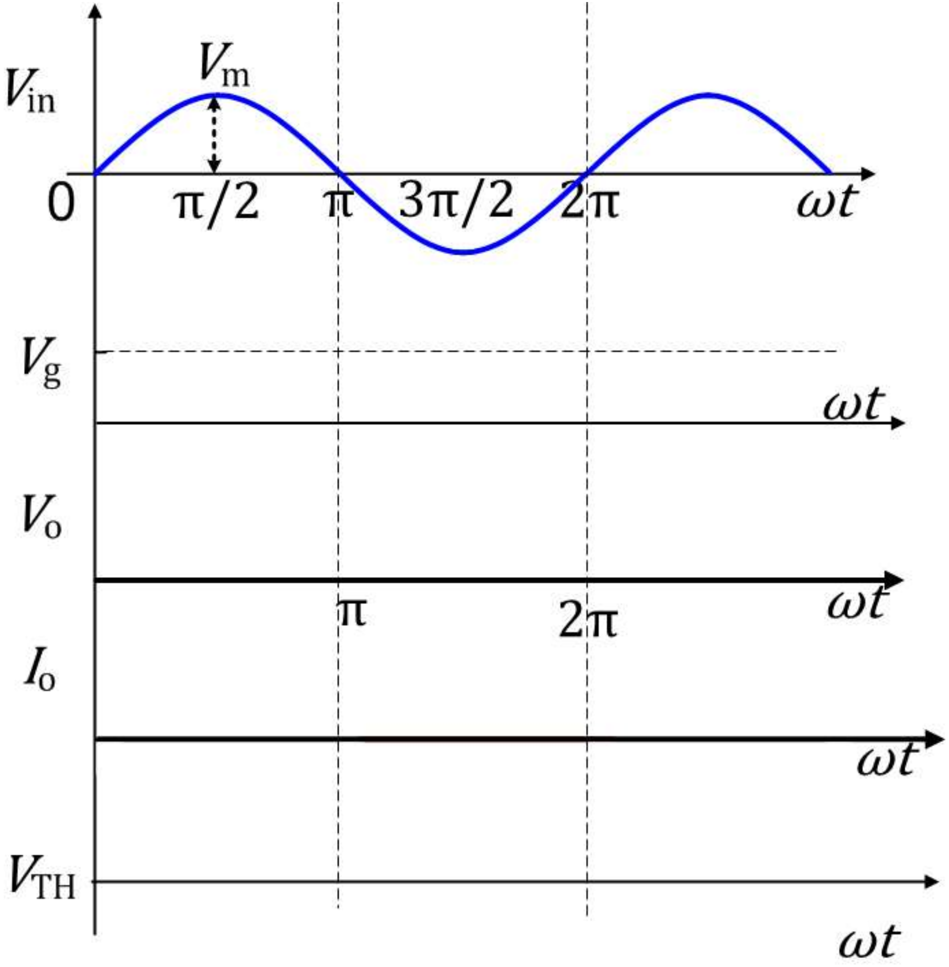
R Triggering Circuit



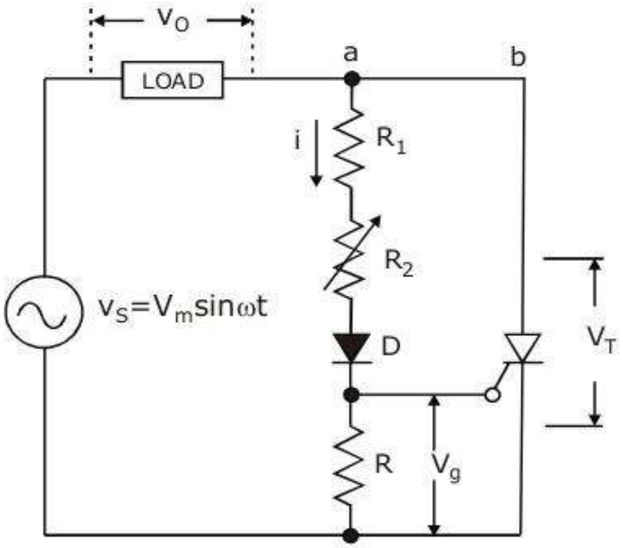


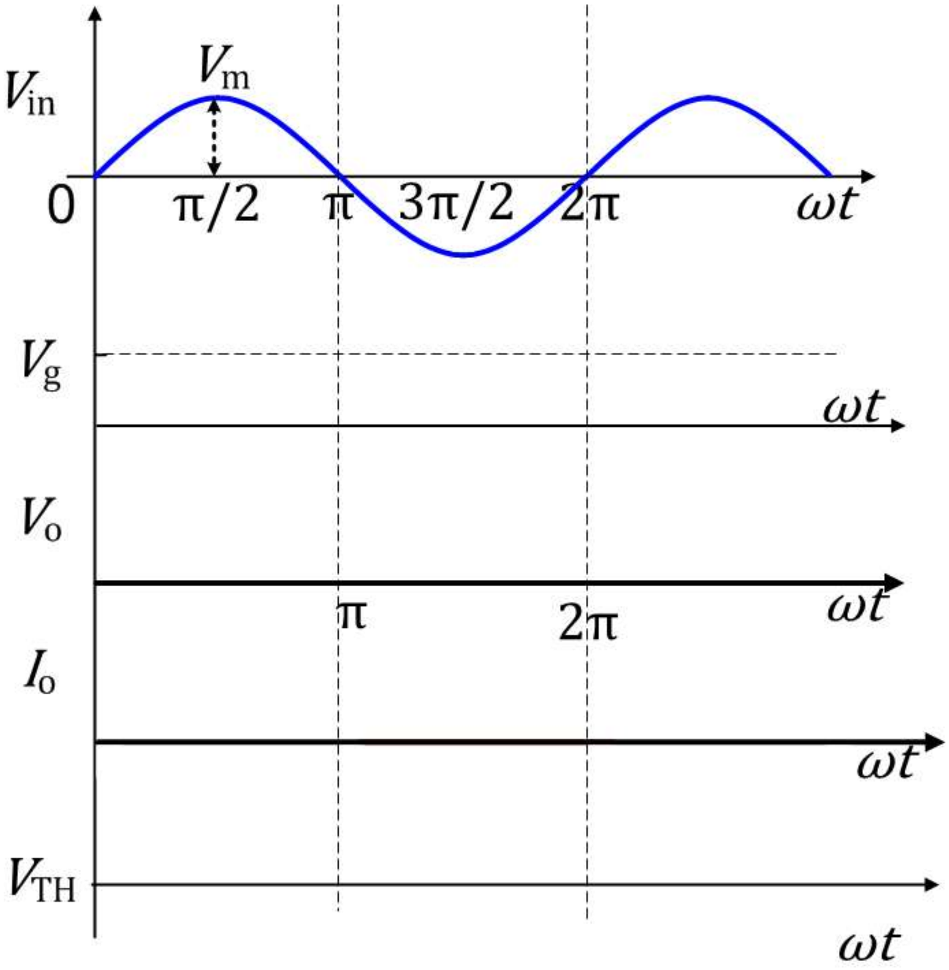
R Triggering Circuit





R Triggering Circuit





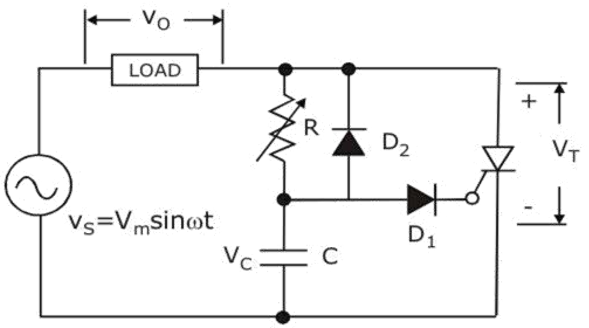
- RC Triggering:

- The Limited range of firing angle by resistance firing circuit can be overcome by RC firing circuit.

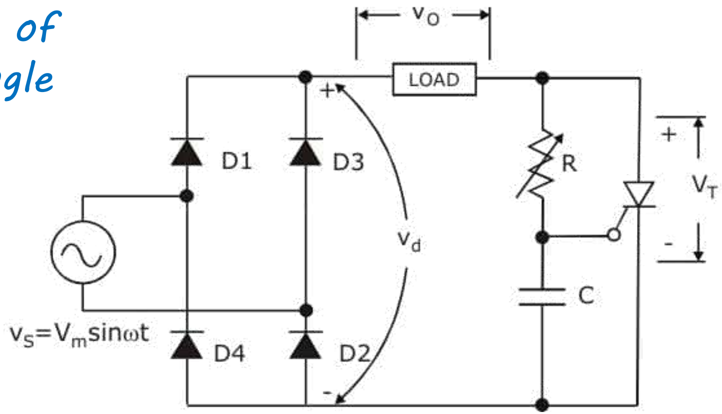
- When capacitor is charges to gate threshold voltage V_{gt} thyristor will triggered and turned ON

- By varying the resistance R charging time of capacitor can be controlled and hence firing angle alpha can be varying.

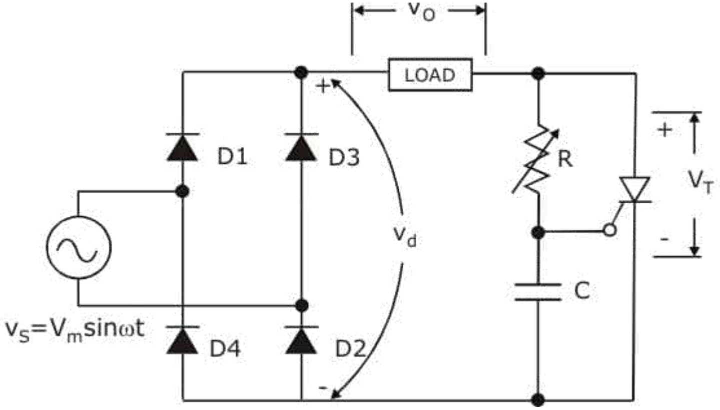
RC Half Wave Circuit

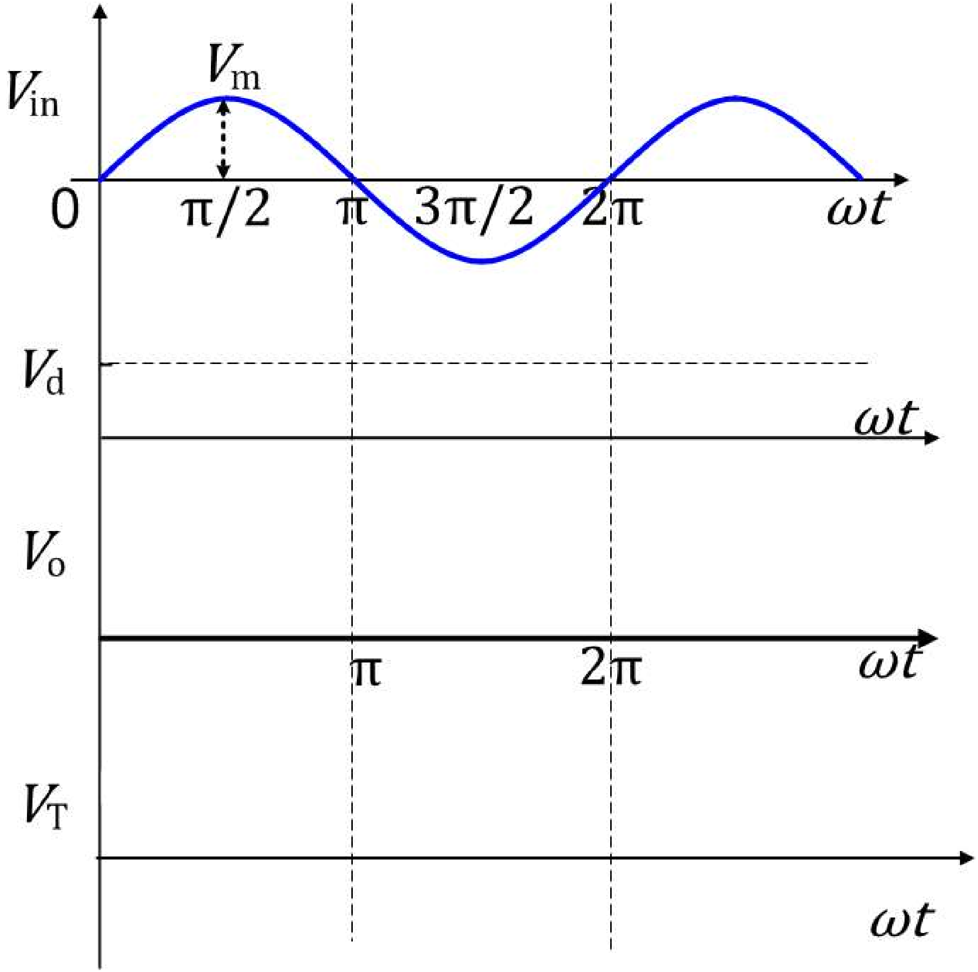


RC Full Wave Circuit

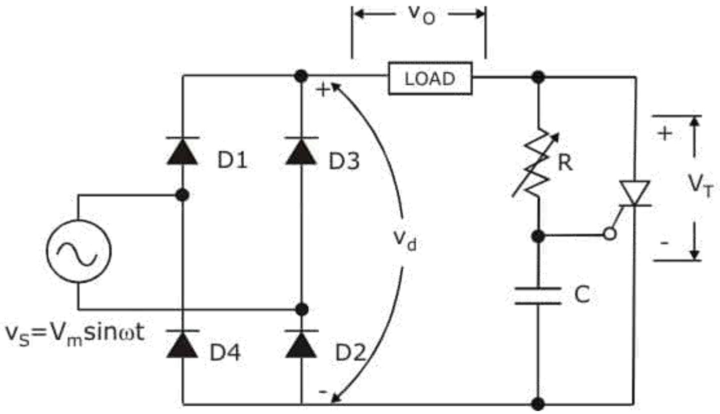


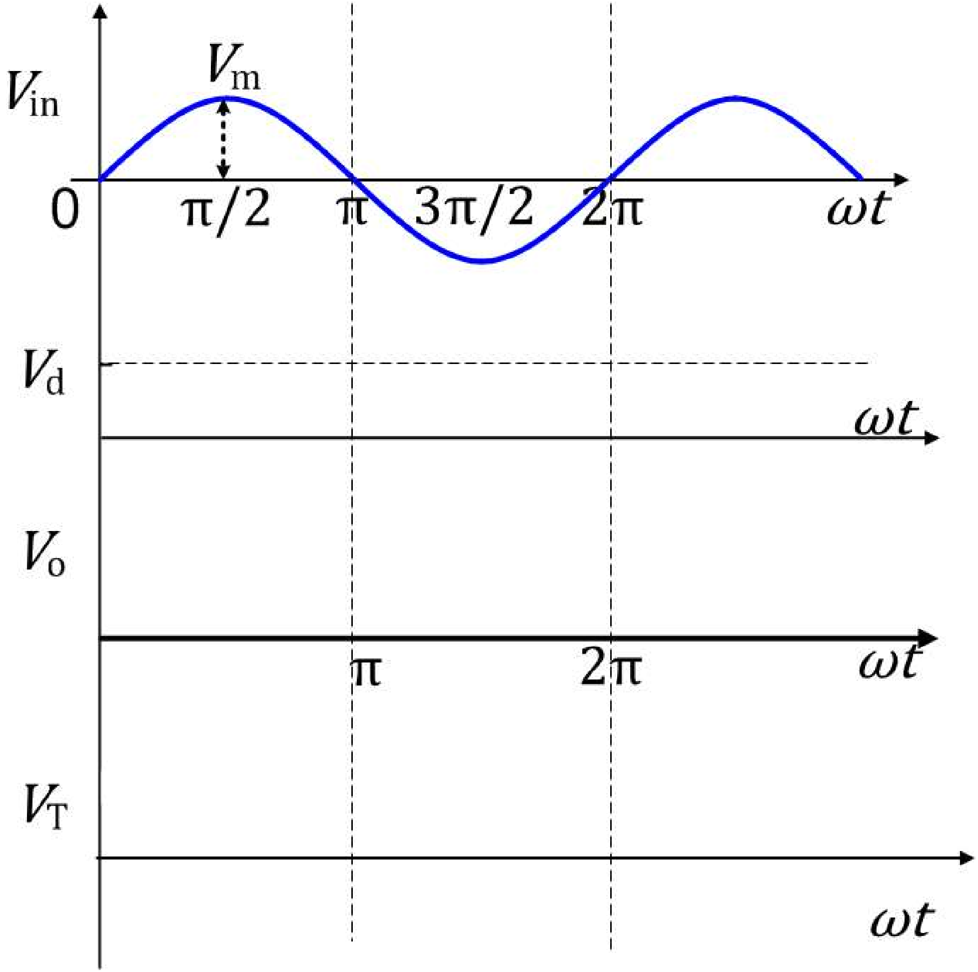
RC Full Wave Circuit



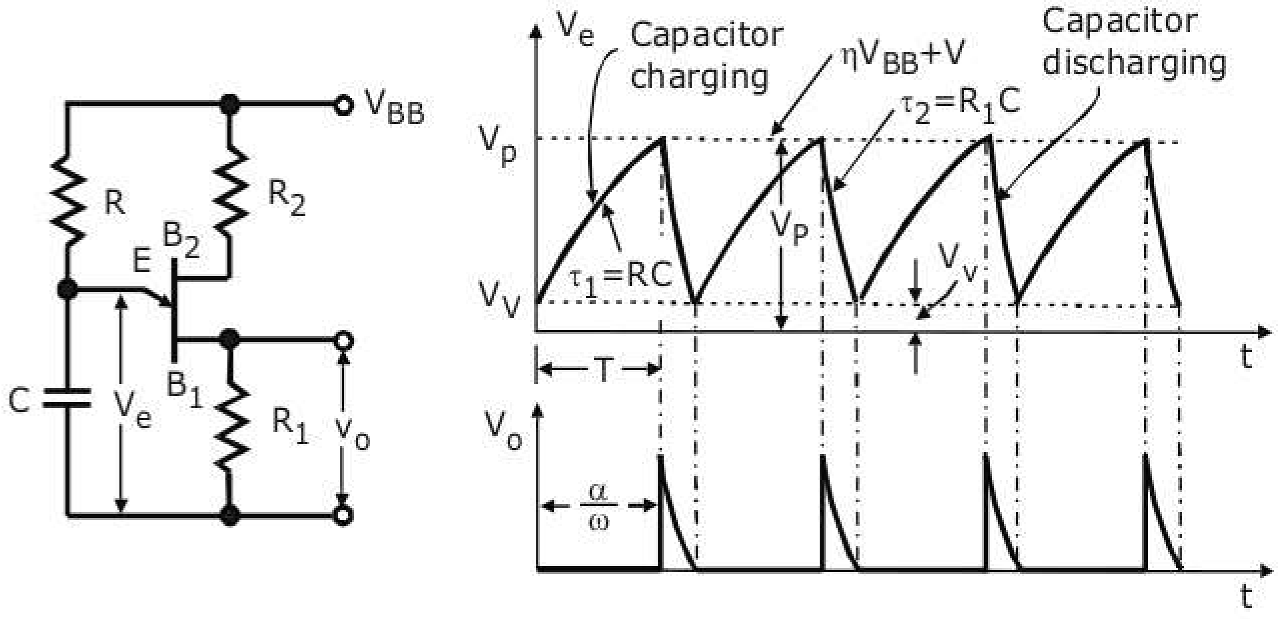


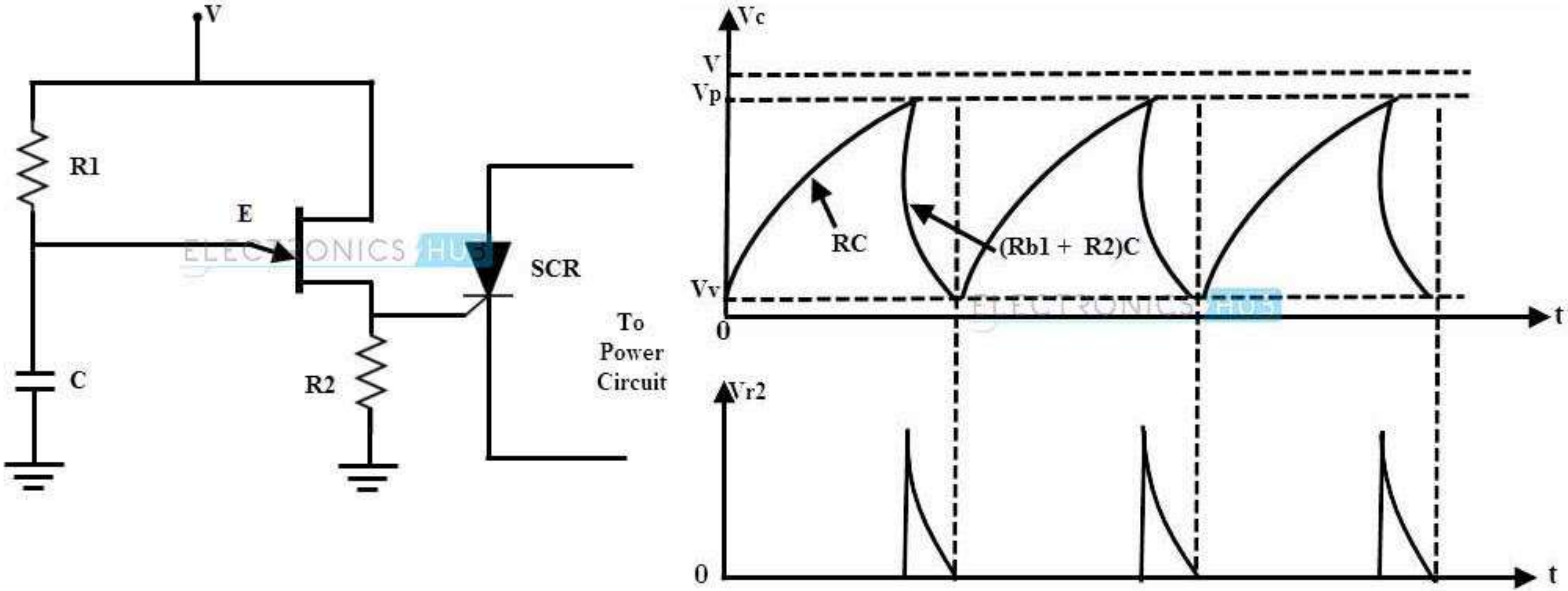
RC Full Wave Circuit





UJT Relaxation Oscillator





V
R1
E
SCR
C
R2
To
Power
Circuit
Vc
V
Vp
RC
(Rb1 + R2)C
Vv
0
t
Vr2
0
t

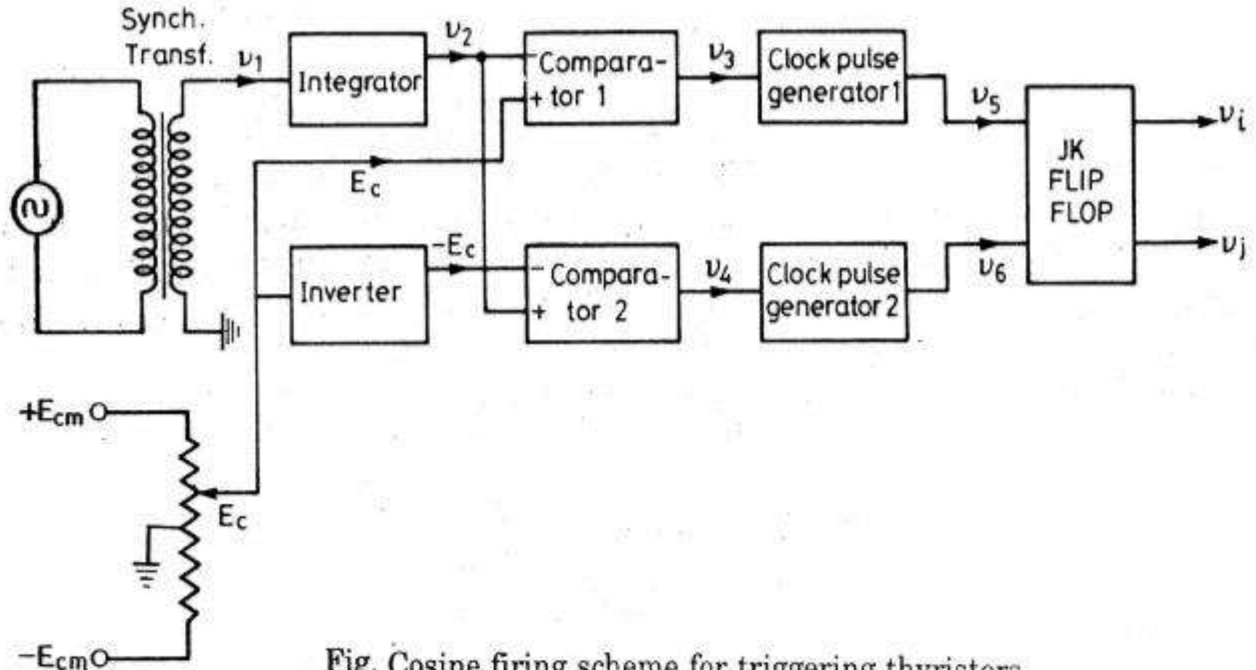


Fig. Cosine firing scheme for triggering thyristors.

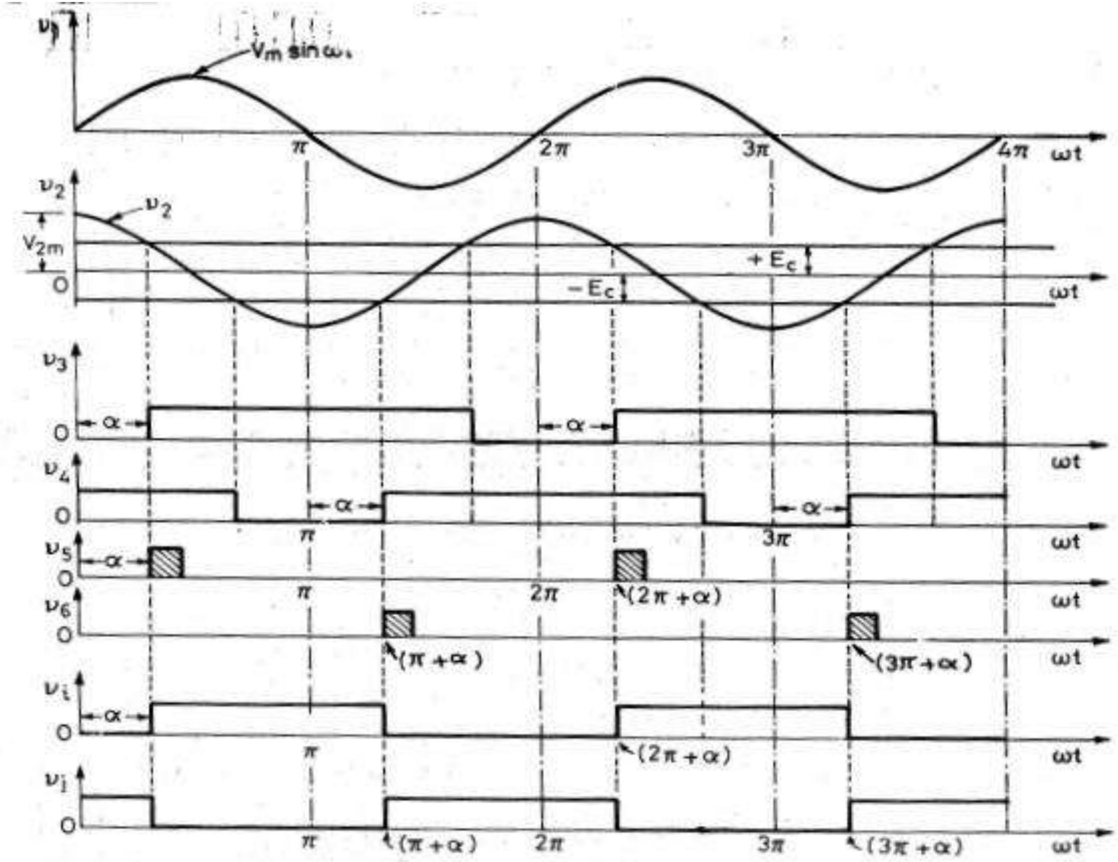


Fig. Waveforms for cosine firing scheme

End

THANK YOU