Source: Power Electronics book by M.D.Singh & K.B.Khanchandani

POWER ELECTRONIC CONVERTEES

The great strides taken in the industrial applications of power electronics during recent years have demonstrated that this versatile tool can be of great importance in increasing production, efficiency and control. Power electronics circuits are also called as power converters. A converter uses a matrix of power semiconductor switches to convert electrical power at high efficiency. The converter system is comprised of switches, reactive components L, C, and transformers. Switches include two terminal devices such as diodes and three terminal devices such as transistors or thyristors. These converters/controllers are generally classified into the following five broad categories:

1. **Phase Controlled Rectifiers (AC to DC Converters)** These con-trollers convert fixed ac voltage to a variable dc output voltage. These converters takes power from one or more ac voltage/current sources of single or multiple phases and delivers to a load. The output variable is a low-ripple de voltage or de current. These controller circuits use line voltage for their commutation. Hence they are also called as line commutated or naturally commutated ac to dc converters. These circuits include diode rectifiers and single/three phase controlled circuits. These controllers are discussed in detail in Chapter 6.

   Applications: High voltage dc transmission systems, DC motor drives, Regulated dc power supplies, Static VAR compensator, Wind generator converters, Battery charger circuits.

2. **Choppers (DC to DC Converter)** A chopper converts fixed de input voltage to a variable dc output voltage. The de 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 the duty, ratio of the device by low power signals from a control unit. Chopper has either a battery, a solar powered de voltage source or a line frequency (50- 60 Hz) derived de voltage source. Choppers are discussed in Chapter 8.

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

3. **Inverters (DC to AC Converter)** An inverter converts a fixed dc voltage to an ac voltage of variable frequency and of fixed or variable magnitude. A practical inverter has either a battery, a solar powered dc voltage source or a line frequency (50 Hz) derived de voltage source (often unregulated). lnverters are widely used from very low-power portable electronic systems such as the flashlight discharge system in a photography camera to very high power industrial systems.

   Inverters are designed using semiconductor devices such as power transistors, MOSFETs, IGBTs, GTOs and thyristors.

   Applications: Uninterruptible power supply (UPS), Aircraft and space power supplies, Induction and synchronous motor drives, High voltage dc transmission system, Induction heating supplies.

4. **Cycloconverters (AC to AC Converters)** These circuits convert input 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 unit.

The output frequency is lower than the source frequency. Output frequency in cycloconverter is a simple fraction such as 1/3, 1/5 and so on of the source frequency. These are mainly used for slow speed, very high power industrial drives.

Applications: AC drives like rotary kilns multi- NM ac motor drives.

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

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

POWER ELECTRONIC APPLICATIONS

The importance of power electronics in industrial automation, energy systems, energy generation and conservation, and indirectly for environmental pollution control is tremendous. As the technology is maturing and cost is decreasing, power electronics is expanding in applications, such as switch mode power supplies (SMPS), UPS systems, electrochemical processes, heating and lighting, static VAR compensation, active filtering, high voltage dc system, photo-voltaic system, and variable frequency motor drives. The motor drives possibly constitute the most fascinating and complex applications of power electronics where the applications include computer peripherals, servos and robotics, pumps and fans, paper and textile mills, rolling mills., wind generation system, variable speed heat pump and air-conditioning, transportation system, ship propulsion etc.

The importance of power electronics is being increasingly visible now-a-days in the energy saving of electrical apparatus by more efficient use of electricity. It indirectly helps in reduction of environmental pollution problem.

Following is the list of some various applications of power-electronics, though it is not exhaustive.

1. Home Appliances:

Refrigerators, sewing machines, photography, air-conditioning, food warming trays, washing machines, lighting, dryers, vacuum cleaners, electric blankets, grinders and mixers, cooking appliances

2. Games and entertainment:

Games and toys, televisions, movie projectors

3. Commercial:

Advertising, battery chargers, blenders, computers, electric fans, electronic ballasts, hand power tools, photocopiers, vending machines, light dimmers.

4. Aerospace

Aircraft power systems, space vehicle power systems, satellite power systems

5. Automotive

Alarms and security systems, electric vehicles, audio and Rf amplifiers, regulators

6. Industrial

Blowers, boilers, chemical processing equipment, contactor and circuit breakers, conveyors, cranes and hoists, dryers, electric furnaces and ovens, electric, vehicles, electromagnets, electronic ignitions, elevators, flashers, gas-turbine starters, generator exciters, induction heating, linear induction motion control, machine tools, mining power equipments, motor drives and starters, nuclear reactor control, oil-well drilling equipment, paper mill machinery, power-supplies, printing press machinery, pumps and compressors, servo systems, steel mill instrumentation, temperature controls ultrasonic generators, tin interruptible power supplies (UPS), welding equipment

7. Medical

Fitness machines, laser power supplies, medical instrumentation

8. Security systems

Alarms and security systems, radar/sonar

9. Telecommunications

Uninterruptable power supplies (UPS), solar power supplies, VLF transmitters, wireless communication power supplies

10. Transportation

Magnetic levitation, trains and locomotives, motor drives. trolly buses, subways

11. Utility Systems:

VAR compensators, power factor correction, static circuit breakers, supplementary energy systems (solar, wind).

Principle of Operation of SCR

SCR is a four layered PNPN switching device, having three junctions J_1, J_2 and J_3. It has three external terminals, namely, the Anode (A), Cathode (K) and Gate (G). The Anode and Cathode are connected to the main power circuit. The gate terminal carries a low-level gate current in the direction gate to cathode. Conventionally, the gate terminal is provided at the P layer near the cathode. This is known as the Cathode Gate.

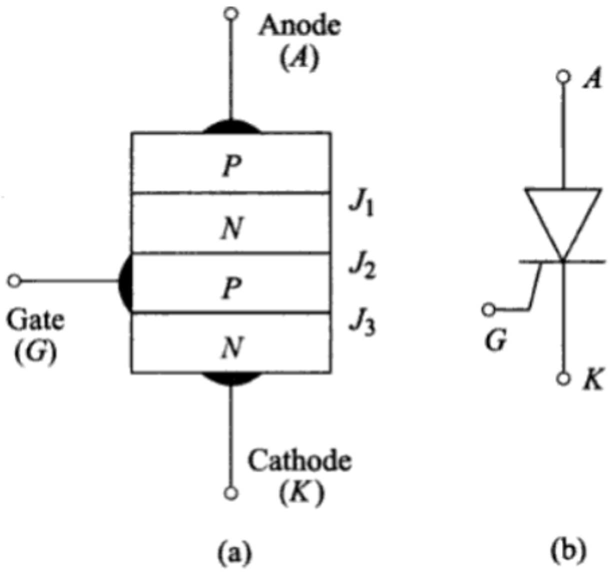


Fig. 2.1 ***(a)*** *Structure* ***(b)*** *symbol*

When the end P layer is made positive with respect to the end N layer, the two outer junctions J_1 and J_3 are forward biased but the middle junction J_2 becomes reverse biased. Thus, the junction J_2 because of the presence of the depletion layer does not allow any current to flow through the device. Only leakage current, negligibly small in magnitude, flows through the device due to the drift of the mobile charges. This current is insufficient to make the device to conduct. In other words, SCR under the forward biased condition does not conduct. This is called as the *forward blocking state or off-state of the device.*

The width of the depletion layer at the junction J_2 decreases with the increase in anode and cathode voltage (width is inversely proportional to voltage). If the voltage between the anode and the cathode is kept on increasing, once it reaches the forward break-over voltage, the depletion layer J_2 vanishes. The reverse biased junction J_2 will breakdown due to the large voltage gradient across its depletion layer. This phenomenon is known as the *Avalanche breakdown.* Since the other junctions J_1 and J_3 are already forward biased there will be a free carrier movement across all the three junctions resulting in a large amount of current flowing through the device from anode to cathode. Due to the flow of this forward current, the device starts conducting and it is then said to be in the conducting state or *on state.*

When the end N layer is made positive with respect to the end P layer, the middle junction J_2 becomes forward biased, whereas the two outer junctions, J_1 and J_3 become reverse biased. The junctions J_1 and J_3 do not allow any current to flow through the device, except a very small amount of leakage current due to the drift of charges which is insufficient to make the device conduct. This is known as the *reverse blocking state or off-state* of the device.

STATIC ANODE-CATHODE CHARACTERISTICS OF SCR

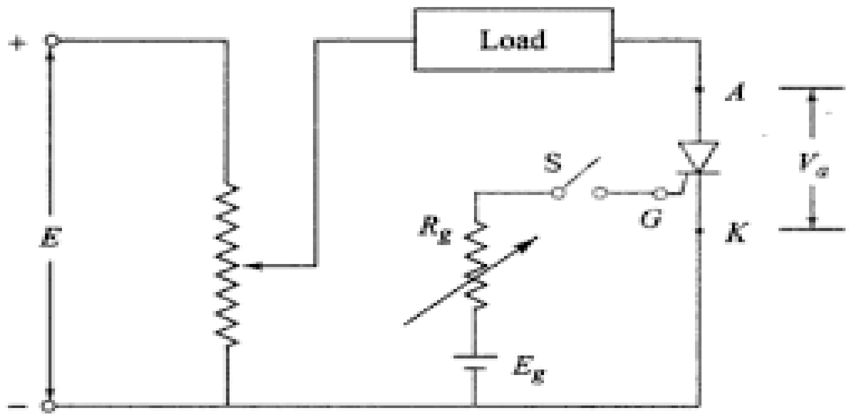


Fig.1 *Elementary circuit*

An elementary circuit diagram for obtaining static V−I characteristics of a SCR is shown in Fig. 1. Here, the anode and cathode are connected to the main source through a load. The gate and cathode are fed from another source Eg.

The static V−I characteristic of an SCR is shown in Fig. 2. Here, Va is the anode-cathode voltage and Ia is the anode current. The thyristor V−I characteristics is divided into three regions of operation. These three regions of operation are described below.

1. Reverse Blocking Region: When the cathode is made positive with respect to anode with the switch S open (Fig.1) the thyristor becomes reverse biased. In Fig. 2, OP is the reverse blocking region. In this region, the SCR exhibits a blocking characteristic. In this reverse biased condition, the outer junction J1 and J3 are reverse biased and the middle junction J2 is forward biased. Therefore, only a small leakage current (in 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 J1 and J3 increasing the current sharply. If this current is not limited to a safe value, power dissipation will increase to a dangerous level that may destroy the device.

If the reverse voltage applied across the device is below this critical value, the device will behave as a high-impedance device (i.e., essentially open) in the reverse direction.

The inner two regions of the SCR are lightly doped compared to the outer layers. Hence, the thickness of the J2 depletion layer during the forward biased conditions will be greater than the total thickness of the two depletion layers at J1 and J3 when the device is reverse biased. Therefore, the forward break-over voltage V_{BO} is generally higher than the reverse break-over voltage V_{BR}.

2. Forward Blocking Region: In this region, the anode is made positive with respect to the cathode and therefore, junctions J1 and J3 are forward biased while the junction J2 remains reverse biased. Hence, the anode current is a small forward leakage current.

The region OM of the V–I characteristic is known as the forward blocking region when the device does not conduct.

3. Forward Conduction Region: When the anode to cathode forward voltage is increased with the gate circuit kept open, leakage current continues to be marginally increasing until voltage V_{BO} called as forward breakdown voltage where Avalanche breakdown occurs and SCR starts conducting. This region of conduction is called as forward conduction region. Anode current is now limited by load resistance in SCR circuit. Once it conducts, it acts as a closed switch with very a little resistance. Hence voltage drop across SCR will be nearly zero in the order of 1-2 volts.

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 the 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). For most industrial applications, this holding current (typically 10 mA) can be regarded as being essentially zero. Note that latching current is associated with turn-on process and holding current with turn-off process.

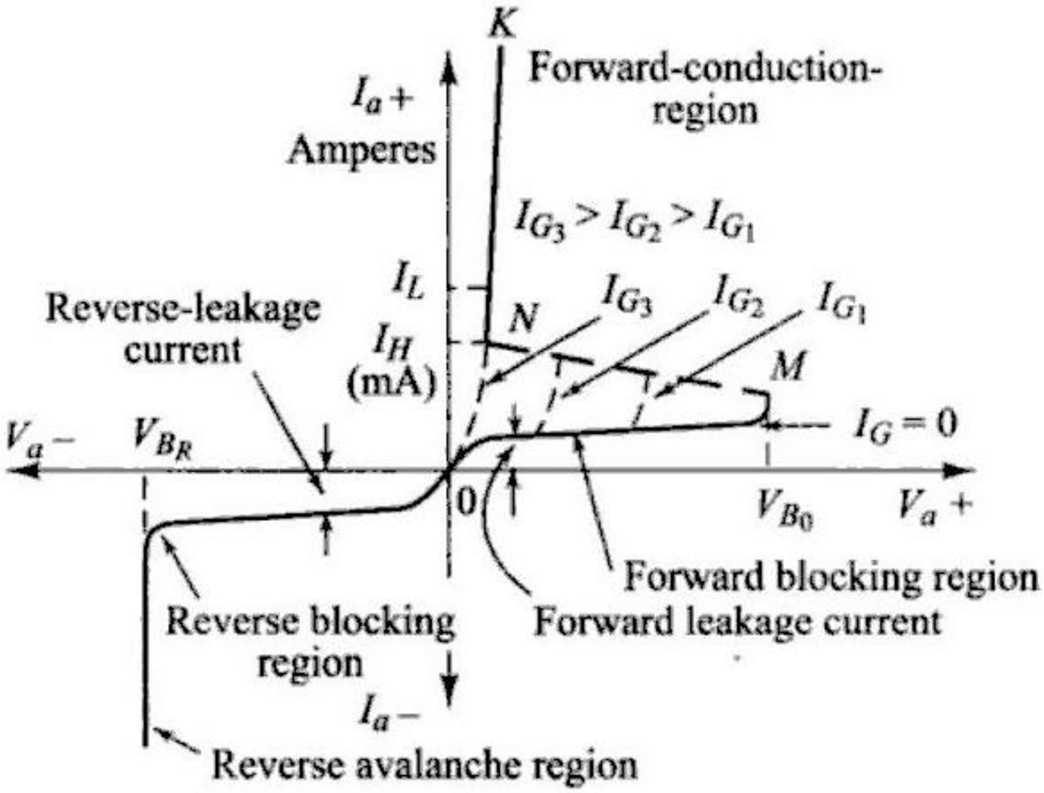


Fig. 2 V-I Characteristics of SCR.

GATE CHARACTERISTICS OF SCR:

In a thvristor, the gate is connected to the cathode through a PN junction and resembles a diode. Therefore, the V-I characteristic of a gate is similar to a diode but varies considerably in units.

The circuit which supplies firing signals to the gate must be designed so that the gate voltage voltage should not exceed the maximum voltage, and power capabilities of the gate.

Figure 2.7 shows the gate characteristics of a typical SCR. Here, positive gate to cathode voltage Vg, and positive gate to cathode current Ig represent d.c. values. Applying gate drive increases the minority carrier density in the inner P layer and thereby facilitate the reverse breakdown of the junction J2.

In Fig. 2.7 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 S1 to S2, must be as close as possible to the permissible

There are maximum and minimum limits for gate voltage and gate current to prevent the permanent destruction of the junction and to provide reliable triggering. Similarly, there is also a limit on the maximum instantaneous gate power dissipation (Pgmax = Vg Ig).

With pulse firing, a larger amount of instantaneous gate power-dissipation can be tolerated if the average-value of Pg, is within the permissible limits. Hence, the gate can be driven harder (greater Vg and Ig) when pulse tiring is used.

This provides for reliable and faster turn-on ot- the device. 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 regions of importance.

(I) 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 (usually 125°C).
(II) 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 tiring points of all devices.
(III) The third region is the largest and shows the limits on the gate-signal for reliable firing.

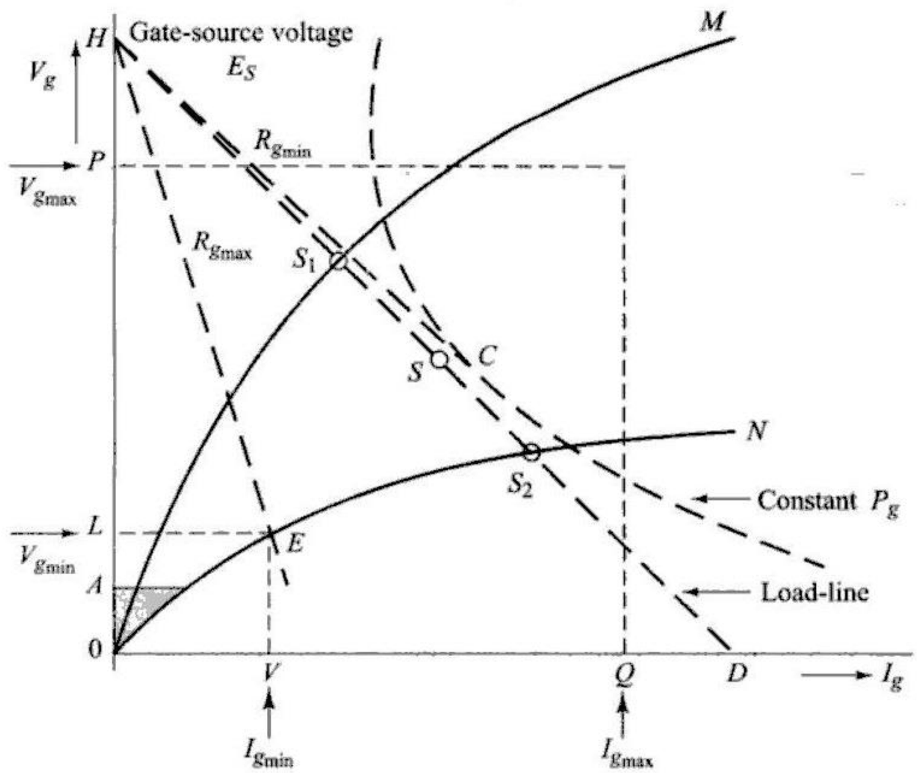


Fig. 2.7 *Gate characteristics*

For selecting the operating point, usually a load line of the gate source voltage Es=OH is drawn as HD. The gradient of the load line HD (=OH/OD) will give the required gate source resistance R. 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 agate source series resistance is obtained by drawing a line HC tangential to Pg curve.

When the thyristor is triggered using gate pulses, it should he 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. 2.8. then $T \geq t_{on}$

For Fig. 2.8 pulses, the duty cycle δ = T/T1. Then, the Average power Pavg is related to the maximum instantaneous power Pmax by

Pavg = Pmax.δ

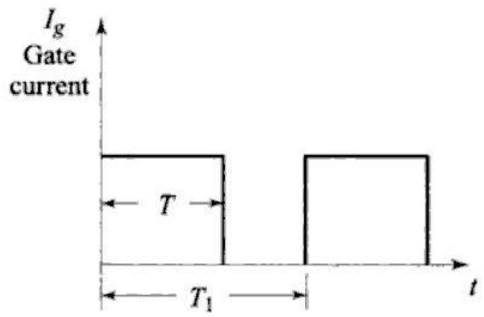


Fig. 2.8 *Pulse gating*

Gate Circuit Parameters:

The Gate Cathode circuit with different circuit parameters is shown in Fig.2.9.

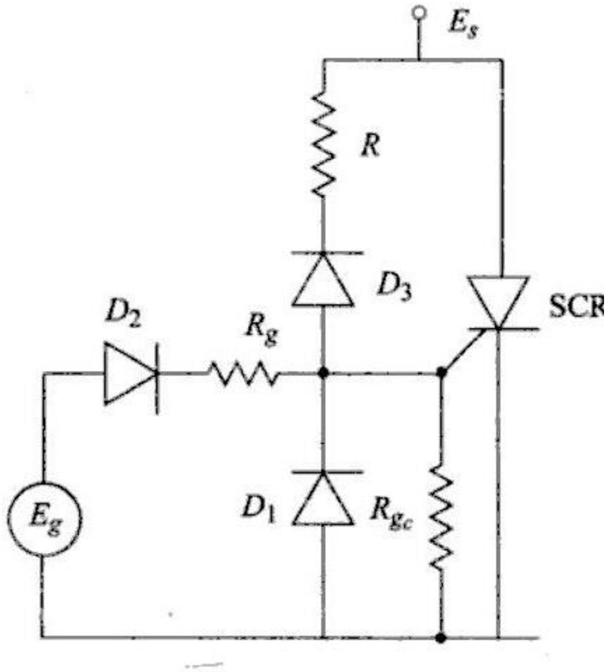


Fig. 2.9 *Gate circuit*

The shunt resistor Rgc, is introduced to bypass the thermally generated leakage current across junction when the device is in the blocking state, in order to improve the thermal-stability of the device.

Diode D1 applies a negative voltage between the gate and the cathode when a reverse voltage is applied across the device. It also serves to limit the reverse voltage applied between the cathode and the gate, if the gate, source voltage Eg is alternating.

A series diode D2 in the circuit will prevent the negative source current. D3 is connected as shown in the figure to block the positive gate current coming from the supply when the device is forward biased.

A shunt capacitor may be connected across gate to cathode to improve the dv/dt capability. However, pulse firing results in a larger portion of the gate drive being bypassed by the capacitor which will increase the delay time and consequently the di/dt rating cif the device is also lowered. Further, when the device is turned ON, the gate acts as a voltage source and charges the capacitor. This charge can provide enough gate current after the anode current has stopped thereby increasing the turn-off time of the SCR and commutation may fail.

If an inductance is connected across gate to cathode, the negative gate current is maintained by the inductance even after the anode-current has stopped, and this will facilitate faster turn-off. However, when pulse firing is used, the negative gate current that continues to flow out of the gate can possibly turn-off the thyristor.

TURN ON METHODS OF A THYRISTOR

A Thyristor can be switched on and off from a non-conducting state to a conducting state in the following ways:

1. **Forward Voltage Triggering:**
   When the gate circuit is open and anode-to-cathode forward voltage is increased, reverse biased junction J_2 will undergo avalanche breakdown at a voltage called the forward breakover voltage $V_{BO.}$ The thyristor changes from OFF state (High voltage with low leakage current) to ON state (low voltage and large forward current). Forward voltage drop across the SCR during the ON state is of the order of 1 to 1.5V and increase slightly with load current.

2. **Thermal Triggering (Temperature Triggering):**
   The Thyristor's depletion layer's width decreases on increasing junction temperature. Hence, when the voltage applied between the anode and cathode is very near to the breakdown voltage, device can be triggered by increasing its junction temperature. Within specified limits, by increasing the junction temperature to a certain value, the reverse biased junction collapses making the device conduct.

3. **Radiation Triggering (Light Triggering):**
   In this method, the energy is imparted by radiation. Thyristor is bombarded with energy particles such as neutrons or photons. This external energy generates electron-hole pairs in the device, thus increasing the number of charge carriers. This leads to instantaneous flow of current and thus the triggering of the device. However, for this type of trigerring to occur, device must have a high value of rate of change of voltage (dv/dt). Light Activated Silicon Controlled Rectifier (LASCR) and Light Activated Silicon Controlled Switch (LASCS) are two examples.

4. **Dv/dt Triggering:**
   With forward voltage across the anode and the cathode, junctions J_1 and J_3 are forward biased and J_2 is reverse biased. 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 tend to flow that turns the device ON. If voltage across the device is denoted by V, charge by Q and capacitance by C_j, then,

$i_c = dQ/dt = d(C_jV)/dt = C_j\, dV/dt + V\, dc_j/dt$

The rate of change of junction capacitance may be negligible as the junction capacitance is almost constant. Contribution of charging current by latter term is negligible and hence above equation becomes

$i_c = C_j\, dV/dt$

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

5. **Gate Triggering:**

This is the most commonly used method for triggering SCRs.
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 specified values of the maximum and minimum gate currents.
A signal is applied between the gate and the cathode of the device. Three types of signals like dc signal, pulse signal or ac signal can be used for this purpose.

i) D.C. Gate Triggering:

A D.C. voltage of proper magnitude and polarity is applied between the gate and the cathode of the device such 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.
Disadvantage: the power and control circuits are D.C. and there is no isolation between the two. Also, a continuous D.C. signal has to be applied at the gate causing more gate power loss.

ii) A.C. Gate Triggering:

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. 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.
Disadvantage: A separate transformer is required to step down the A.C. supply, which adds to the cost.

iii) Pulse Gate Triggering:

This is the most commonly used method of triggering. 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.

TURN-OFF MECHANISM (TURN-OFF CHARACTERISTIC)

Once the SCR is turned-on and an appreciable forward current is flowing through it, the gate has no control on it and the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current.

Process of turn-off of SCR is is also called as Commutation.

However, if' a forward voltage is applied immediately after reducing the anode current to zero, it will not block the forward voltage and will start conducting again, although it is not triggered by a gate pulse. It is, therefore, necessary to keep the device reverse biased for a finite period before a forward anode voltage can be reapplied.

The turn-off time of the thyristor is defined as the minimum time interval between the instant at which the anode current becomes zero, and the instant at which the device is capable of blocking the forward voltage.

The turnoff time is illustrated by the waveforms shown in Fig. 2.11. The total turn-off time is divided into two time intervals the reverse, recovery time t_{rr} and the gate recovery time t_{gr}.

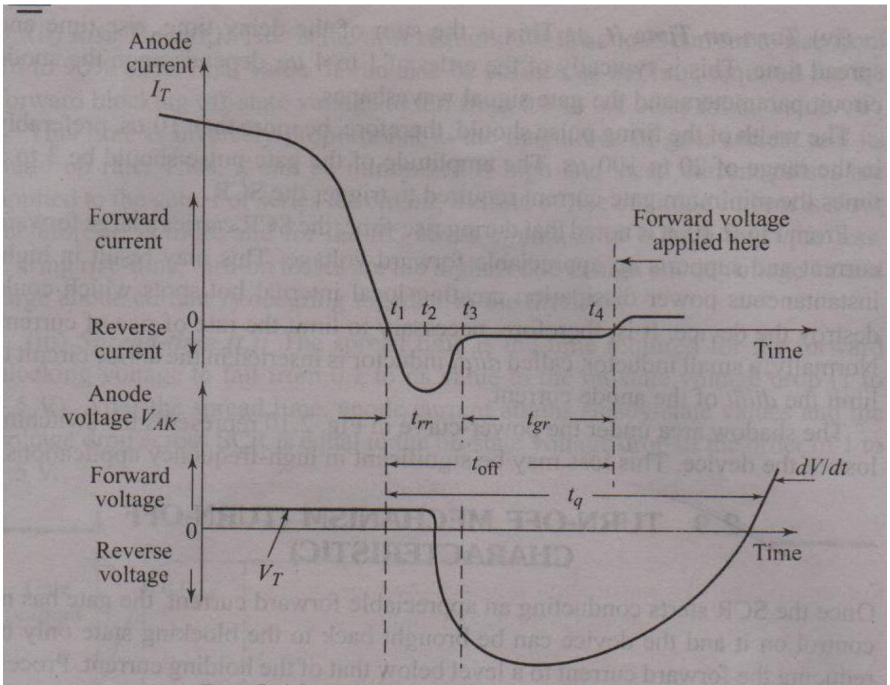


Fig. 2.11 *Waveforms during SCR turn-off*

At the instant t_1, the anode forward current becomes zero. During the reverse recovery time, t_1 to t_3, the anode current flows in the reverse direction. At the instant t_2 a reverse anode voltage is developed and the reverse recovery current continues to decrease,

At t_3 junction J_1 and J_3 are able to block a reverse voltage. However, the thyristor is not yet able to block a forward voltage because carriers, called *trapped charges* , are still present at the junction J_2. During the interval t_3 to t_4, these carriers recombine. At t_4 the recombination is complete and therefore, a forward voltage can he reapplied at this instant.

The SCR turn-off time is the interval between t_4 and t_1. In an SCR, this time varies in the range 10 to 100 µs. Thus, the total turn-off time (t_q) required for the device is the sum of the duration for which the reverse recovery current flows after the application of reverse voltage, and the time required for the recombination of all excess carriers in the inner two layers of the device.

Turn-Off Methods

The term commutation in SCRs is to transfer current from one thyristor to another. A thyristor itself cannot turn off once it is conducting. The circuit in which it is connected should reduce the thyristor current to zero to turn it off.

The two methods by which a thyristor can be commutated are as follows:

1. Natural Commutation

This is the most simplest and widely used method as it uses a.c. voltage to effect the current transfer. In an a.c. supply, the current passes through zero at every half cycle.

At the end of every positive half cycle, the anode current reaches zero. As it passes through natural zero, a reverse voltage will appear across the thyristor which immediately turn-off the device. This process is called Natural Commutation as no external source is required to turn-off the device. This method may use a.c. mains supply voltages or the voltages generated by local rotating machine.

2. Forced Commutation

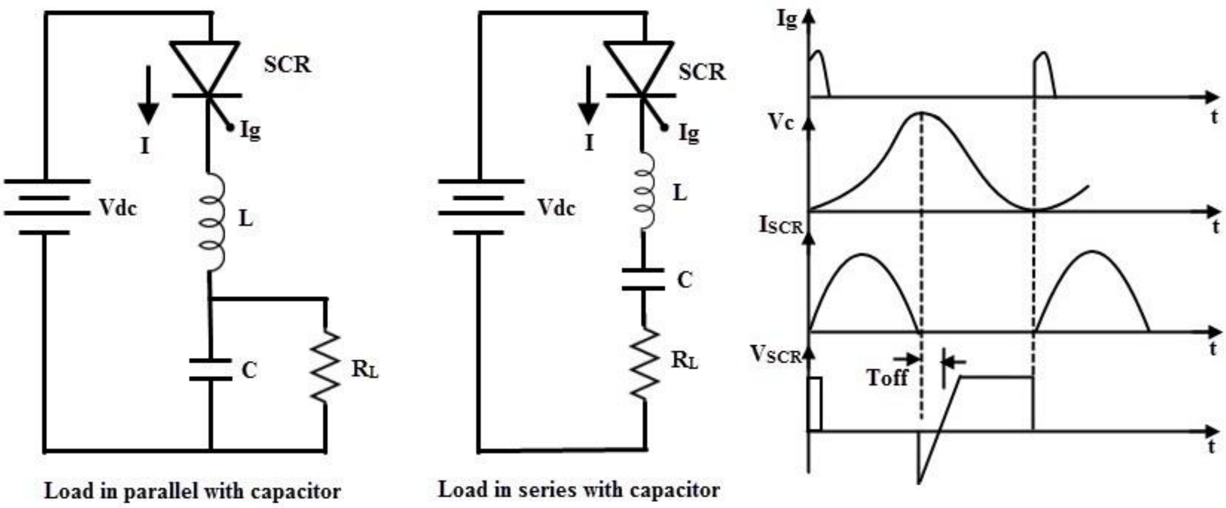
In the case of d.c. circuits, for switching off thyristor, forward current must be forced to zero. This can only be done with the help of an external circuit. The external circuit required for commutation is called commutation circuits and the components used are called commutation components namely inductance and capacitance. With the help of this circuit, reverse voltage will appear across the thyristor which will make the device to turn-off.

Based on the arrangement of the commutation components and the manner in which zero current is achieved, it is classified into various types.

Class A - Self Commutation by Resonating the Load

This is also known as Resonant Commutation. LC components are used where either (i) load resistance is in parallel with Capacitor as shown in Fig. 2.12a or (ii) it is in series with the Capacitor as shown in Fig. 2.12b.

The load resistance RL and the other components are chosen such that their combination forms an underdamped resonant circuit.



(a) Load in parallel with Capacitor (b) Load in series with Capacitor (c) Waveforms for Load in parallel with capacitor

Fig. 2.12 Class A Commutation Circuit.

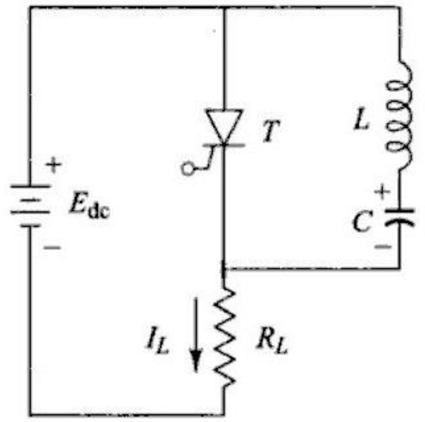
When the thyristor is triggered by applying a gate pules, the forward current suddenly increases. This current starts charging the capacitor.

As the voltage across capacitor starts building up, the SCR cathode voltage increases as a result the net voltage across SCR decreases and current also starts decreasing. When the capacitor voltage reaches the maximum supply Vdc, anode current becomes zero and SCR is turned off, since the potential difference between anode and cathode is zero at this point.

Now capacitor starts discharging through the load and reaches zero voltage gradually. Again to switch on SCR a gate pulse has to be applied.

Class B – Self Commutation by an LC Circuit:

In this Class-B circuit the advantage is that the commutation circuit does not carry the load current. Whereas, the Class-A commutation circuits carry the load current. The commutating circuit and the relevant waveforms are shown in Fig. 2.15 and 2.16.



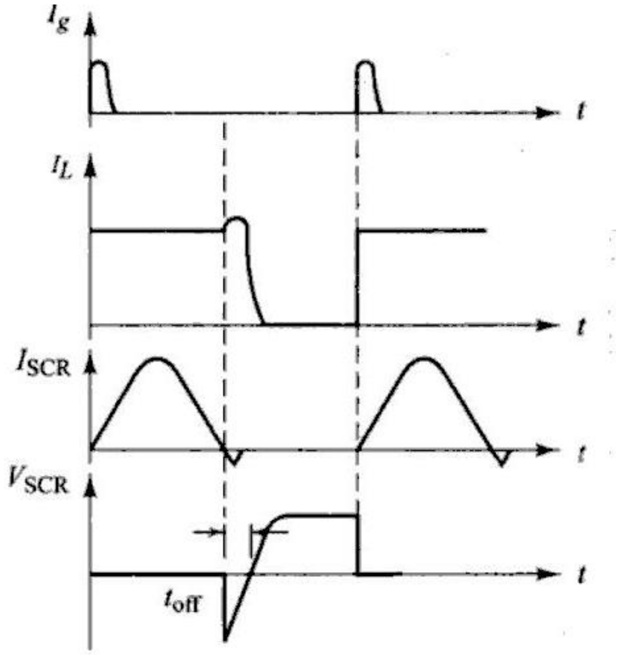


Fig. 2.15 *Class B commutation circuit* **Fig. 2.16** *Associated waveforms*

Initially, as soon as the supply voltage Ed, is applied, the capacitor C starts getting charged with its upper plate positive and the lower plate negative, and it charges up to the voltage Edc. When thyristor T is triggered the circuit current flows in two directions: (1) The load current I_L flows through the path +Edc, T R_L -Edc, and (2) Commutating current Ic.

The moment thyristor T is turned ON, capacitor C starts discharging 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 Ic starts flowing which Opposes the load current I_L. When the commutating current is greater than the load current, thyristor becomes turned OFF. When the thyristor T is turned OFF, capacitor C again starts getting charged to its original polarity through L and the load.

Once the thyristor is ON, it switches off after sometime on its own, hence it is self commutation type. 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, where the thyristor is required to be in conduction state and off state for a specified duration of time.

Gate Trigger Circuits

The general blck diagram of a gate-trigger circuit in a single phase converter is as shown in Fig 1.

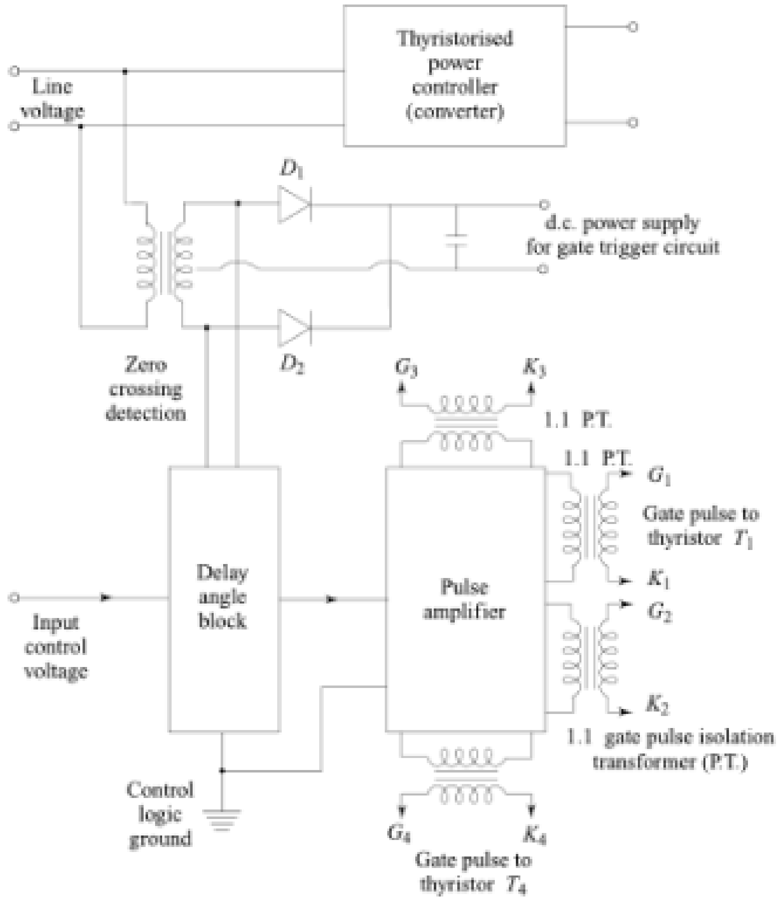


Fig 1. General Block diagram of a Thyristor Gate Trigger Circuit

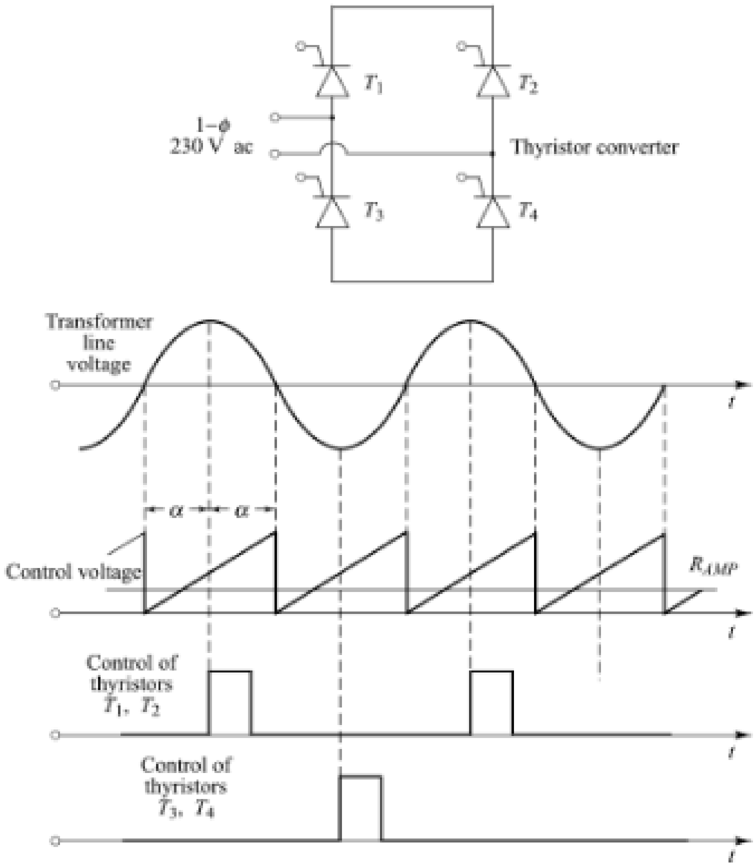


Fig.2 Waveforms of the Gate trigger circuit

(Instead of Fig. 2, use the Figure drwan in the Class)

- The thyristors are at line potential and the trigger circuit supply voltage is derived from theis line voltage for synchronization through a transformer which isolates the line voltage from trigger circuit.
- A DC voltage is generated for the gate circuit by rectification.
- The AC synchronization voltage is converted into ramp voltage in the delay angle block, which gets synchronized to the zero crossing of the line voltage. (as shown in Fig 2.)
- The ramp voltage is compared with the control voltage.
- During alternate half cycles, when the ramp voltage equals the control voltage, a pulse signals of controllable duration is generated and these pulses are used to trigger the SCR's.
- Thus, the delay angle can be varied over 0-180 degrees by suitably varying the control voltage.

Resistance Firing Circuit:

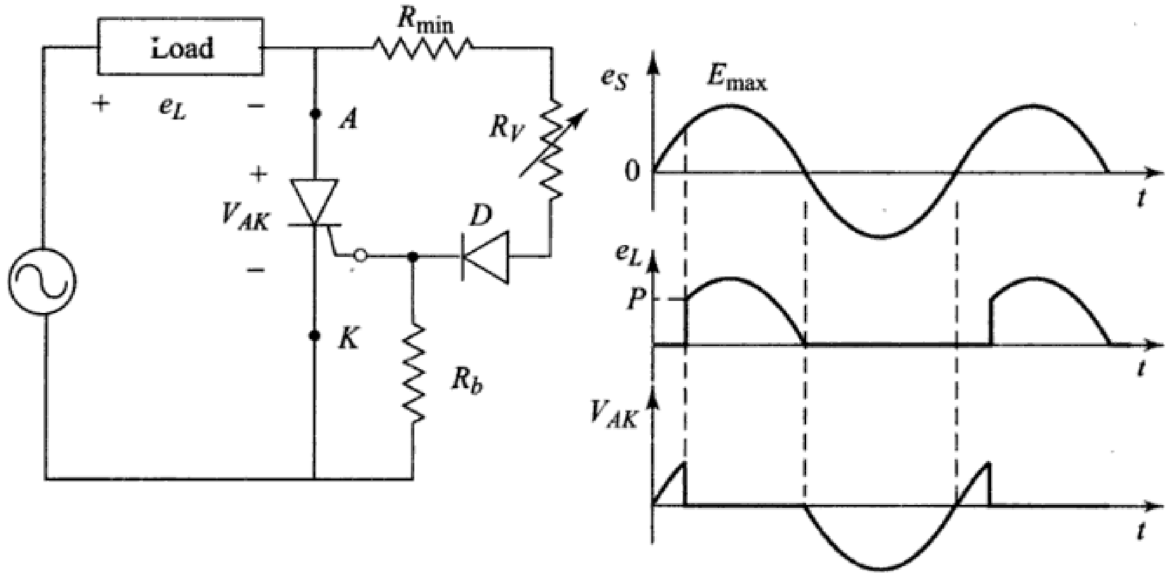


Fig.1 *R-firing circuit and associated voltage waveforms*

It is a simple method of firing the SCR at varying trigger angles using ac gate supply instead of gate pulses.

The ac supply of gate is derived from the main anode ac supply e_s through a resistor R_{min} and Rv and a diode D.

Operation:

- As e_s, goes positive, dode D and SCR is forward biased. But SCR will not conduct until corresponding gate voltage produce gate current that exceeds the minimum gate current Ig(min) to fire the SCR.
- The gate current will increase as e_s increases towards its peak value. When Ig reaches Ig(min) SCR turns "ON" and load voltage e_L will approx be equal to e_s.
- SCR remains "ON" and $e_L = e_s$, until e_s decreases to the point where the load current is below SCR holding-current.
- When the anode current below holding value, SCR turns "OFF" and remains "OFF" as duirng negative half cycle of the input as SCR is reverse biased. SCR is now an open switch.
- The diode is employed to prevent 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 Emax.
- The same sequence is repeated when e_s again goes positive.

By increasing the value of Rv, the gate current reaches Ig(min) lately and firing angle is increased.

Resistance firing is the simplest and most economical, but it has limited range of firing angle control i.e 0 degree to 90 degrees.

In Fig. 1 Rv is variable resistance and Rb is the stabilizing resistance. The function of Rmin is to limit the gate current to a safe value when Rv is zero. (This current should not exceed maximum permission gate current Igm).

The value of Rmin can be calculated from eqn $Vm/Rmin \leq Igm$

Or $Rmin \geq Vm/Igm,$ where, Vm- Maximum value of source voltage.

The stabilization resistor Rb should have such a value that the maximum voltage drop across it does not exceed maximum possible gate voltage Vg(max). This can happen only when Rv is zero. Uunder this condition,

$$I\ Rb \leq Vg(\mathrm{max})$$

$$Vm.(Rb/(Rmin+Rb)) \leq Vg(max)$$

$$Vm.Rb \leq (Rmin+Rb).Vg(max)$$

$$Vm.Rb \leq Rmin.Vg(max)+Rb.Vg(max)$$

$$Rb.(Vm-Vg(max)) \leq Rmin.Vg(max)$$

$$\mathbf{Rb \leq (Rmin.Vg(max))/(Vm-Vg(max))}$$

The SCR will trigger when the instantneous anode voltage $e_{s,\ is}$

e_s = Ig(min) (Rv + Rmin) + Vd + Vg(min); where Vd is the diode drop

Resistance-Capacitance Firing circuit:

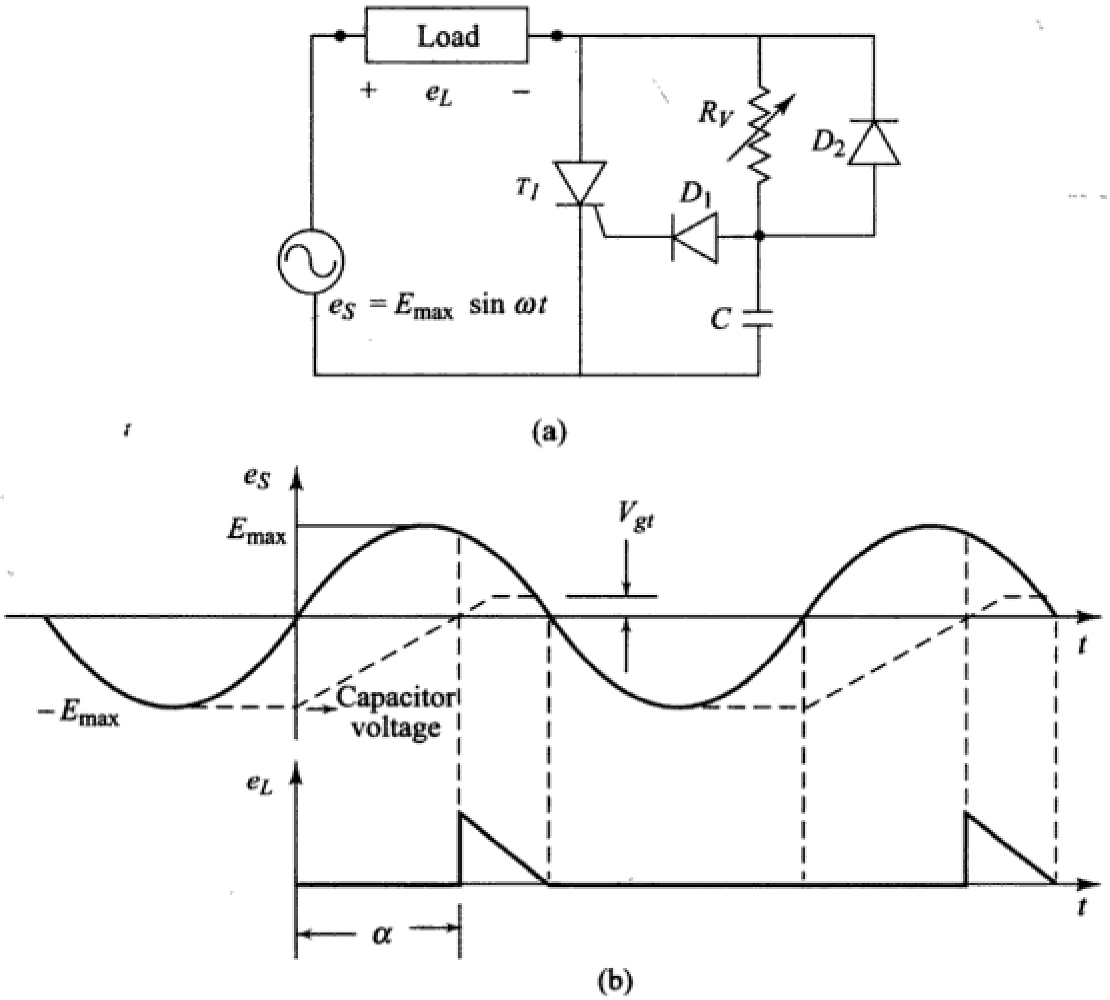


Fig.1 ***(a)*** *RC firing circuit,* ***(b)*** *voltage-waveform*

Fig.1 above shows an RC half wave trigger circuit. By the inclusion of the capacitor, the gate voltage donot raise in phase with the supply voltage, since capacitor takes some time to reach the maximum voltage level of the input. The rise time depends on the RC time constant. Hence, it is possible to delay the firing angle from 0 to 180 degrees in RC triggering.

By varying resistor R_v, the firing angle can be controlled from 0 to 180 degrees.

- In the negative half cycle , capacitance 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 attains zero value.
- During positive half cycle, SCR anode voltage passes through zero and becomes positive and capacitor C begins to charge through R_v from the initial voltage $-E_{max}$.

- When the capacitor charges to positive voltage is equal to gate trigger voltage $V_c = V_{gt}$ ($V_{g(min)} + V_{D1}$) SCR is triggered.
- During negative half cycle, the diode D_1 donot conduct and SCR is also turns off.

In the range of power frequencies, the RC for zero output voltage is given by $R_vC >= 1.3(T/2) = 4/\omega$, where T =1/f =period of ac line frequency .

Therefore, the maximum value of R_v is given by

$$e_s = I_{g(min)}R_v + e_c$$

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

Hence, $R_v <= (e_s - V_{g(min)} - V_{D1})/I_{g(min)}$

where, e_s is the instantaneous supply voltage at which the thyristor will turn ON.

Resistor Capacitor -Full-Wave Trigger Circuit:

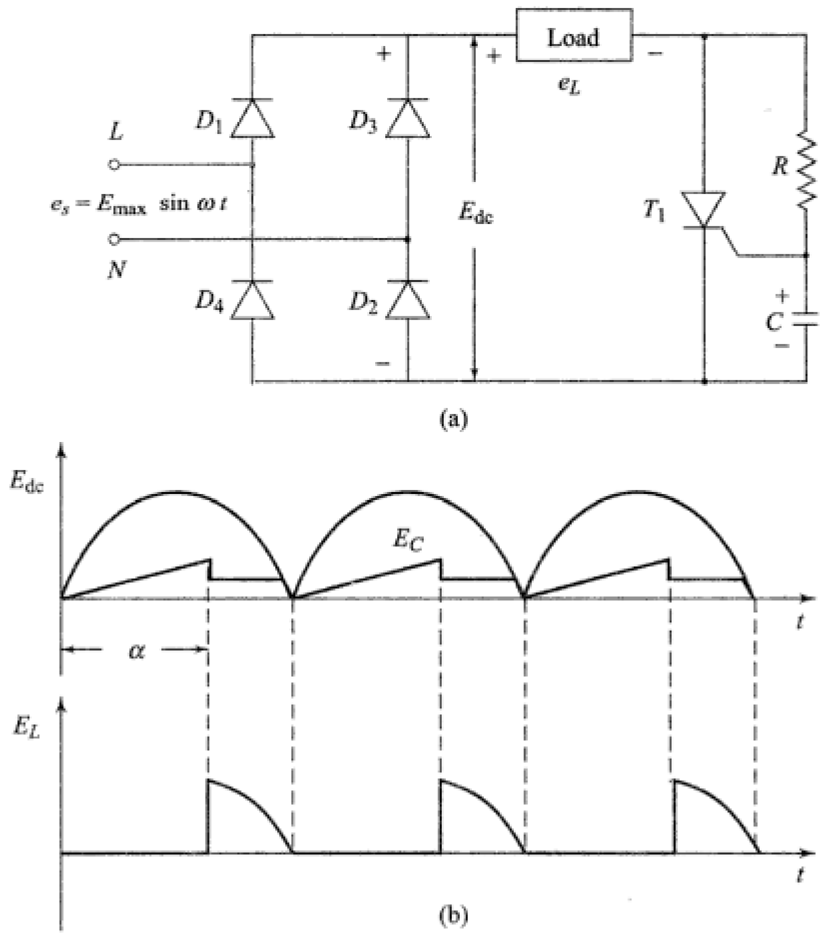


Fig.1 *(a) RC full-wave trigger circuit (b) with waveforms*

Since a full wave diode bridge rectifier is used, the anode supply voltage to SCR is a full wave pulsating DC. Hence, SCR is fired during each half cycle of the ac mains supply.

- In this circuit, the initial voltage from which capacitor C charges is almost zero.
- Capacitor C is set to this low positive voltage by clamping action of SCR gate.
- When capacitor charges to a voltage equal to V_{gt} , SCR triggers and rectified voltage E_{dc} appears across load as e_L.
- The value of RC is obtained from the following relation

  $RC >= 50\ (T/2) = 157/\omega$

  The value of R is given by $R <= (e_s - V_{gt})/I_{g(min)}$

Section 3.6.3 – UJT Relaxation Oscillator

The UJT is often used as a trigger device for SCRs, TRIACs, non-sinusoidal oscillators, sawtooth generators, phase-control, and timing circuits. The most common UJT circuit in use today is the relaxation oscillator shown in Fig. 3.18. Also, this type of circuit is basic to other timing and trigger circuits. The operation is as follows:

Let us consider the situation in which the capacitor is at zero volts and the switch is suddenly closed at t = 0 applying E_{dc} to the circuit. Since V_e= 0, the UJT emitter diode is reverse-biased and the UJT is "off" The amount of reverse bias is V_x volts which can be obtained using the voltage divider rule:

$$V_x = \frac{(R_1 + R_{B_1})E_{dc}}{R_1 + R_{B1} + R_2 + R_{B2}} \qquad (3.11)$$

In many cases, R1 and R2 are much smaller than RB1 and rb2 and Vx becomes approximately equal to ηE_{dc} (Eq 3.9)

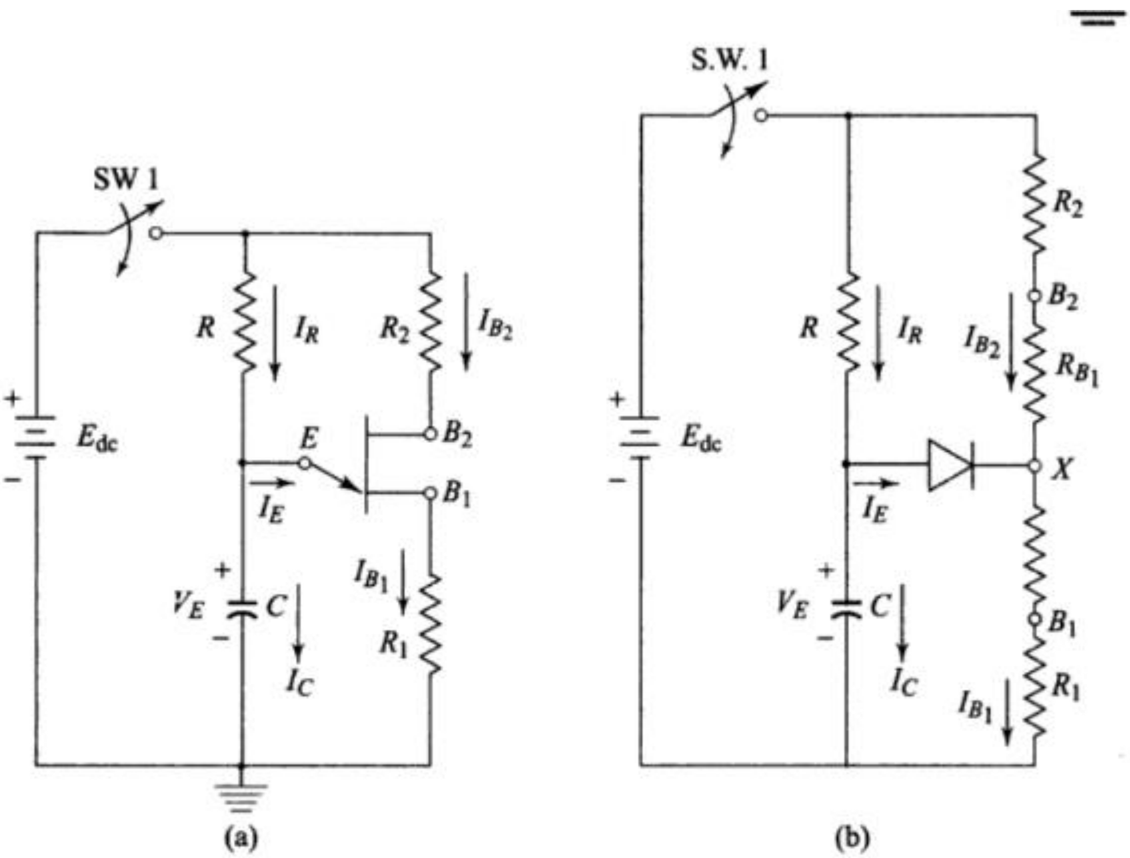


Fig. 3.18 ***(a)*** *UJT basic-relation oscillator* ***(b)*** *its equivalent circuit*

In this condition the only emitter current flowing will be small-reverse-leakage, I_{E0}. Also, R_{B1} will be at its "off" value (typically 4 KΩ). Thus we can consider the emitter to be open ($I_E \approx 0$) and the capacitor will begin to charge toward the input voltage E_{dc}, through resistor R. The capacitor voltage increases with a time constant of RC as illustrated in Fig. 3.19 (a). It will continue to increase until the voltage at the emitter reaches the peak-point value, V_{p1} given by Eq. (3.10). At this time, the emitter diode becomes forward biased and the UJT turns 'on' with R_{B1} dropping to a very low value (typically 10 ohms). Since the diode is now forward-biased, the capacitor will discharge through the low-resistance path containing the diode, R_{B1} and R_1.

The capacitor discharge time constant is normally very short compared to its charging time constant (see Fig. 3.19(b)). An analytical expression for the discharge time constant is difficult to obtain since R_{B1} will continually change as the current IE decreases. The discharging capacitor provides the emitter current needed to keep the UJT "on"; it will remain "on" until /E drops below the valley current /E, at which time the UJT will turn "off." This occurs at time T2 when the capacitor voltage has dropped to the valley voltage V, (typically 2-3 volts). At this time, RBI returns to its "off' value, the diode is again reverse-biased and $I_E \approx 0$.

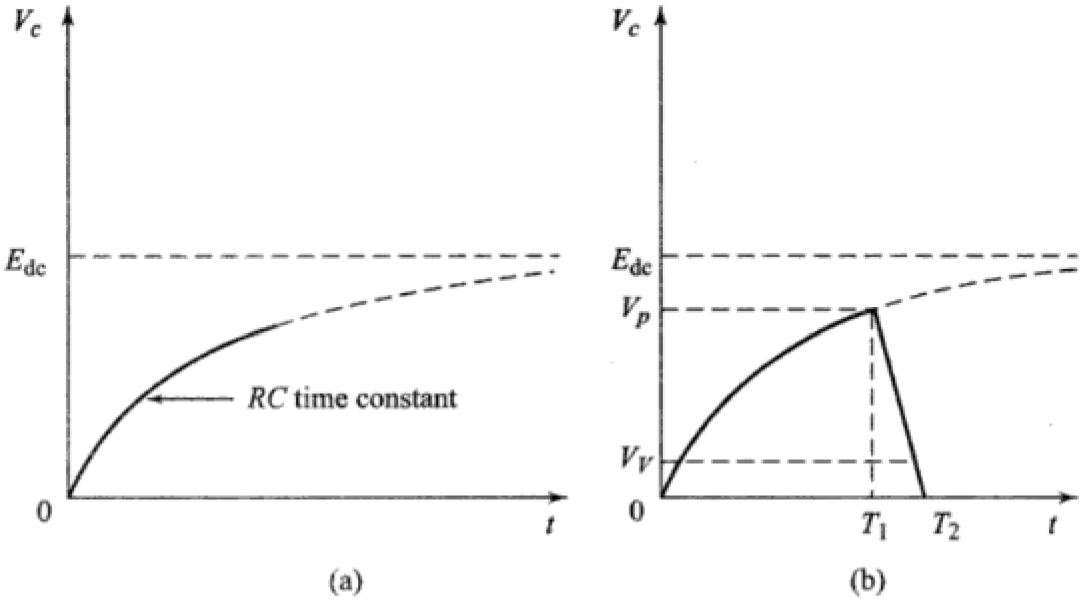


Fig. 3.19 *Capacitor waveform*

The capacitor will begin charging towards E_{dc} once again and the previous chain of events will repeat itself indefinitely as long as power is applied to the circuit. The result is a periodic sawtooth type waveform as shown in Fig. 3.20 (a).

To calculate the frequency of this waveform, we first calculate the period of one cycle. The length of one period, T1, is essentially the time it takes for the capacitor to charge to V_p since the discharge time T2 is usually relatively short. Thus $T \approx T_1$ and is given by

$$T = R.C.\ \log_e \left(\frac{E_{dc}}{E_{dc} - V_p} \right) \tag{3.12}$$

In most cases, $V_p \approx \eta\, E_{dc} + V_0$ and the period can be written as

$$T \approx R.C.\ \log_e \left[\frac{E_{dc}}{E_{dc}(1-\eta) - V_D} \right] \tag{3.13}$$

The small diode drop V_D can often be ignored if $E_{dc} > 10$ V, resulting in the more approximate expression,

$$T \approx R.C.\ \log_e \left[\frac{1}{1-\eta} \right] \tag{3.14}$$

Examination of Eq. 3.14 brings out an important point, namely that T is relatively independent of supply voltage E_{dc}. This characteristic is important when designing a stable oscillator circuit. The oscillator frequency is given by 1/T and can be obtained by using either of the three previous equations for T.

Pulse outputs

The UJT relaxation oscillator circuit can also supply pulse waveforms. If the output is taken from B_1, the result is a train of pulses occurring during the discharge of the capacitor through the UJT emitter. The waveforms of V81 is illustrated in Fig. 3.20(b). The amplitude of the B1 pulses is always less than V_{in} but is greater for larger values of C. The voltage at B1 during the UJT "off' time will be very small and is determined by the voltage divider formed by R1, Rim and R2 [see Fig. 3.18(b)] That is,

$$V_{B1}\ (\text{off}) = \left(\frac{R_1}{R_1 + R_{BB} + R_2} \right) E_{dc} \tag{3.15}$$

The rise time of the pulses at B_1 is very short (less than 1 its), but the fall time depends on the values of C and R1. A larger value of C or R1 will cause a slower capacitor discharge and a longer fall-time. If the output is taken at B2, a waveform of negative going pulses is obtained as shown in Fig. 3.20(c). This results from the decrease in RBI when the UJT turns "on". This increases IB7 which increases the drop across R2 and thus reduces V. The amplitude of this pulses is usually about a couple of volts, but can be increased by increasing R2.

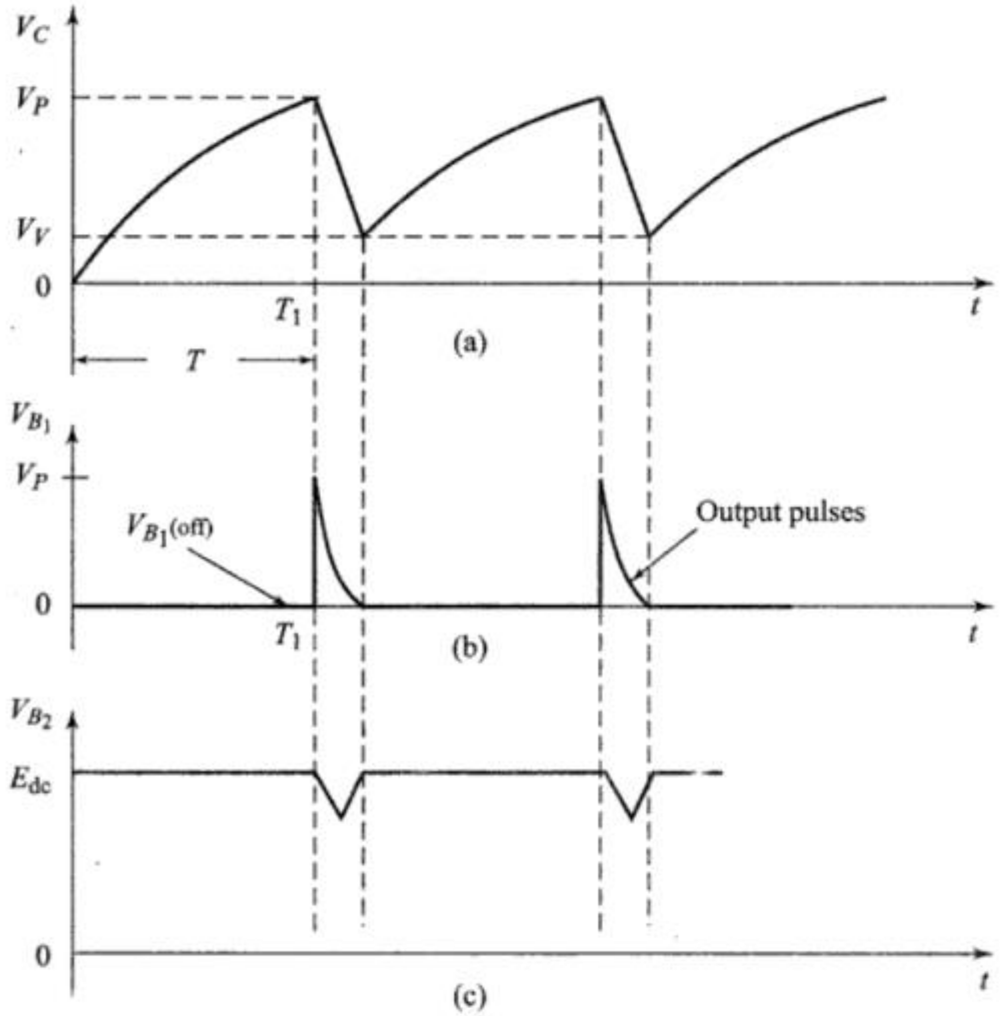


Fig. 3.20 *Waveform for UJT relation — oscillator*

The pulses at B1 are usually the ones of most interest, they are of relatively high amplitude and are not affected by loading since they appear across a low-valued resistor R1. These positive pulses are often used to trigger SCRs or other gated PNPN devices. The amplitude of these pulses is to some degree dependent on the value of C. For values of C of 1 j.iF or greater, the amplitude of the pulses is approximately equal to V41, (less than 2-3 V VJT drop). As C becomes smaller, the B1 pulse decrease in amplitude. The reason for this is that the smaller value for C discharges a significant amount during the time that the UJT is making its transition from the "off' to "on" state. Thus, when the UJT finally reaches the "on" state, C has lost some of its voltage (Vp) and less voltage can appear across RI as the capacitor continues its discharge.

Varying the frequency

The frequency of oscillations is normally controlled by varying the charging time constant RC. There are, however, limits on R. These limits are:

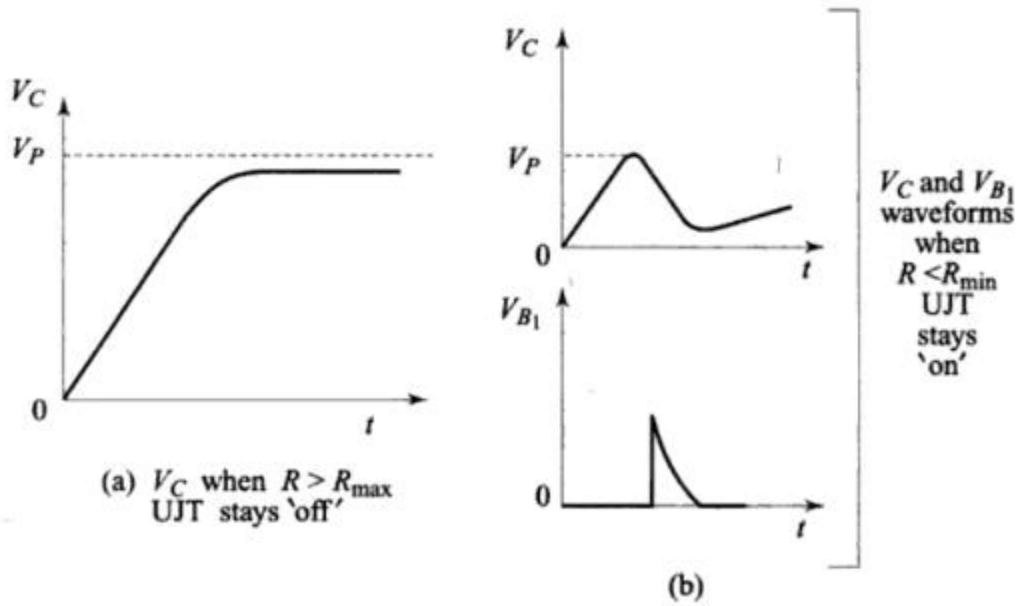


Fig. 3.21 ***(a)*** *V_c waveform when $R > R_{max}$;* ***(b)*** *V_c and R_{B_1} when $R<R_{min}$*

If R is smaller than /2„,,„, the capacitor will reach V,, and discharge through the UJT, but the Ulf will not turn "off" since the current through R is greater than the Iv needed to hold the UJT "on". The capacitor and V8 waveforms will consists of a single (Fig. 3.21(b)) representing one charge and discharge interval. This single pulse operation is sometimes used in time delay applications. The time delay is given by Eq. 3.12. Examination of Eq. 3.16 indicates that to obtain a greater upper limit on frequency (a lower the value of /v should be made larger. Similarly, to obtain a smaller lower limit on frequency (a higher R.) the value of /0 should be made smaller. UJTs with /„ as high as 20 mA and I_p as low as 1 AA are presently available, resulting in a possible frequency range of 4000: 1. The frequency may also be varied by varying C. The lower limit on C is normally around 0.001 i.tF, while the upper limit depends on the size of RI (which limits on discharge current). In most applications of this circuit, the value of C is kept fixed and a variable resistor is used for R. The temperature stability of the UJT relaxation oscillator frequency is normally very good. This is because q varies only slightly with temperature and the only variation in VI, is due to the small decrease in VD (2 mV/°C) with temperature. Its stability of frequency with variations in temperature and supply voltage coupled with its simplicity and low cost make the UJT oscillator a popular circuit for timing and pulsing applications.