MODULE-1

Introduction: History, Power Electronic Systems, Power Electronic Converters and Applications. Thyristors: Static Anode-Cathode characteristics and Gate characteristics of SCR, Turn-On methods, Turn-Off mechanisms, Turn-Off Methods: Natural and Forced Commutation – Class A and Class B types, Gate Trigger Circuit: Resistance Firing Circuit, Resistance capacitance firing circuit, Unijunction Transistor: Basic operation and UJT Firing Circuit.

1.1 INTRODUCTION:

Electrical engineering field may be divided into three areas of specialization:

*Electronics *Power *Control

Electronics with the study of solid state semiconductor devices and circuits for the processing of information at low power levels. Power area deals with both static and rotating power equipment for the generation, transmission distribution and utilization of electrical power. The control area deals with the stability and response characteristics of closed loop systems using feedback on a continuous or sampled-data basis.

Power electronics deals with the use of electronics for the control and conversion of large amounts of electrical power. The design of power electronics involves interactions between the source and the load, and utilizes small-signal electronic control circuits as well as power semiconductor devices.

1.2 POWER ELECTRONIC SYSTEMS: The block diagram of a generalized power electronic system is shown in figure 1.1. Power source may be an ac supply system or dc supply system. (In India, 1-phase and 3-phase 50Hz ac supplies are readily available).

Power modulator performs one or more of the following functions:

- Converts electrical energy of the source as per the requirement of the load.
- Selects mode of operation of the motor, i.e. motoring or breaking.
- Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.
- During transient operations, such as starting, breaking and speed reversal, it restricts source and motor currents within permissible values.

Motors commonly used in power electronic systems are: DC Motors, Induction Motors, Synchronous Motors, Stepper Motors, Brushless Motors and Switched Reluctance Motors.

Power modulators are controlled by a control unit. Control unit operates at much lower voltage and power levels. Sensing unit measures the load parameters, say speed in case of a rotating machine and compares it with the command. The difference of two parameters processed by the control unit now controls the turn-on of power semiconductor devices which are used in power modulators.

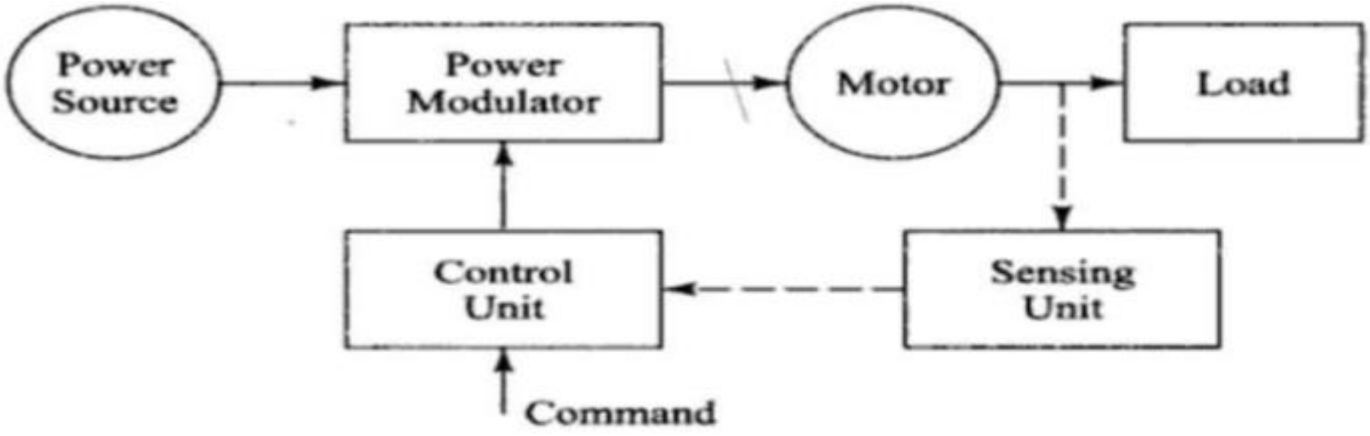


Fig. 1.1: Block diagram of power electronic system

1.3 POWER SEMICONDUCTOR DEVICES: Power Semiconductor Devices can be classified into 3 categories based on degree of controllability:

1. Uncontrolled turn-on and turn-off devices: The on & off states are controlled by power circuit. Ex: Diode.
2. Controlled turn-on and uncontrolled turn-off devices: Turned on by a control signal & turned off by power circuit. Ex: Thyristors (SCR).
3. Controlled turn-on and turn-off devices: Turned on & turned off by controlled signals. Ex: BJT, MOSFET, GTO, SITH, SIT, IGBT.

BJT, MOSFET, MCT & IGBT can withstand unipolar voltage whereas thyristors and GTOs can withstand bipolar voltages. BJT, MOSFET, SIT & IGBT requires continuous signal for keeping them in turn on state but SCR, GTO & SITH requires pulse-gate signal for turning them ON and once these devices are turned ON, gate-pulse is removed.

TRIAC & RCT possess bidirectional current capability whereas all other devices are unidirectional current devices.

Thyristors are used for high power low frequency applications and are available with 8000V and 4000A ratings. GTOs are used for large voltage-fed inverter applications and are available with 6000V and 6000A ratings.

Insulated Gate Bipolar Junction Transistor (IGBT) are available with 3500V and 1200A ratings. Integrated Gate Commutated thyristor (IGCT) are available with 6000V and 6000A ratings.

1.4 POWER ELECTRONIC CONVERTERS: Power electronic circuits are also called as power converters. A converter uses matrix of power semiconductor switches to convert electrical power at high efficiency. The converter system is comprised of switches, relative components L, C, and transformers. The converters are generally classified into following five broad categories:

1. Phase Controlled Rectifiers (AC to DC converters): These controllers converts fixed ac voltage to a variable dc output voltage. These converters takes power from voltage / current sources of single or multiple phases and delivers to a load. The output is low-ripple DC voltage or DC current. These controller circuits use line voltage for their commutation. Hence they are also called as line commuted or naturally commuted ac to dc converters. These circuits include diode rectifiers and single /three phase controlled circuits.

Applications: DC motor drives, High voltage dc transmission system, Battery Charger circuits, Regulated DC power supplies, Wind generator converters.

2. Choppers (DC to DC converters): A chopper converts fixed dc input voltage and to a variable dc output voltage. The dc output voltage may be different in amplitude than the input source voltage. Choppers are designed using semiconductor devices such as power transistors, IGBTs, GTOs, Power MOSFETs and thyristors. Output voltage can be varied steplessly by controlling duty ratio of the device from a control circuit. Chopper has either a battery, a solar powered dc voltage source or line frequency derived from dc voltage source.

Applications: DC drives, Subway cars, Switch mode power supplies, Battery driven vehicles, Electric traction.

3. Inverters (DC to AC converters): An inverter Converts fixed dc input voltage into an ac output voltage of variable frequency and fixed or variable output AC voltage. An inverter has either a battery, a solar powered dc voltage source or line frequency derived from dc voltage source. Inverters are designed using semiconductor devices: Power transistors, IGBTs, GTOs, MOSFETs and thyristors. Inverters are widely used from very low-power portable electronic systems such as digital camera to a high power industrial systems.

Applications: Uninterruptible Power Supplies (UPS), Aircraft and space power supplies, HVDC system, Induction and synchronous motor drives, Induction heating supplies.

4. Cycloconverters (AC to AC converters): These circuits convert power at one frequency to output power at a different frequency through one stage conversion. These are designed using thyristors and are controlled by triggering signals derived from a control circuit. The output frequency is lower than the source frequency. Output frequency is a simple fraction such as 1/3, 1/5 and so on of source frequency. These are mainly used for slow speed, very high power industrial drives.

Applications: AC Drives like rotary kilns multi-MW ac motor drives, Traction vehicles.

5. AC Voltage Controllers (AC Regulators): These converters converts fixed ac voltage directly to a variable ac voltage at the same frequency using line commutation. These converters employs thyristorised voltage controller. Stepless control of output voltage can be obtained by controlling firing angle of converter thyristors by low power signals from a control circuit.

Applications: Speed control of fans & pumps, Lighting control, Electronic tap changers.

1.5 POWER ELECTRONIC APPLICATIONS: The applications of power electronics in various sectors are listed below:

- **DOMESTIC APPLICATIONS (Home Appliances):** Cooking Appliances, Air Conditioners, Refrigerators & Freezers, Vacuum Cleaners, Grinders & Mixers, Sewing machines etc.
- **COMMERCIAL APPLICATIONS:** Battery chargers, Computers, Electric fans, photocopiers, light dimmers, hand power tools, vending machines etc.
- **INDUSTRIAL APPLICATIONS:** Pumps, compressors, blowers and fans, machine tools, arc furnaces, induction furnaces, lighting control circuits, industrial lasers, induction heating, welding equipment, UPS, conveyors, cranes, dryers, paper mill machinery etc.
- **GAMES & ENTERTAINMENT:** Toys, TV's, Movie projectors etc.
- **AEROSPACE APPLICATIONS:** Space vehicle power systems, satellite power systems, aircraft power systems.
- **AUTOMOTIVE APPLICATIONS:** Alarms & Security systems, electric vehicles, audio and RF amplifiers, regulators.
- **MEDICAL APPLICATIONS:** Fitness Machines, Medical Instrumentation, Laser power supplies.
- **SECURITY SYSTEMS:** Alarms & Security systems, RADAR / SONAR.
- **TELECOMMUNICATIONS:** UPS, Solar power supplies, Wireless communication power supplies.
- **TRANSPORTATION:** Magnetic levitation, trains & locomotives, trolley buses, subways, traction control of electric vehicles, battery chargers for electric vehicles.
- **UTILITY SYSTEMS:** VAR Compensators, Supplementary energy systems (solar, wind).

1.6 THYRISTORS: 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. The thyristors has four or more layers and three or more junctions. The SCR is universally referred to as the *thyristor.*

1.6.1 PRINCIPLE OF OPERATION OF SCR: The structure and symbol of SCR is shown in figure 1.2. It is a four layered, PNPN switching device structure with three junctions J_1, J_2, J_3. It has three terminals, namely, the anode (A), cathode (K) and the gate (G).

When the anode is made positive with respect to the cathode, junctions J_1, & J_3 are forward biased and junction J_2 is reverse biased. Thus the junction J_2 because of the presence of depletion layer, will not allow any current to flow through the device. Only leakage current of small magnitude flows through the device. This current is insufficient to make the device conduct. The SCR is then said to be in the *forward blocking state* or *off state.*

When the anode is made negative with respect to the cathode, junctions J_1, & J_3 are reverse biased and junction J_2 is forward biased. Thus the junctions J_1, & J_3 will not allow any current to flow through the device. Only leakage current of small magnitude flows through the device. This current is insufficient to make the device conduct. The SCR is then said to be in the *reverse blocking state* or *off state.*

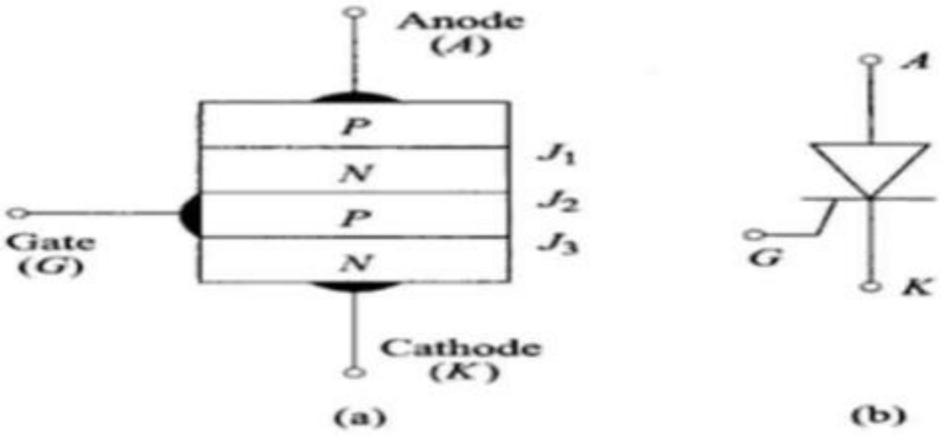


Fig. 1.2: (a) Structure (b) Symbol

The width of depletion layer at J_2 decreases with increase in anode to cathode voltage. As this voltage is increased to a large value, the reverse biased J_2 will breakdown and this phenomenon is known as due to *avalanche breakdown.* Since junctions J_1, & J_3 are already forward biased, there will be a large amount of current flowing through the device from anode to cathode. The device starts conducting and is said to be in *conducting state* or *on state.*

1.6.2 STATIC ANODE CATHODE CHARACTERISTICS OF SCR:

An Elementary circuit for obtaining static V-I characteristics of SCR is shown in fig 1.3. Here anode & cathode are connected to main source through a load. The gate and cathode are fed from source E_g.

The Static V-I characteristics is shown in 1.4. Here, V_a is the anode-cathode voltage and I_a is the anode current. The V-I characteristics is divided into 3 regions of operations.

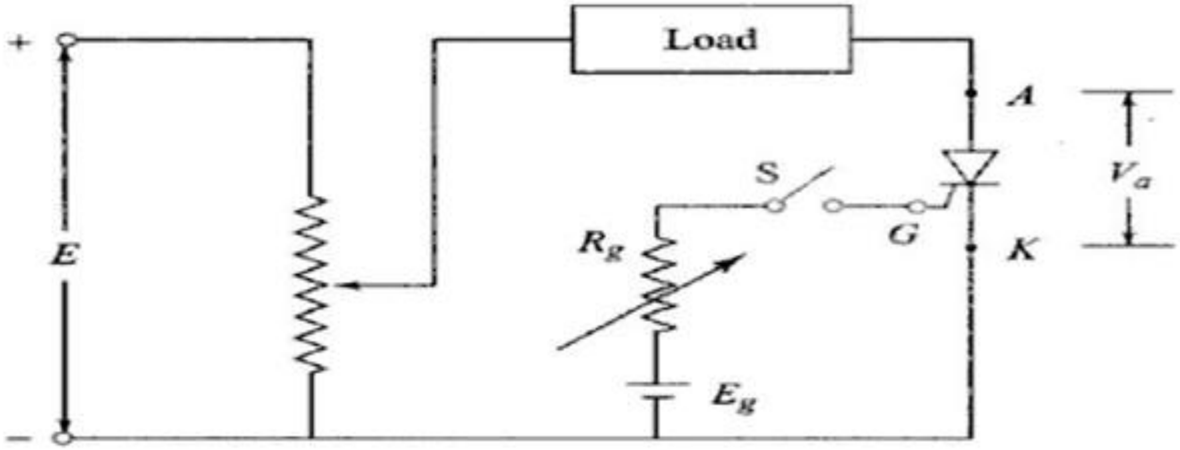


Fig. 1.3: Elementary circuit

1. Reverse blocking region: When the cathode is made positive with respect to the anode with switch S open, the SCR becomes reverse biased. In fig. 1.4, OP is the reverse blocking region. In this reverse biased condition, outer junctions J_1, & J_3 are reverse biased and middle junction J_2 is forward biased. Therefore, only a small leakage current (mA) flows. If the reverse voltage is increased, then at a critical breakdown level called reverse breakdown voltage V_{BR}, an avalanche will occur at J_1, & J_3increasing the current sharply. If this current is not limited to a safe value, the device may destroy. The region PQ is the reverse avalanche region.

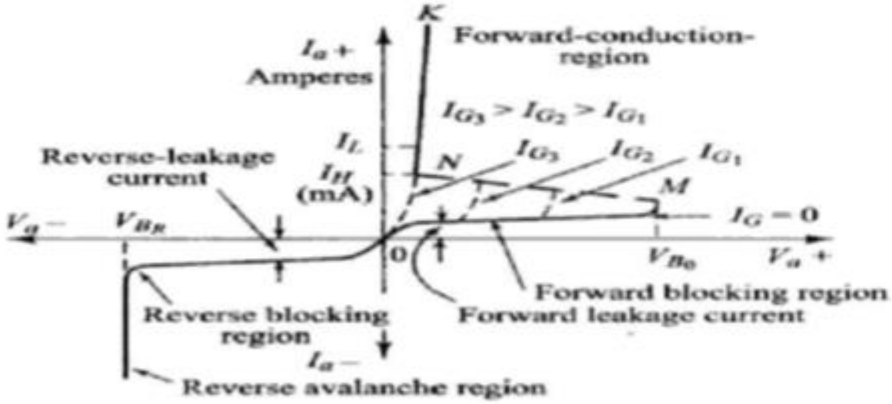
2. Forward blocking region: In this region, anode is made positive with respect to the cathode and therefore, junctions J_1, & J_3 are forward biased while junction J_2 remains reverse biased. Hence the anode current is small forward leakage current. The region OM is known as the forward blocking region when the device does not conduct.

3. Forward conduction region: When the anode to cathode voltage is increased with gate open, avalanche breakdown occurs at junction J_2 at a critical forward break-over voltage (V_{BO}) and the SCR switches into a high conduction mode. In fig 1.4, the V_{BO} is point M, when the device latches on to the conducting state. The region MN shows that as soon as device latches to ON state, voltage across the device drops and suddenly very large amount of current starts flowing the device. The region NK is called as forward conduction state.

When a gate-signal is applied, the SCR turns-on before V_{BO} is reached. The forward voltage at which the device switches to ON state depends upon the magnitude of gate current; higher the gate current, lower is the forward breakover voltage. In fig 1.4, for $I_G=0$, the forward breakover voltage is V_{BO}. For I_{G1}, forward breakover voltage is less than V_{BO} and for $I_{G2} > I_{G1}$, it is still further reduced.

Once the SCR is conducting, a forward current that is greater than the minimum value, called the *latching current* (I_L), the gate signal is no longer required to maintain the device in its ON state. Removal of gate current does not affect the conduction of the anode current.

The SCR will return to its original forward blocking state if the anode current falls below a low level, called the *holding current* (I_H).



V_{Bo} — Forward breakover voltage; V_{BR} — Reverse breakover voltage; I_G — Gate current; I_L — Latching current; and I_H — Holding current

Fig. 1.4: V-I Characteristics

1.7 TWO TRANSISTOR MODEL OF SCR: The operation of an SCR can also be explained in a very simple way by considering it in terms of two transistors. This is known as the two transistor analogy of the SCR. The SCR can be considered as an npn and a pnp transistor, where the collector of one transistor is attached to the base of the other and vice versa, as shown in Fig.1.5. This model is obtained by splitting the two middle layers of the SCR into two separate parts.

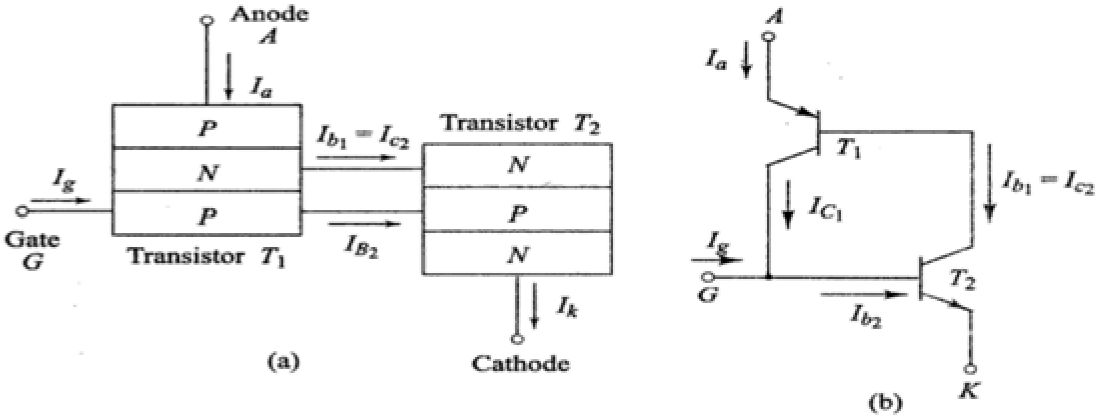


Fig. 1.5: Two transistor analogy of SCR

It is observed from the figure that the collector current of transistor T_1 becomes the base current of transistor T_2 and vice versa.

$$\therefore I_{c1} = I_{b2} \text{ and } I_{b1} = I_{c2}$$

$$\text{Also, } I_k = I_a + I_g \tag{1.1}$$

Now, we have the relation from transistor analysis,

$$I_{b1}=I_{e1}-I_{c1} \tag{1.2}$$

$$\text{Also, } I_{c1} = \alpha\ 1 I_{e1} + I_{co1} \tag{1.3}$$

where I_{co1} is the reverse leakage current of the reverse biased junction J_2.

Substituting Eq. (1.3) in Eq. (1.2) we get

$$I_{b1} = I_{e1} - \alpha\ 1 I_{e1} - I_{co1}$$

$$I_{b1} = (1-\alpha 1)I_{e1} - I_{col}$$

From figure it is evident that the anode current of the device becomes the emitter current of transistor T1 that is $I_a = I_{e1}$

$$\therefore I_{b1} = (1 - \alpha 1)I_a - I_{col} \tag{1.4}$$

Also, $I_{c2} = \alpha 2\ I_{e2} + I_{co2}$

From figure, it is also observed that the cathode current of the SCR becomes the emitter-current of transistor T_2. $\therefore I_k=I_{e2}$

$$\therefore I_{c2}=\alpha 2\ I_k + I_{co2} \tag{1.5}$$

But

$$I_{b1} = I_{c2} \tag{1.6}$$

Substituting Eqs, (1.4) and (1.5) in Eq. (1.6)), we get

$$(1-\alpha 1)\ I_a - I_{col} = \alpha 2\ I_k+I_{co2} \tag{1.7}$$

Substituting Eq. (1.1) in Eq. (1.7), we get

$$1-\alpha 1)\ I_a - I_{co1} = \alpha 2\ (I_a + I_g) + I_{co2}$$

$$(1 - \alpha 1 - \alpha 2)\ I_a = \alpha 2\ I_g + I_{co2} + I_{co1}$$

$$[1 - (\alpha 1 + \alpha 2)]\ I_a = \alpha 2\ I_g + I_{co1} + I_{co2}$$

$$I_a = [\alpha 2\ I_g + I_{co1} + I_{co2}] \ / \ [1-(\alpha 1+\alpha 2)] \tag{1.8}$$

Assuming the leakage current of transistor T_1 and T_2 to be negligible small, we have

$$I_a = \alpha 2\ I_g \ / \ [1 - (\alpha 1+\alpha 2)] \tag{1.9}$$

From Eq. (1.9), it can be analyzed that if $(\alpha 1+\alpha 2) = 1$, the value of anode current I_a becomes infinite, that is, the anode current suddenly attains a very high value, approaching infinity. In other words, we can say that the device suddenly latches into conduction (ON) state from the non-conduction (OFF) state. This characteristic of the device is known as its regenerative action. This can also be stated as the gate current I_g is of such a value that $(\alpha 1+\alpha 2)$ approaches unity value, the device will trigger. This turn-on condition $\{(\alpha 1+\alpha 2) \geq 1\}$ of the SCR can be satisfied in the following ways:

(a) If the temperature of the device is very high, the leakage current through it increase, which may then satisfy the required condition to turn it on.

(b) When the current through the device is extremely small, the alphas will be very small and the condition for breakover can be satisfied only by large values of hole multiplication factor Mp and electron multiplication factor the Mn. Near the breakdown voltage of junction J_2, the multiplication factors are very high and the required condition for breakover can be obtained by increasing the voltage across the device to V_{BO}, which will close the breakdown voltage of junction J_2.

(c) The required condition for breakover can also be realized by increasing α_1 and α_2. In Fig.1.5, if a current I_g is injected into the base P in the same direction as the current I_a across J_2, the current gain of the NPN transistor can now be increased independently of the anode to cathode voltage V_a and current I_a because α_2 depends on $(I_a + I_g)$ and α_1 would still, depend on I_a. The total current gain will now depend on I_g and independent means of breakover is obtained.

1.8 GATE CHARACTERISTICS OF SCR: The circuit which supplies firing signals to the gate must be designed:
(1) to accommodate these variations
(2) not to exceed the maximum voltage, and power capabilities of the gate
(3) to prevent triggering from false signals or noise
(4) to assure desired triggering

Fig. 1.6 shows the gate characteristics of a typical SCR. Here, positive gate to cathode voltage Vg and positive gate to cathode current Ig represent dc values.

All possible safe operating points for the gate are bounded by the low and high current limits for the V-I characteristics, maximum gate voltage, and the hyperbola representing maximum gate power.

Within these boundaries there are three region of importance:

(1) The first region OA lies near the origin (shown hatched) and is defined by the maximum gate voltage that will not trigger any device. This value is obtained at the maximum rated junction temperature. The gate must be operated in this region whenever forward bias is applied across the thyristor and triggering is not necessary.

(2) The second region is further defined by the minimum value of gate-voltage and current required to trigger all devices at the minimum rated junction temperature. This region contains the actual minimum firing points of all devices. In a sense, it is a forbidden region for the firing circuit because a signal in this region may not always fire all devices or never fire any at all. In Fig.1.6, OL and OV are the minimum gate-voltage and gate current limits respectively.

(3) The third region is the largest and shows the limits on the gate-signal for reliable firing. Ordinarily, a signal in the lower left part of this region is adequate for firing. For applications, where fast turn-on is required, a 'hard' firing signal in the upper right part of the region may be needed.

In Fig. 1.6 curves ON and OM corresponds to the possible spread of the characteristic for SCRs of the same rating. For best results, the operating point S, which may change from S_1 to S_2, must be as close as possible to the permissible P_g curve and must be contained within the maximum and minimum limits of gate voltage and gate current.

For selecting the operating point, usually a load line of the gate voltage Es = OH is drawn as HD. The gradient of the load line HD (=OH/OD) will give the required gate source resistance Rg . The maximum value of this series resistance is given by the line HE, where **E** is the point of intersection of lines indicating the minimum gate voltage and gate current. The minimum value of gate source series resistance is obtained by drawing a line HC tangential to Pg curve.

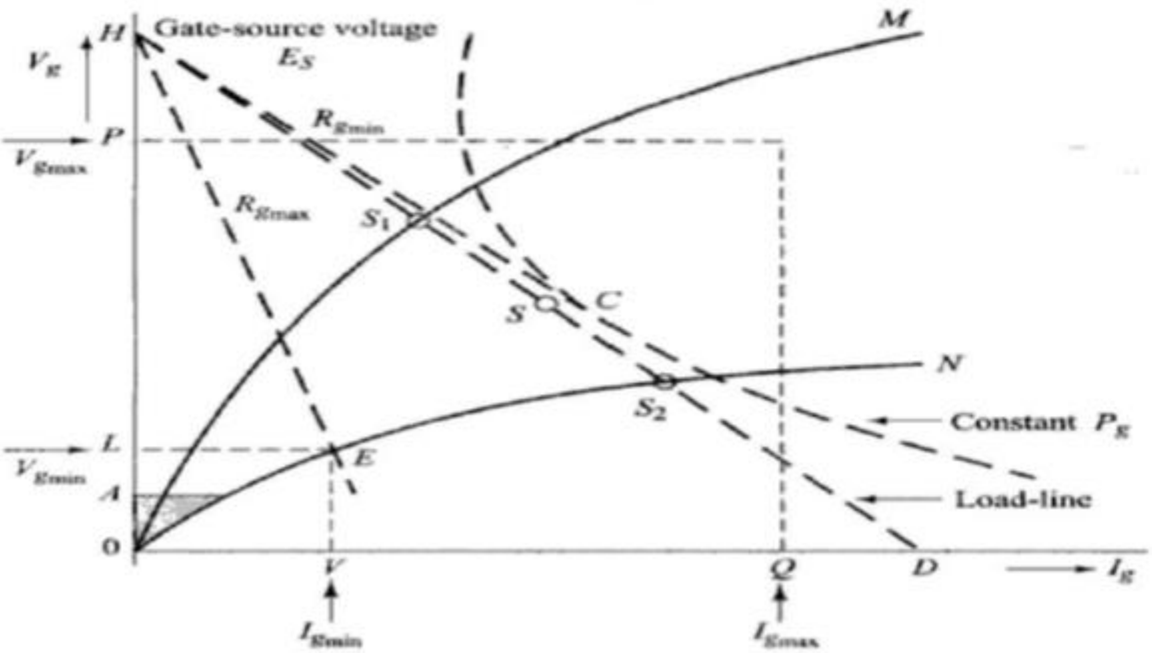


Fig. 1.6: Gate characteristics of SCR

The SCR turn-on time can be reduced by using gate current of higher magnitude. It should be ensured that pulse width is sufficient to allow the anode current to exceed the latching current. In practice, the gate pulse width is usually taken as equal to or greater than SCR turn-on time, t_{on}. If T is the pulse width as shown in Fig.1.7 then, $T \geq t_{on}$

With pulse firing, if the frequency of firing f is known, the peak instantaneous gate power dissipation P_{gmax} can be obtained as

$$P_{gmax} = V_g I_g = P_{gav} / f\,T \tag{1.10}$$

where $f = 1 / T_1$ = frequency of firing or pulse repetition rate in Hz and
T= pulse width in second

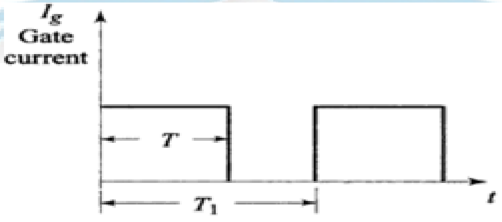


Fig. 1.7: Pulse gating

A duty cycle is defined as the ratio of pulse-on period to the periodic time of pulse. In the Fig.1.7 pulse-on period is T and the periodic time is T_1. Therefore, duty-cycle is given by

$$\delta = T / T_1 = f\,T \tag{1.11}$$

From Eq. (1.10),

$$P_{gav} / \delta \leq P_{gmax} \tag{1.12}$$

1.9 TURN–ON METHODS OF A THYRISTOR: A thyristor can be switched from a non-conducting state to a conducting state in several ways described as follows:

1. Forward voltage triggering: When anode to cathode forward voltage is increased with gate circuit open, the reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltage V_{BO} .At this voltage , a thyristor changes from OFF state to ON state characterized by a low voltage across it with large forward current.

2. Thermal Triggering (Temperature Triggering): In a thyristor, when the voltage applied between the anode and cathode is very near to its breakdown voltage, the device can be triggered by increasing its junction temperature. By increasing the temperature to a certain value, a situation comes when the reverse biased junction collapses making the device conduct. This method of triggering the device by heating is known as thermal triggering process.

3. Radiation Triggering (Light Triggering): In this method, the energy is imparted by radiation. Thyristor is bombarded by energy particles such as neutrons or photons. With the help of this external energy, electron-hole pairs are generated in the device, thus increasing the number of charge carriers. This leads to instantaneous flow of current within the device and the triggering of the device. Light activated silicon controlled rectifier (LASCR) and light activated silicon controlled switch (LASCS) are the examples of this type of triggering.

4. dv/dt Triggering: With forward voltage across the anode and cathode of a device, the junctions J_1 and J_3 are forward biased, whereas the junction J_2 becomes reverse biased .This reverse biased junction J_2 has the characteristics of a capacitor due to charges existing across the junction. If a forward voltage is suddenly applied, a charging current will flow tending to turn the device ON. If the voltage is impressed across the device is denoted by V, the charge by Q_b and the capacitance by C_j, then

$$i_c = \frac{dQ}{dt} = \frac{d(CjV)}{dt} = C_j\frac{dV}{dt} + V\frac{dCj}{dt} \qquad (1.13)$$

The rate of change of junction capacitance may be negligible as the junction capacitance is almost constant. The contribution to charging current by the later term is negligible. Hence the above equation reduces to

$$i_c = C_j\, dv/\, dt \qquad (1.14)$$

Therefore, if the rate of change of voltage across the device is large, the device may turn on even though the voltage appearing across the device is small.

5. Gate Triggering: This is most common and efficient method to turn ON the SCR. In laboratories, almost all the SCR devices are triggered by this process. By applying a positive signal at the gate terminal of the device, it can be triggered much before the specified breakover voltage. The conduction period of the SCR can be controlled by varying the gate signal within the specified values of the maximum and minimum gate currents.

For gate triggering, a signal is applied between the gate and the cathode terminals. Three types of signals can be used for this purpose. They are either DC signal, AC signal or pulse signals.

i) DC Gate Triggering: In this type of triggering, a dc voltage is applied between the gate and the cathode of the device in such a way that the gate becomes positive with respect to the cathode. When the applied voltage is sufficient to produce the required gate current, the device starts conducting.

One drawback of this scheme is that both the power and control circuits are dc and there is no isolation between the two.

Another disadvantage of this process is that a continuous dc signal has to be applied, at the gate causing more gate power loss.

ii) AC Triggering: AC source is most commonly used for the gate signal in all application of thyristor control adopted for ac applications. This scheme provides the proper isolation between the power and the control circuits. The firing angle control is obtained very conveniently by changing the phase angle of the control signal.

However, the gate drive is maintained for one half cycle after the device is turned ON, and a reverse voltage is applied between the gate and the cathode during the negative half cycle. The drawback of this scheme is that a separate transformer is required to step down the ac supply, which adds to the cost.

iii) Pulse Triggering: This is the most popular method for triggering the device. In this method, the gate drive consists of a single pulse appearing periodically or a sequence of high frequency pulses. This is known as carrier frequency gating. A pulse transformer is used for isolation.

The main advantage of this method is that there is no need of applying continuous signals and hence, the gate losses are very much reduced. Electrical isolation is also provided between the main device supply and its gating signals.

1.10 TURN OFF METHODS: The term commutation basically means the transfer of current from one path to another. In thyristor circuits, this term is used to describe process of transferring current from one thyristor to another. It is not possible for a thyristor to turn itself OFF; the circuit in which it is connected must reduce the thyristor current to zero to enable it to turn-off. *'Commutation'* is the term to describe the methods of achieving this.

Commutation is one of the fundamental principles the use of thyristors for control purposes. A thyristor can operate in two modes: in OFF state i.e. open circuit, or in ON state i.e. short circuit. By itself it cannot control the level of current or voltage in a circuit. Control can only be achieved by variation in the time thyristors when switched ON and OFF, and commutation is central to this switching process. All thyristor circuits, therefore, involve the cyclic or sequential switching of thyristors. The two methods by which a thyristor can be commutated are as follows:

1. Natural Commutation: The simplest and most widely used method of commutation makes use of the alternating, reversing nature of ac voltages to effect the current transfer. In ac circuits, the current always passes through zero in every half cycle. As the current passes through natural zero, a reverse voltage will simultaneously appear across the device. This immediately turns-off the device. This process is called as natural commutation since no external circuit is required for this purpose. This method may use ac mains supply voltages or the ac voltages generated by local rotating machines or resonant circuits. The line commutated converters and inverters comes under this category.

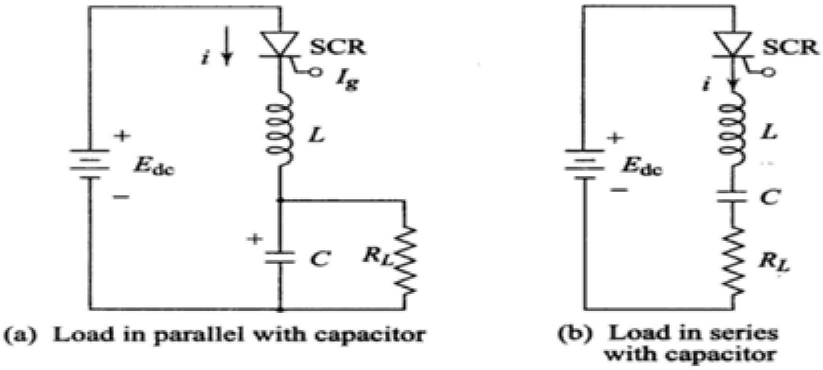
2. Forced Commutation: Once thyristors are operating in the ON state, carrying forward current, they can only be turned OFF by reducing the current flowing through them to zero for sufficient time to allow the removal of charged carriers.

In case of dc circuits, for switching off the thyristors, the forward current should be forced to be zero by means of some external circuits. The process is called forced commutation and the external circuits required for it are known as commutation circuits. The components (inductance and capacitance) which constitute the commutating circuits are called as commutating components. A reverse voltage is developed across the device by means of a commutating circuit that immediately brings the forward current in the device to zero, thus turning off the device.

The six basic methods of commutation by which thyristors may be turned OFF are:

i) Class A- Self commutation by resonating the load
ii) Class B- Self commutation by an LC circuit
iii) Class C- Complementary commutation
iv) Class D- Impulse or auxiliary commutation
v) Class E- External pulse commutation
vi) Class F- AC line commutation

1. 10.1 CLASS A- SELF COMMUTATION BY RESONATING THE LOAD: This is also known as resonant commutation. This type of commutation circuit using L-C components in-series-with the load are shown in Fig. 1.8.



(a) Load in parallel with capacitor (b) Load in series with capacitor

Fig. 1.8: Class A commutation circuit

In Fig.1.8 (a), load R_L is in parallel with the capacitor and in Fig.1.8 (b) load R_L is in series with the L-C circuit. In this process of commutation, the forward current passing through the device is reduced to less than the level of holding current of the device. Hence, this method is also known as the current commutation method. The waveforms of the thyristor voltage, current and capacitor voltages are shown in Fig. 1.9.

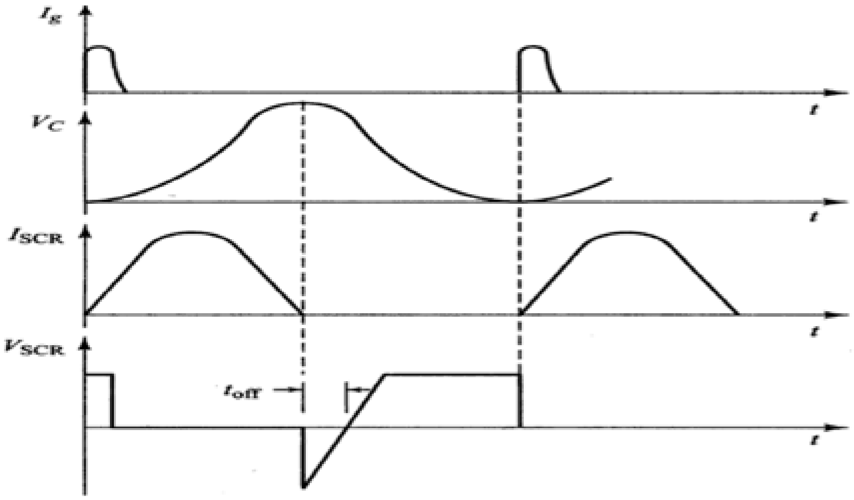
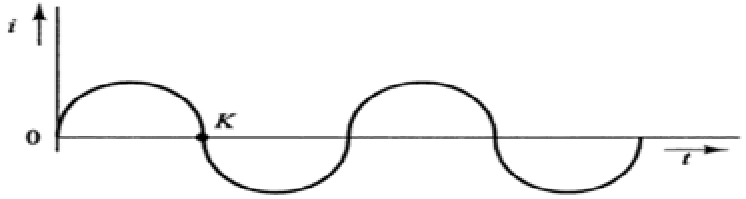
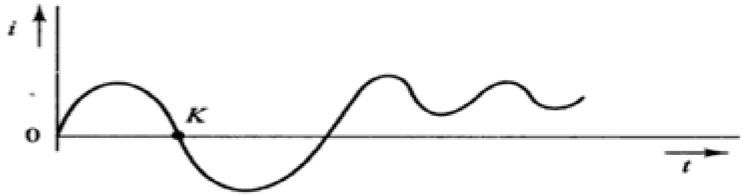


Fig. 1.9: Voltages and currents in class A (Load in parallel with capacitor)

The load resistance R_L and the commutating components are so selected that their combination forms an underdamped resonant circuit. When such a circuit is excited by a dc source, a current of the nature shown in Fig.1.10 will be obtained across the device.



(a) Waveforms of the current produced in Fig. 1.8 (b) (series capacitor)



(b) Waveforms of the current produced in Fig. 1.8 (a) (parallel capacitor)

Fig. 1.10

This current, has zero value at the point *K* where the device is automatically turned OFF. Beyond point *K*, the current is reversed in nature which assures definite commutation of the device. The thyristor when ON carries only the charging current of capacitor *C* which will soon decay to a value less than the holding current of the device, when capacitor *C* is charged up to the supply voltage E_{dc}. This simultaneously switches off the thyristor.

The time for switching off the device is determined by the resonant frequency which in turn depends on the values of the commutating components *L* and *C*, and the total load resistance.

This type of commutation circuits are most suitable for high frequency operation, i.e., above 1000 Hz. This commutation circuit is used in series inverter.

1.10.2. CLASS B-SELF COMMUTATION BY AN LC CIRCUIT: In this method, the LC resonating circuit is across the SCR and not in series with the load. The commutating circuit is shown in Fig.1.11 and the associated waveforms are shown in Fig.1.12.

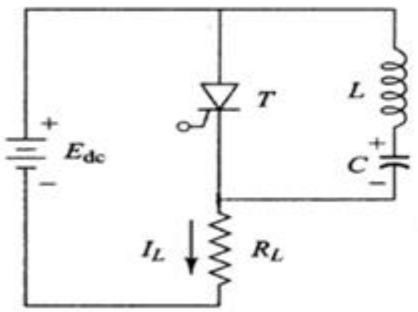


Fig. 1.11: Class B commutation circuit

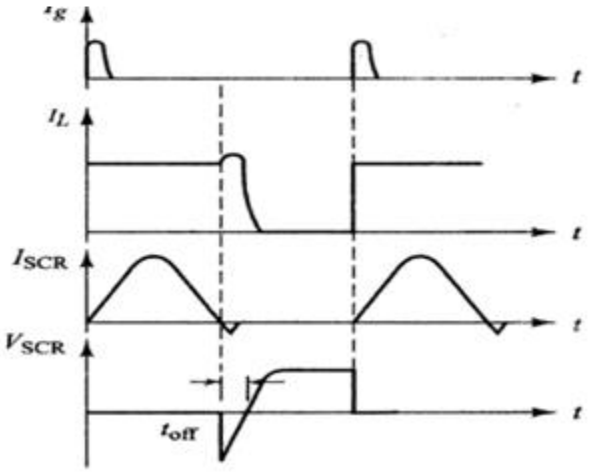


Fig. 1.12: Associated waveforms

Initially as soon as supply voltage E_{dc} is applied, the capacitor C starts getting charged and it charges up to the voltage E_{dc}.

When thyristor is T is triggered, the circuit current flows in two directions:

1. The load current I_L flows through E_{dc+} -- T -- RL -- E_{dc-} -- , and
2. Commutating current I_c.

The moment thyristor is T is turned ON, capacitor C starts getting discharged through the path C_+ -- L – T – C_- . When the capacitor C becomes completely discharged, it starts getting charged with reverse polarity. Due to the reverse voltage, a commutating current I_c starts flowing which opposes the load current I_L. When commutating current I_c is greater than the load current I_L, thyristor T becomes turned off. When the thyristor is T is turned OFF, the capacitor C starts getting charged to its original polarity through L and the load. Thus, when it is fully charged, the thyristor will be ON again.

Hence, thyristor after getting ON for some time automatically gets OFF and after remaining in OFF state for some time, it again gets turned ON. The desired frequency of ON and OFF states can be obtained by designing the commutating components as per the requirement. The main application of this process is in dc chopper circuits.

1.11 GATE TRIGGER CIRCUITS:

1.11.1 Resistance firing circuit: The circuit in Fig.1 shows a simple method for varying the trigger angle and therefore, the power in the load. Instead of using a gate pulse to trigger the SCR, the gate current is supplied by an ac source of voltage e_S through R_{min}, R_v, and the series diode D. The circuit operates as follows:

(a) As e_S goes positive, the SCR becomes forward-biased from anode to cathode; however, it will not conduct (e_L=0) until its gate current exceeds $I_{g(min)}$.

(b) The positive e_S also forward biases the diode and the SCRs gate-cathode junction; this causes flow of a gate current i_g.

(c) The gate current will increase as e_S increases towards its peak value. When i_g reaches a value equal to $I_{g(min)}$, the SCR turns "on" and e_L will approximately equal e_s.

(d) The SCR remains "on" and $e_L \approx e_S$ until e_S decreases to the point where the load current is below the SCR holding-current. This usually occurs very close to the point until $e_S = 0$ and begins to go negative.

(e) The SCR now turns off and remains off while e_S goes negative since its anode-cathode is reverse biased, and since the SCR is now an open switch, the load voltage is zero during this period.

(f) The purpose of the diode in the gate-circuit is to prevent the gate-cathode reverse bias from exceeding peak reverse gate voltage during the negative half-cycle of e_S. The diode is chosen to have peak reverse- voltage rating greater than the input voltage E_{max}.

(g) The same sequence is repeated when e_S again goes positive.

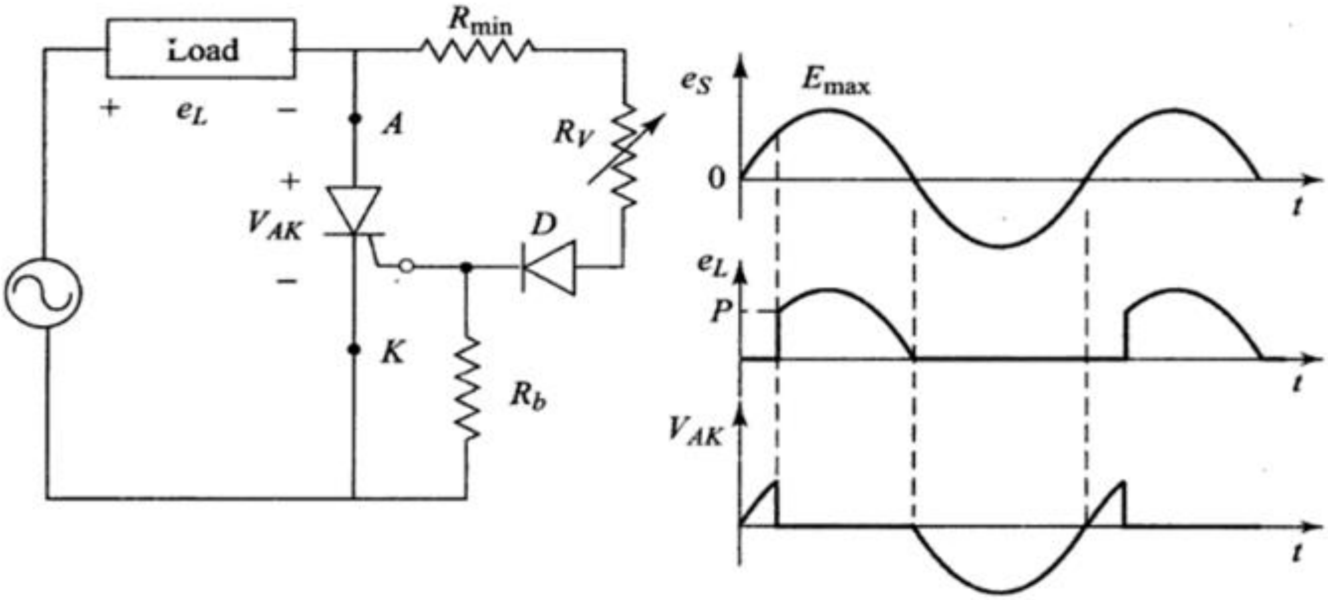


Fig. 1.13: R firing circuit & associated waveforms

The load-voltage waveform in Fig.1.13 can be controlled by varying R_V which varies the resistance in the gate circuit. If R_V is increased, the gate current will reach its trigger value $I_{g(min)}$ at a greater value of e_S making the SCR to trigger at a latter point in the e_S positive half-cycle. Thus, the trigger angle **α** will increase.

The opposite will occur if R_V is decreased. Of course, if R_V is made large enough the SCR gate current will never reach $I_{g(min)}$ and the SCR will remain off. The minimum trigger angle is obtained with R_V equal to zero.

As shown in Fig.1 the limiting resistor $R_{(min)}$ is placed between anode and gate so that the peak gate current of the thyristor I_{gm} is not exceeded. In the worst case, that is when the supply voltage has reached its peak, E_{max},

$$Rmin \geq Emax / Igm \tag{1.15}$$

The stabilizing resistor R_b should have such a value that the maximum voltage drop across it does not exceed maximum possible gate voltage $V_{g(max)}$. From the voltage distribution,

$$Rb \leq [(Rv+Rmin)\cdot Vg(max)] / [Emax - Vg(max)] \tag{1.16}$$

The thyristor will trigger when the instantaneous anode voltage, e_S, is

$$e_S = Ig(min)\ (Rv + Rmin) + Vd + Vg(min) \tag{1.17}$$

where $I_{g(min)}$ = minimum gate current to trigger the thyristor,

V_d = voltage drop across the diode,

$V_{g(min)}$ = gate-voltage to trigger, corresponding to $I_{g(min)}$.

The resistance trigger shown in Fig.1.13 is the simplest and most economical circuit. However, it suffers from several disadvantages. First, the trigger angle **α** is greatly dependent on the SCR's $I_{g(min)}$, which, as we known, can vary widely even among SCRs of a given type and is also highly temperature dependent. In addition, the trigger angle can be varied only up to an approximate value of 90° with this circuit. This is because e_S is maximum at its 90° point and the gate current has to reach $I_{g(min)}$ somewhere between 0–90°, if it will if at all. This limitation is that the load voltage waveform can only be varied from **α** = 0° to **α** = 90°.

1.11.2. Resistance-Capacitance (RC) Firing Circuit of SCR (Half Wave): Figure 1 shows the RC half wave trigger circuit. By the *RC* network, a larger variation in the value of the firing angle can be obtained by changing the phase and amplitude of the gate current. By varying the resistor R_v, the firing angle can be controlled from 0 to 180°. In the negative half-cycle, capacitor *C* charges through diode D_2 with lower plate positive to the peak supply voltage E_{max}. This capacitor voltage remains constant at E_{max} until supply voltage zero value. Now, as the SCR anode voltage passes through zero and becomes positive, capacitor *C* begins to charge through R_v from the initial voltage $- E_{max}$. When the capacitor charges to positive voltage equal to gate trigger voltage, V_{gt} (= $V_{g(min)} + V_{D1}$), SCR is triggered and after this, the capacitor holds to a small positive voltage, as shown in Fig.1.14.

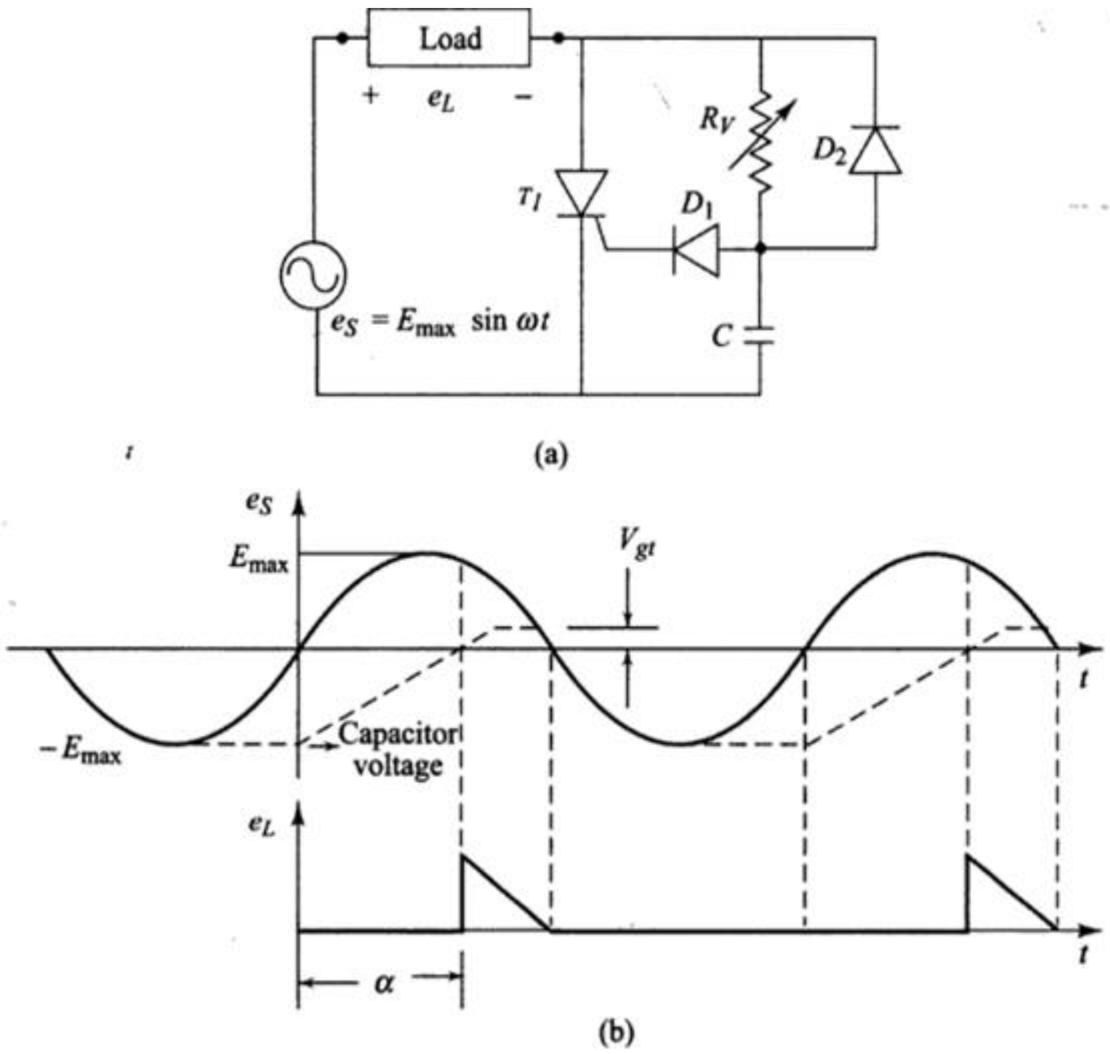


Fig. 1.14: (a) RC firing circuit (b) Voltage waveform

During negative half-cycle, the diode D1 prevents the breakdown of the gate to cathode junction. In the range of power-frequencies, the RC for zero output voltage is given by

$$R_vC \geq 1.3T / 2 = 4 / w \tag{1.18}$$

Where T = 1 / f = period of ac line frequency in seconds.

The thyristor will turn ON when the capacitor voltage equals ($V_{g(min)} + V_{D1}$), provided the gate current $I_{g(min)}$ is available. Therefore, the maximum value of R_v is given by

$$e_S \geq I_{g(min)} R_v + e_C \tag{1.19}$$

$$= I_{g(min)} R_v + V_{g(min)} + V_{D1} \tag{1.20}$$

OR $$R_v \leq [e_S - V_{g(min)} - V_{D1}] / I_{g(min)} \tag{1.21}$$

where e_S is the instantaneous supply voltage at which the thyristor will turn ON. From equations 1.18 and 1.21 the suitable values of R_v and C can be obtained.

1.12 UNIJUNCTION TRANSISTOR (UJT): UJT is a three terminal, single junction device. The three terminals are Emitter (E), Base 1 (B1) and Base 2 (B2). The UJT is always operated as a switch and finds most frequent applications in oscillators, timing circuits and SCR / TRIAC trigger circuits.

1.12.1 Basic operation: The basic structure of a unijunction transistor is shown in figure 1.15. It essentially consists of a lightly-doped N-type silicon bar with a small piece of heavily doped P-type material alloyed to its one side to produce single P-N junction. The silicon bar, at its ends, has two ohmic contacts designated as Base-1 (B_1) and Base-2 (B_2), as shown and the P-type region is termed the emitter (E). The emitter junction is usually located closer to terminal Base 2 than Base 1.

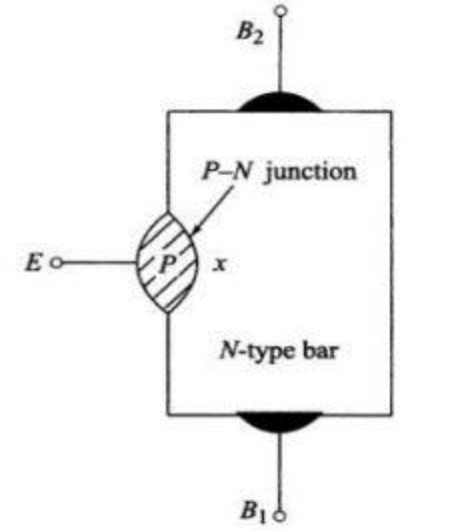


Fig. 1.15: Basic UJT structure

An interbase resistance R_{BB}, exists between B_1 and B_2. R_{BB} is essentially the resistance of N-type bar. This interbase resistance is broken into two resistances, the resistance from B_1 to emitter, called R_{B1} and resistance from B_2 to emitter, called R_{B2}. Since emitter is closer to B_2, the value of R_{B1} is greater than R_{B2}.

The operation of the UJT can better be explained with the aid of an equivalent circuit. The UJT's circuit symbol and its equivalent circuit are shown in figure 1.16. The diode represents the P-N junction between the emitter and the base-bar (point x). The arrow through RB1, indicates that it is variable.

The essence of UJT operation can be stated as follows:

(a) When the emitter diode is reverse biased, only a very small emitter current flows. Under this condition, RB1 is at its normal high-value (typically 4 kΩ). This is the UJT's "off" state.

(b) When the emitter diode becomes forward biased, R_{B1} drops to a very low value (reason to be explained later) so that the total resistance between E and B_1 becomes very low, allowing emitter current to flow readily. This is the "on" state.

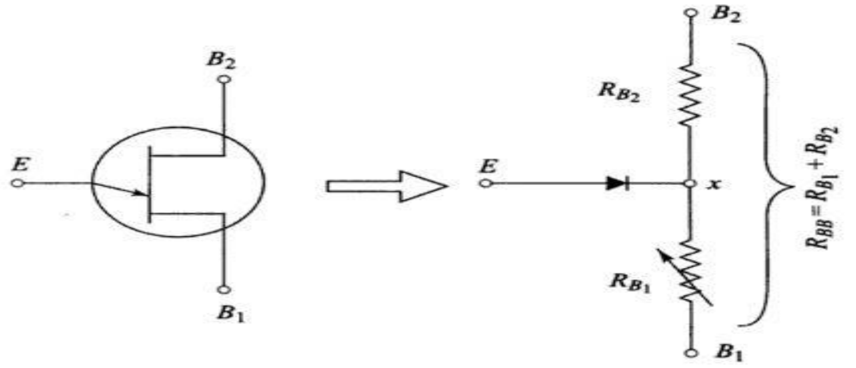


Fig. 1.16: UJT Symbol and Equivalent circuit

1.12.2 Circuit Operation: The UJT is normally operated with both B_2 and E biased positive relative to B_1 as shown in below figure. B_1 is always the UJT reference terminal and all voltages are measured relative to B_1. The V_{BB} source is generally fixed and provides a constant voltage from B_2 to B_1. The V_{EE} source is generally a variable voltage and is considered the input to the circuit. Very often, V_{EE} is not a source but a voltage across a capacitor.

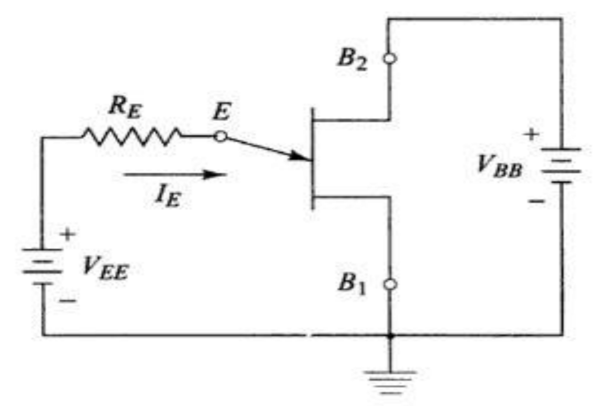


Fig. 1.17: Normal UJT biasing

We will analyze the UJT circuit operation UJT equivalent circuit, shown in Fig. 1.18(a). and utilize the UJT emitter-base-1 V_E-I_E curve shown in Fig. b. The curve represents the variation of emitter current I_E, with emitter-base-1 voltage, V_E, at a constant B_2-B_1 voltage.

The "Off" state: If we neglect the diode for a moment, then R_{B1} and R_{B2} form a voltage divider that produces a voltage Vx, from point x relative to the ground.

$$V_x = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} \times V_{BB} = \underbrace{\frac{R_{B_1}}{R_{BB}}}_{\eta} \times V_{BB}$$

simply,

$$V_x = \eta \, V_{BB} \tag{1.22}$$

Where η is the internal UJT voltage divider ratio R_{B1}/R_{BB} called as the *intrinsic standoff ratio*. Values of η typically range from 0.5 to 0.8 but are relatively constant for a given UJT.

The voltage at point x is the voltage on the N-side of the P-N junction. The V_{EE} source is applied to the emitter which is the P-side. Thus, the emitter diode will be reverse-biased as long as V_{EE} is less than V_x. This is the “off” state and is shown on the V_E-I_E curve as being a very low current region. In the “off” state, then, we can say that the UJT has a very high resistance between E and B_1, and I_E is usually a negligible reverse leakage current. With no I_E, the drop across R_E is zero and the emitter voltage, V_E, equals the source voltage.

The UJT “off” state, as shown on the V_E-I_E curve, actually extends to the point where the emitter voltage exceeds V_x by the diode threshold voltage, V_D, which is needed to produce the forward current through the diode. The emitter voltage and this point, P, is called the peak-point voltage, V_P, and is given by

$$V_P = V_x + V_D = \eta V_{BB} + V_D \tag{1.23}$$

where V_D is typically 0.5 V.

The “On” state: As V_{EE} increases, the UJT stays “off” until V_E approaches the peak-point value VP, then things begin to happen. As V_E approaches V_p, the P-N junction becomes forward biased and begins to conduct in the opposite direction.

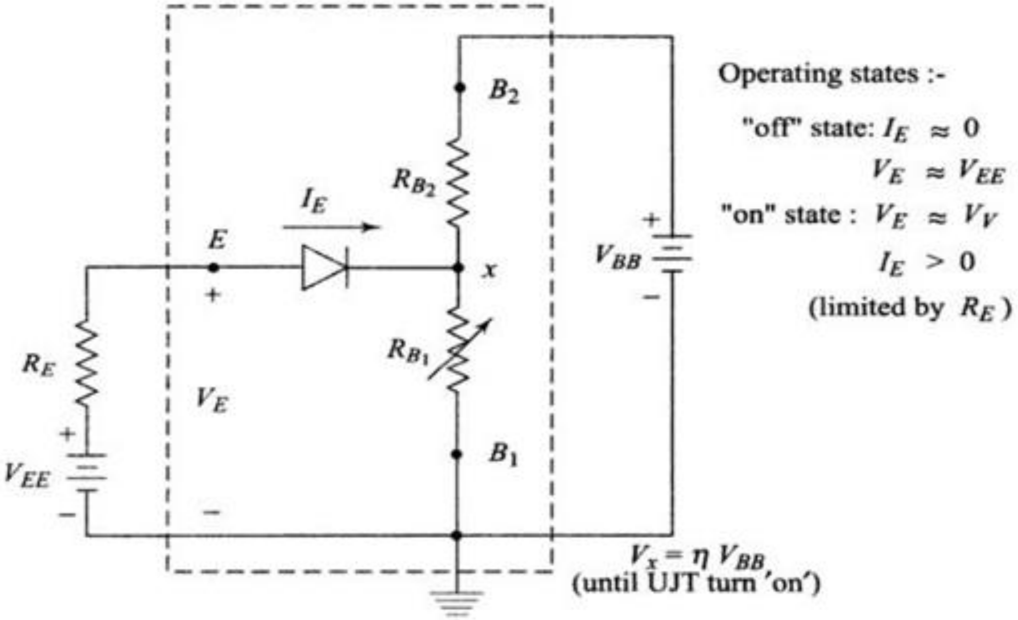


Fig. 1.18 (a): Equivalent circuit for UJT analysis

Note on the V_E-I_E curve that IE becomes positive near the peak point P. When V_E exactly equals V_P, the emitter current equals I_P, the peak-point current. At this point, holes from the heavily doped emitter are injected into the N-type bar, especially into the B_1 region. The bar, which is lightly doped, offers very little chance for these holes to recombine. As such, the lower half of the bar becomes replete with additional current carriers (holes) and its resistance R_{B1}, is drastically reduced. The decrease in R_{B1} causes V_x to drop. This drop, in turn causes the diode to become more forward biased, and I_E increases even further. The larger I_E injects more holes into B_1 further reducing R_{B1}, and so on. When this regenerative or snowballing process ends, R_{B1} has dropped to a very small value (2-25 Ω) and I_E can become very large, limited mainly by external resistance R_E.

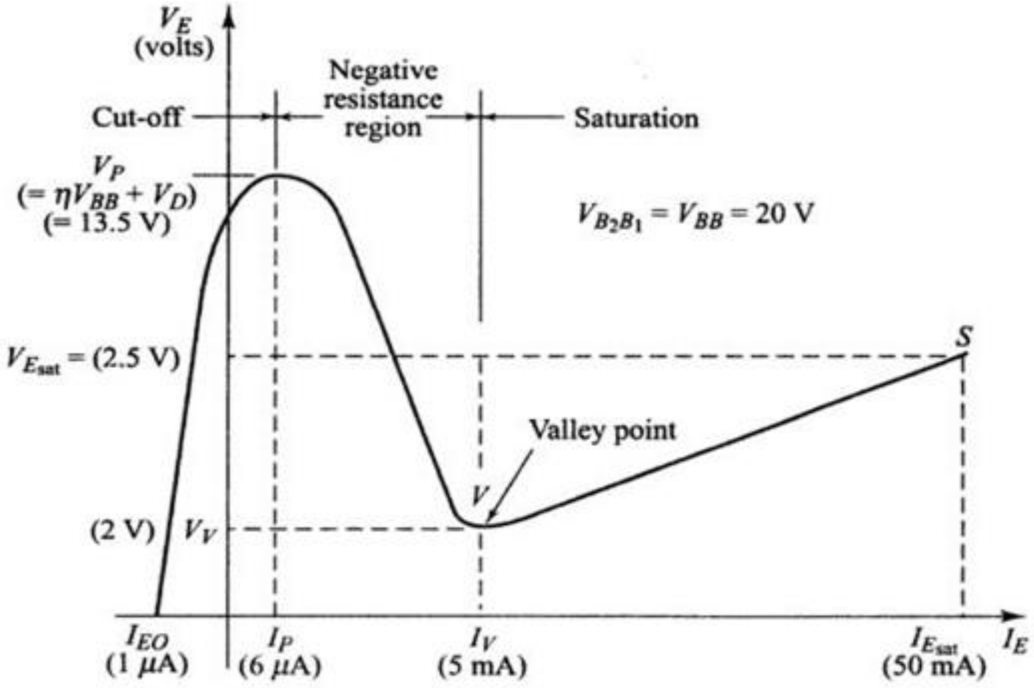


Fig. 1.18 (b): Typical UJT V-I characteristic curve

The UJT operation has switched to the low-voltage, high-current region of its V_E-I_E curve. The slope of this “on” region is very steep, indicating a low resistance. In this region, the emitter voltage V_E, will be relatively small, typically 2V, and remains fairly constant as I_E is increased up to its maximum rated value, I_E(sat). Thus, once the UJT is “on,” increasing V_{EE} will serve to increase I_E while V_E remains around 2V.

Turning “Off” the UJT Once it is “on,” the UJT‘s emitter current depends mainly on VEE and R_E. As VEE decreases, I_E will decrease along the “on” portion of the V_E-I_E curve. When I_E decreases to point V, the valley point, the emitter current is equal to I_V, the valley current, which is essentially the holding current needed to keep the UJT “on”. When I_E is decreased below I_V, the UJT turns “off” and its operation rapidly switches back to the “off” region of its V_E-I_E curve, where IE = 0 and V_E – V_{EE}. The valley current is the counterpart of the holding current in PNPN devices and generally ranges between 1 and 10 mA.

Applications of UJT:

Unijunction transistors are used extensively in oscillator, pulse and voltage sensing circuits. Some of the important applications of UJT are discussed below:

(i) UJT relaxation oscillator.

(ii) Overvoltage detector.

1.13 SYNCHRONIZED UJT-TRIGGERING (RAMP TRIGGERING):

Synchronized UJT triggering circuit is shown in Fig. 1.19. The diode bridge D1−D4 rectifies ac to dc Resistor R_s lowers E_{dc} to a suitable value for the zener diode and UJT. The zener diode D_z is used to clip the rectified-voltage to a fixed voltage V_z. This voltage V_z is applied to the charging circuit RC.

Capacitor C charges through R until it reaches the UJT trigger voltage V_p. The UJT then turns "on" and *C* discharges through the UJT emitter and primary of the pulse-transformer. The windings of the pulse transformer have pulse voltages at their secondary terminals. Pulses at the two secondary windings feed the same in-phase pulse to two SCRs of a full wave circuit. SCR with positive anode voltage would turn ON. Rate of rise of capacitor voltage can be controlled by varying R. The firing angle can be controlled up to about 150°. This method of controlling the output power by varying charging resistor R is called as ramp control, open loop control or manual control.

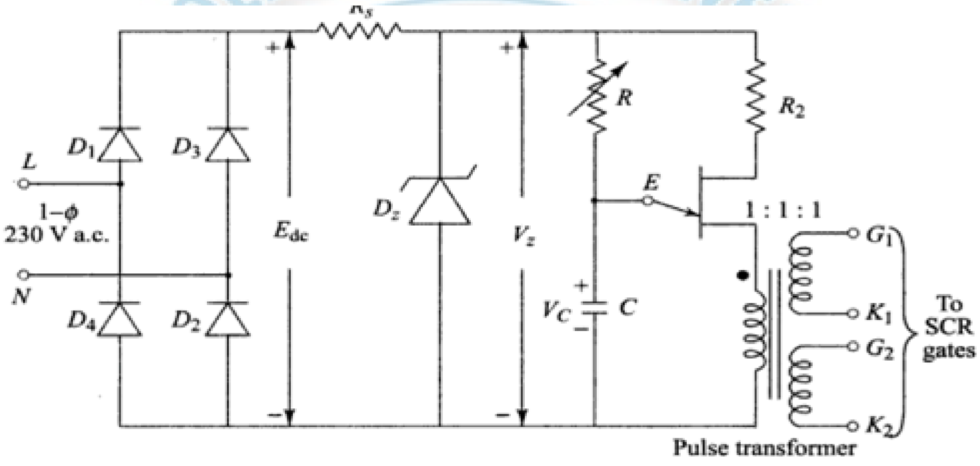


Fig. 1.19: Synchronized UJT triggering circuit

As the zener diode voltage V_z goes to zero at the end of each half cycle, the synchronization of the trigger circuit with the supply voltage across SCRs is achieved. Thus the time *t*, equal to α/ω, when the pulse is applied to SCR for the first time, will remain constant for the same value of R. The various voltage waveforms are shown in Fig.1.20.

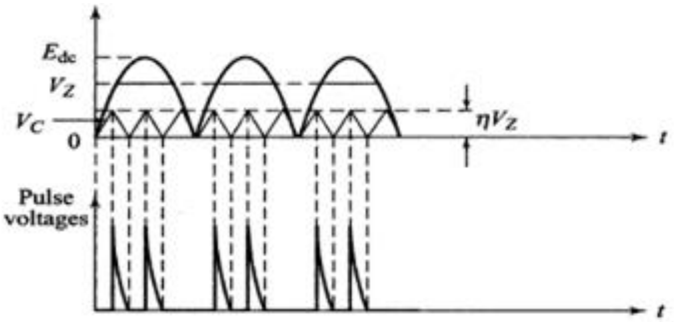


Fig. 1.20: Generation of output pulses