Northern technical university

Technical institute / Mosul

Power Electronics

Electrical Department

(Power & Networks)

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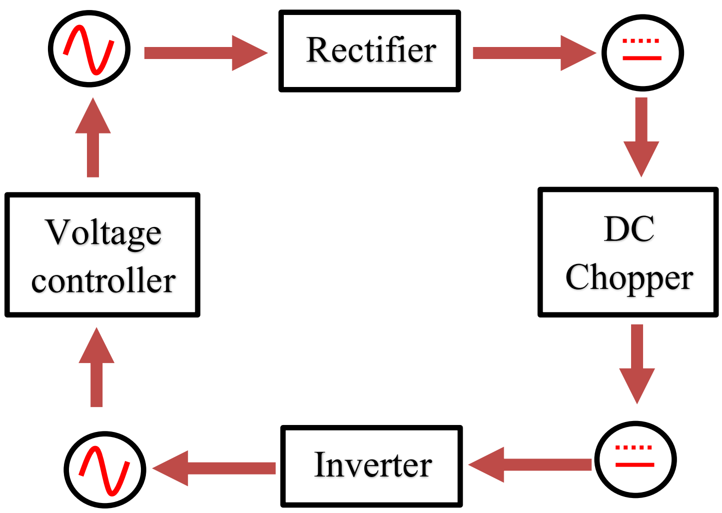
Part 1

Power Electronic Switches

Power Electronic circuits

Branch of electrical engineering devoted to conversion and control of electric power using electronic converter based on semiconductor power switches. Power conversion is changing the voltage and the frequency.

It is very important to study power electronics and its component because it is now used in each field of industrial, to change voltage from one type to other and control the speed of DC and AC motors.



The basic element in power electronic circuit is the switch.

Power Electronic Switches

There are three types of power electronics switches:

1- Uncontrolled switches: they are uncontrolled turn - on and off switches (power Diode).

2- Fully-controlled switches: they are controlled turn - on and off switches like power transistors (BJT, MOSFET, IGBT) and Gate Turn Of thyristor (GTO).

3- Semi-controlled switches: they are controlled turn on but uncontrolled turn-off switches like most of thyristors.

Advantages of semiconductor control switches:

1- Small size.

2- Light weight.

3- High speed.

4- Low control power.

5- Low drop voltage.

6- No mechanical parts.

7- Reliable operation.

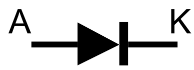
Disadvantages:

1- Limited temperature range, so heat sinks or other materials are necessary.

2- Excess reverse voltage may damage the device.

Diode as power switch

A diode has two terminals : a cathode and an anode, a diode conducts when its anode voltage is higher than that of the cathode, and the forward voltage drop of a power diode is very low, typically 0.5 and 1.2 V. if the cathode voltage is higher than its anode voltage, a diode is said to be in blocking mode.



The symbol of Power Diode

Power diodes are of three types:

1- General purpose diode.

The general purpose diodes are available up to 6000 V , 4500 A,

2- High speed (or fast recovery) diode.

The fast recovery diodes are rating up to 6000 V 1100 A and the reverse recovery time varies between 0.1 and 5 μs. the fast recovery diodes are essential for high frequency switch of power converters

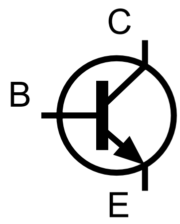
3- Schottky diode.

The Schottky diodes have low on-state voltage and very small recovery time, typically nanoseconds. The leakage current increases with the voltage rating and their ratings are limited to 100 V, 300 A.

Transistor as power switch

The bi-junction transistor (BJT):

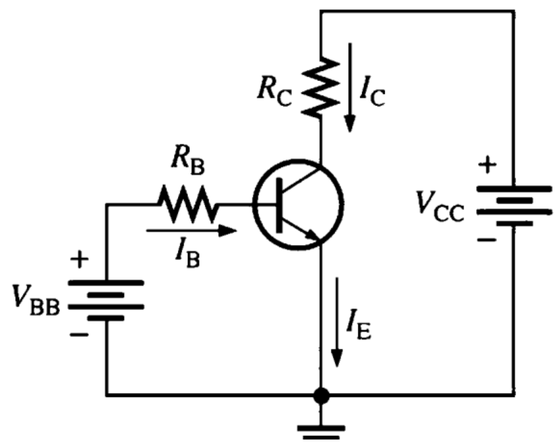
The bi-junction transistor (BJT) consists of 2 p-n junctions with three layers named as collector, base, and emitter.



The symbol of bi-junction transistor (BJT)

There are two categories of transistors PNP and NPN, the transistor is a current operating device. The base controls the amount of majority carries which are emitted from the emitter (E) to be collected in the collector (C). E and C are doped more than B so base region has higher resistance.

The amount of current flow in the base-emitter circuit controls the amount of current that flows in the collector circuit.
Small changes in base-emitter current yields a large change in collector-current.

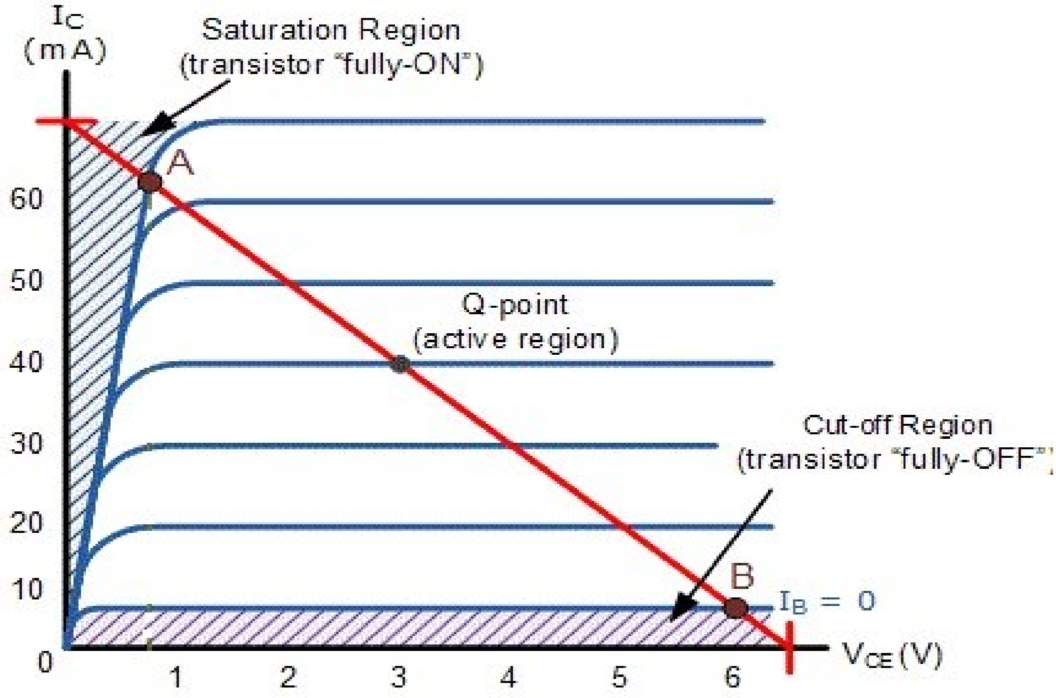


The factor of this change is called beta

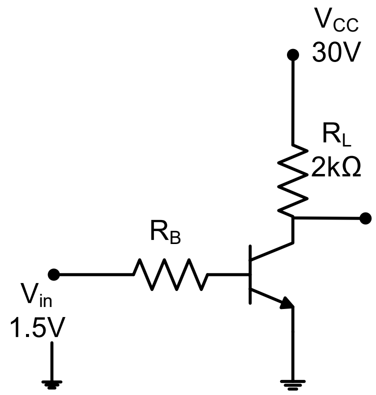
$$\beta = \frac{I_{C(sat)}}{I_{B(min)}}$$

$$10 < \beta < 1000$$

V I characteristic of transistor



Ex(1): In the following switching circuit β = 45, $V_{CE(sat)}$ = 0.15 V, V_{BE} = 0.65 V, find the value of R_B to get overdriven transistor switch.



$$V_{RL} = V_{CC} - V_{CE} = 30 - 0.15 = 29.85\ V$$

$$I_{C(sat)} = \frac{V_{RL}}{R_L} = \frac{29.85}{2000} = 14.92\ mA$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta} = \frac{14.92 \times 10^{-3}}{45} = 332\ \mu A$$

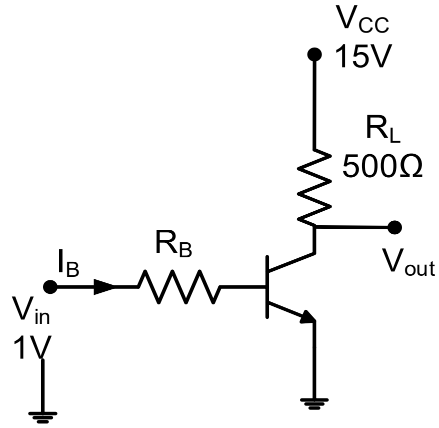
To get overdriven $I_B = 3 \times I_{B(min)}$

$$= 3 \times (332 \times 10^{-6}) = 996\ \mu A \approx 1\ mA$$

$$V_{R_B} = V_{in(max)} - V_{BE} = 1.5 - 0.65 = 0.85\ V$$

$$R_B = \frac{V_{R_B}}{I_B} = \frac{0.85}{1 \times 10^{-3}} = 850\ \Omega$$

Ex(2): Find the value of R_B if $\beta = 50$ and $V_{BE} = 0.65$ V , $V_{in} = 1$ V, the circuit is overdriven.



$$I_C = \frac{V_{CC}}{R_L} = \frac{15}{500} = 30\ mA$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta} = \frac{30 \times 10^{-3}}{50} = 600\ \mu A$$

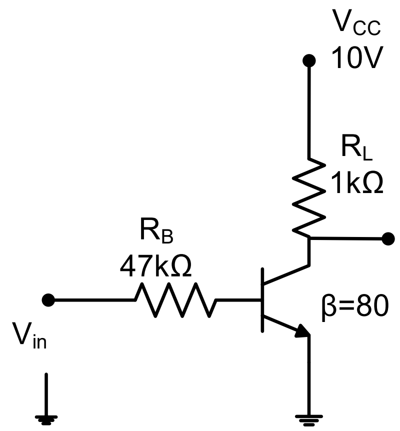
To get overdriven $\quad I_B = 3 \times I_{B(min)}$

$$I_B = 3 \times 600 \times 10^{-6} = 1.8\ mA$$

$$I_B \times R_B = V_{in} - V_{BE}$$

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{1 - 0.65}{1.8 \times 10^{-3}} = 194\ \Omega$$

Ex(3): Calculate the input voltage that make the transistor saturated $V_{BE(sat)} = 0.7$ V.



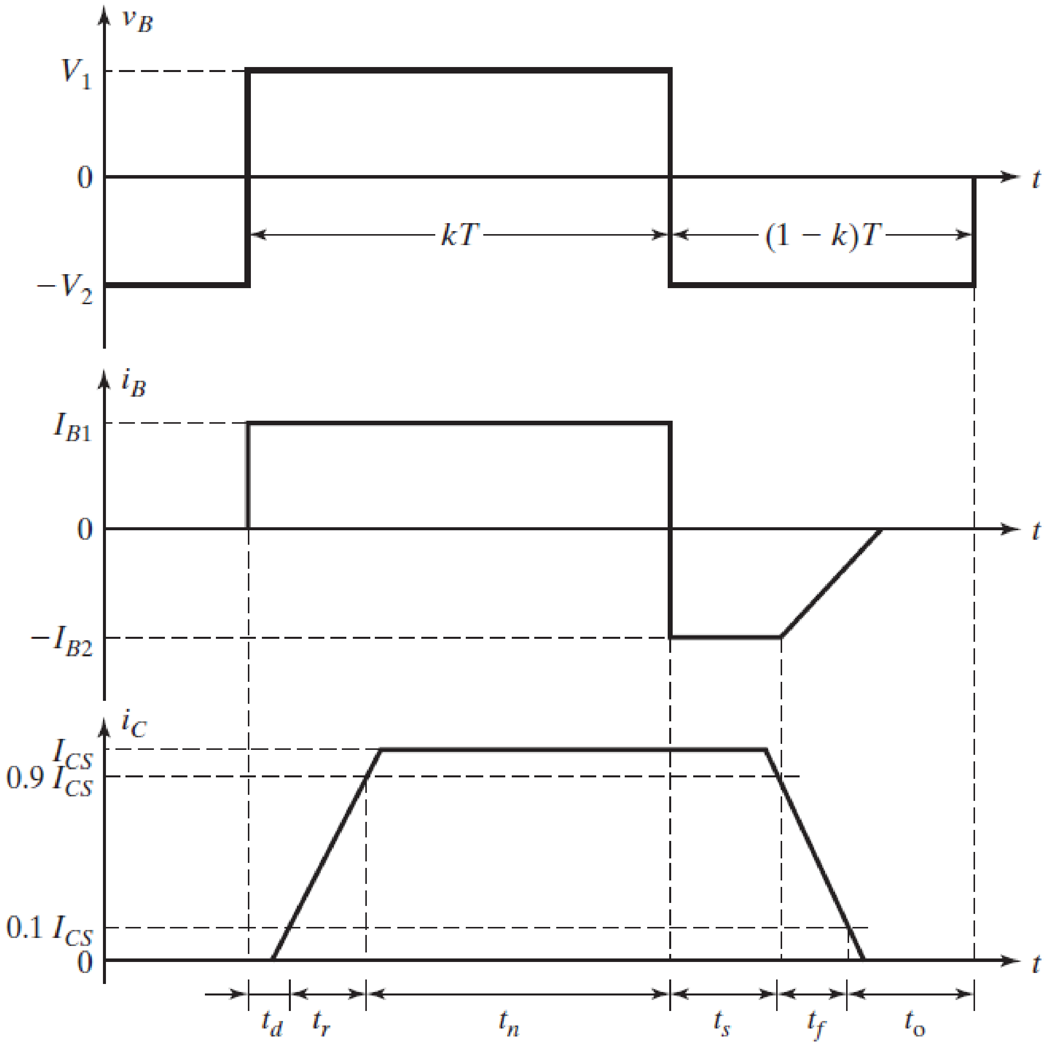
$$I_{C(sat)} = \frac{V_{CC}}{R_L} = \frac{10}{1000} = 10\ mA$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta} = \frac{10 \times 10^{-3}}{80} = 0.125\ mA$$

$$V_{in} = I_B \times R_B + V_{BE}$$

$$= 0.125 \times 10^{-3} \times 47 \times 10^{3} + 0.7 = 6.575\ V$$

BJT switching time



$t_{on} = t_d + t_r$

t_d : delay time ; 0 to 0.1 $I_{c(sat)}$.

t_r : rising time ; 0.1 to 0.9 $I_{c(sat)}$.

$t_{off} = t_s + t_f$

t_s : storage time ; 1 to 0.9 $I_{c(sat)}$.

t_f : fall time ; 0.9 to 0.1 $I_{c(sat)}$.

A capacitor (C) across the base used to give impulsive current may reduce tr and t_f to a value near to zero by vanishing saturation charge excess, choosing value of C near to 100 pf is expected either decided experimentally or by calculation depending on transistor characteristics.

Ex(4): In an overdriven transistor as switch circuit, V_{CC} = 10 V, V_i = 7.7 V, R_B = 7 kΩ, β = 30, calculate the value of speed up capacitor to reduce rise time (t_r) from 25 μsec to 12 μsec, and R_C, $\mathbf{V_{BE} = 0.7\ V}$.

$$V_i = I_B R_B + V_{BE(sat)}$$

$$I_B = \frac{V_i - V_{BE}}{R_B} \qquad\qquad I_B = \frac{7.7 - 0.7}{7 \times 10^3} = 1\ mA$$

Overdriven **:** $\mathrm{I_B = 3I_{B(min)}}$

$$I_{B(min)} = \frac{I_B}{3} = \frac{1 \times 10^{-3}}{3} = 0.33\ mA$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta}$$

$$I_{C(sat)} = \beta I_{B(min)} = 30 \times 0.33 \times 10^3 = 10\ mA$$

$$R_C = \frac{V_{CC}}{I_C} = \frac{10}{10 \times 10^{-3}} = 1\ k\Omega$$

$$I_C = \frac{Q}{t_r} \qquad\qquad Q = I_C \times t_r \quad \& \quad Q = C \times V_{in}$$

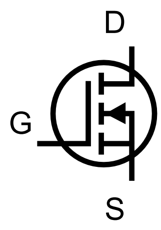
$$C = \frac{I_C \times t_r}{V_{in}} = \frac{10 \times 10^{-3} \times 12 \times 10^{-6}}{7.7} = 15.5 \times 10^{-9} F = 15.5\ nF$$

HW (1): For transistor switch circuit, if R_B = 20 KΩ, R_C = 1.2 k, β = 45, $I_{B(min)}$= 0.5 mA, t_r = 15 μs, V_{BE} = 0.7 V.

1- Write input & output equations ?
2- Calculate V_{in} to make the transistor on as overdriven ?
3- Calculate value of speed up capacitor to make t_r = 10 μs ?

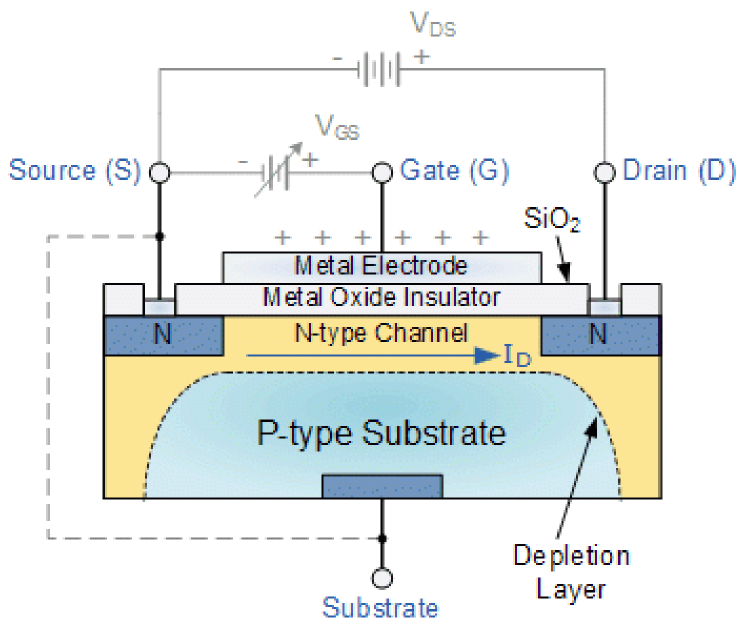
MOSFET as power switch

The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is a one kind of FET (Field Effect Transistor), which consists of three terminals namely gate, source and drain. Here, the drain current is controlled by the voltage of gate terminal Therefore, these transistors are voltage controlled devices.



The symbol of n-channel enhancement mode MOSFET

These transistors are available in 4 different types such as P-channel or N-channel with either in enhancement mode or depletion mode. The source and Drain terminals are made of N-type semiconductor for N-channel MOSFETs and equally for P-channel devices. The gate terminal is made of metal and detached from source & drain terminals using a metal oxide. This insulation roots low power consumption & it is a benefit in this transistor. Therefore, this transistor is used where P and N channel MOSFETs are used as building blocks to reduce the power consumption like digital CMOS logic**.**



MOSFETs are classified into two types which are enhancement mode and depletion mode, the most type which used is enhancement mode type .

And enhancement mode is classified into P-channel and N-channel type.

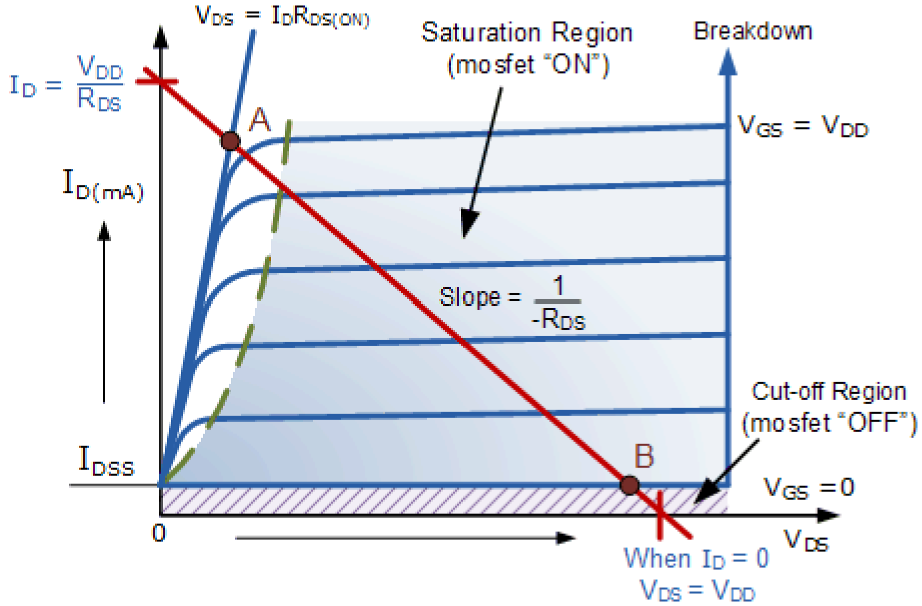
The switching table for enhancement mode type MOSFETs:

MOSFET type	V_{GS} = +ve	V_{GS} = 0	V_{GS} = -ve
N-Channel Enhancement	ON	OFF	OFF
P-Channel Enhancement	OFF	OFF	ON

Working Principle of MOSFET

The working of MOSFET depends upon the MOS (metal oxide semiconductor) which is the essential part of the MOSFET. The oxide layer presents, among the two terminals such as source and drain. By applying +ve or -ve gate voltages, we can set from P-channel to N-channel. When +ve voltage is applied to the gate terminal, then the holes existing under the oxide layer with a repulsive force and holes are pushed down through the substrate. The deflection region occupied by the bound -ve charges which are associated with the acceptor atoms.

MOSFET characteristic



Difference between BJT and MOSFET

1- The **BJT** is a bipolar junction transistor whereas **MOSFET** is a metal oxide semiconductor field effect transistor.

2- A **BJT** has three terminals namely base, emitter and collector, while a **MOSFET** has three terminals namely source, drain and gate.

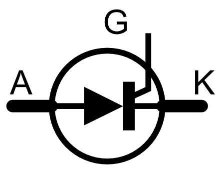
3- Nowadays, in analog and digital circuits, **MOSFET**s are used more than **BJT**s.

4- The **BJT** is a current controlled device and **MOSFET** is a voltage controlled device.

5- The structure of the **MOSFET** is more complex than **BJT**

Thyristor as power switch

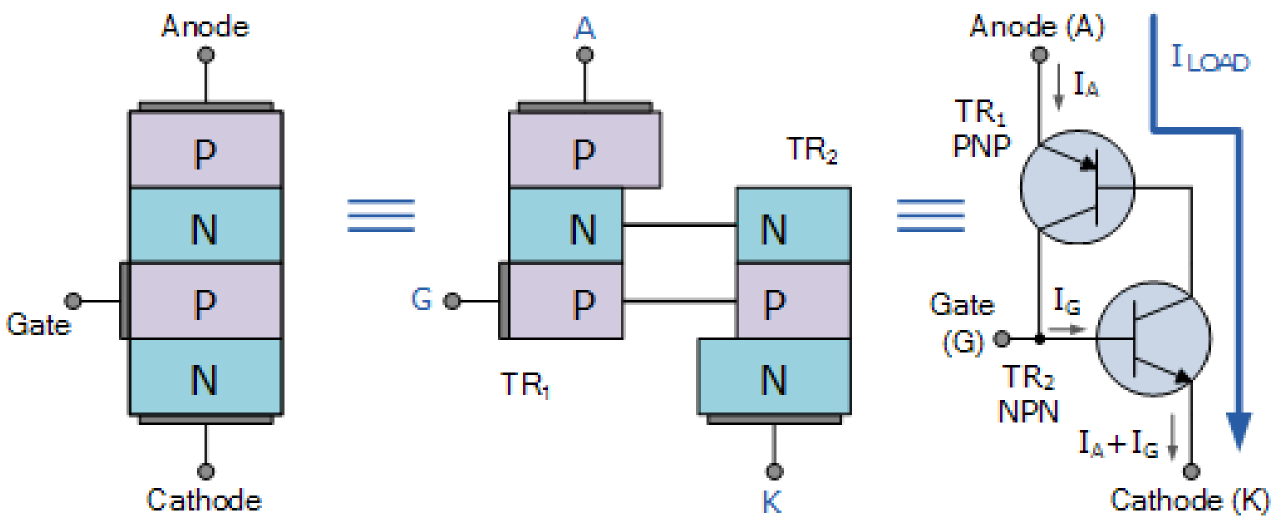
It is a multi-layer semiconductor device, The thyristor is a three-terminal device labelled: "Anode", "Cathode" and "Gate" and consisting of three PN junctions which can be switched "ON" and "OFF", and is represented by the symbol as shown.



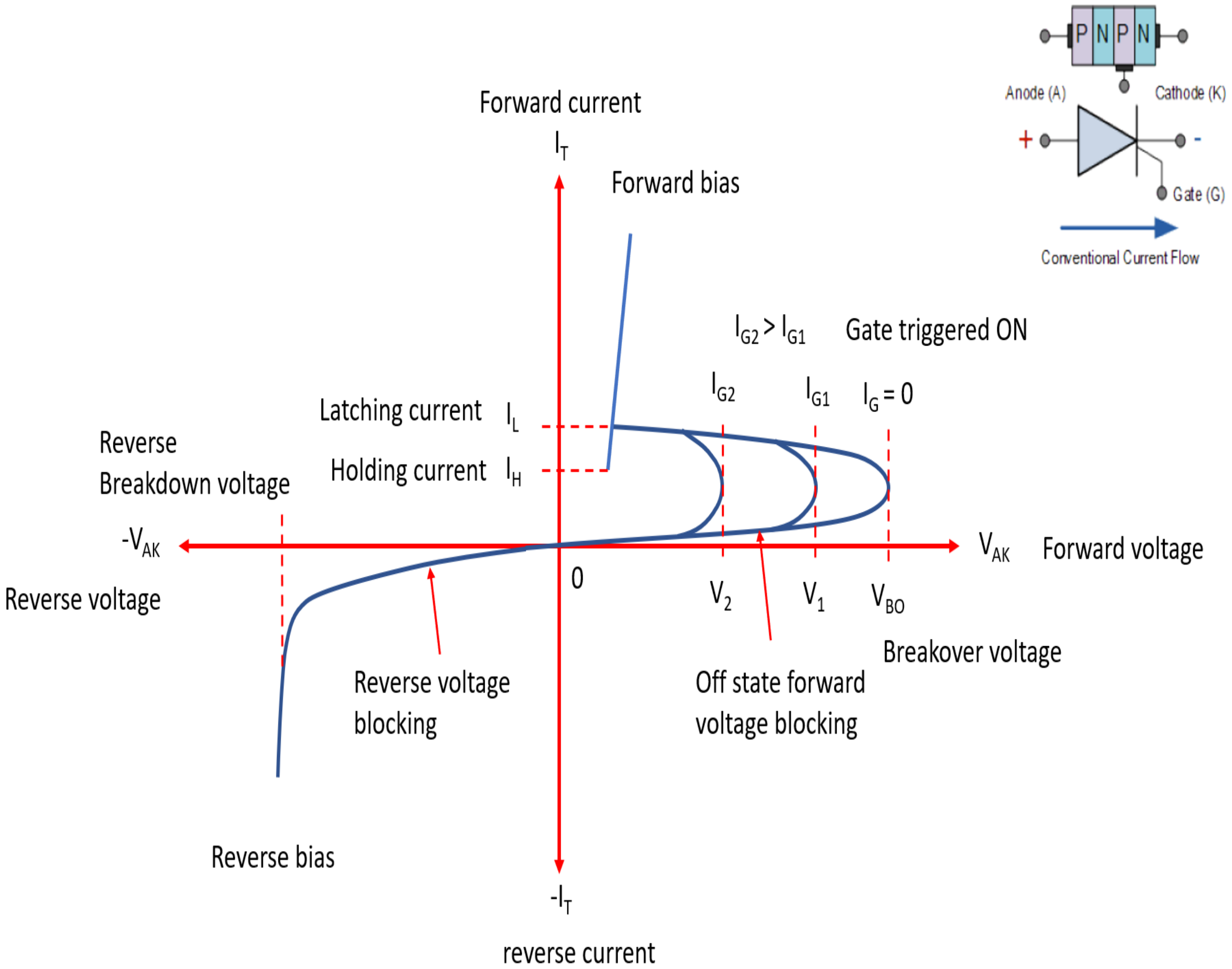
The symbol of Thyristor

The Thyristor is a unidirectional device, like the diode, which is only conduct current in one direction. In other words, thyristors can operate only in the switching mode and cannot be used for amplification like transistor.

A Thyristor's Two Transistor Analogy



Thyristor I-V Characteristics Curves



Static Characteristics of a Thyristor

- Thyristors are semiconductor devices that can operate only in the switching mode.
- Thyristor are current operated devices, a small Gate current controls a larger Anode current.
- Conducts current only when forward biased and triggering current applied to the Gate.
- The thyristor acts like a rectifying diode once it is triggered “ON”.
- Anode current (I_A) must be greater than **holding current (I_h)** to maintain conduction.
- There is no current flow when reverse biased, no matter even gate current is applied.
- Once the thyristor is triggered “ON”, it will be latched “ON” conducting even when a gate current is no longer applied, if Anode current is above **latching current (I_L)**.

Thyristors are high speed switches that can be used to replace electromechanical relays in many circuits as they have no moving parts, no contact arcing or suffer from corrosion or dirt. But in addition to simply switching large currents “ON” and “OFF”, thyristors can be made to control the mean value of an AC load current without dissipating large amounts of power. A good example of thyristor power control is in the control of electric lighting, heaters and motor speed.

Thyristor turn on methods

The SCR can be made to conduct or switching into conduction mode is performed by any one of the following methods.

1. Forward voltage triggering
2. Temperature triggering
3. dv/dt triggering
4. Light triggering
5. Gate triggering

1. Forward Voltage Triggering (undesirable)

By increasing the forward anode to cathode voltage, the depletion layer width is also increasing at junction J2. This also causes to increase the minority charge carriers accelerating voltage at junction J2. This further leads to an avalanche breakdown of the junction J2 at a forward breakover voltage V_{BO}.

At this stage SCR turns into conduction mode and hence a large current flow through it with a low voltage drop across it. During the turn ON state the forward voltage drop across the SCR is in the range of 1 to 1.5 volts and this may be increased with the load current.

In practice this method is not employed because it needs a very large anode to cathode voltage. And also, once the voltage is more than the V_{BO}, it generates very high currents which may cause damage to the SCR. Therefore, most of the cases this type of triggering is avoided.

2. Temperature Triggering (undesirable)

The reverse leakage current depends on the temperature. If the temperature is increased to a certain value, the number of hole-pairs also increases. This causes to increase the leakage current and lead to the breakdown of the junction.

3. dv/dt Triggering (undesirable)

In forward blocking state junctions J1 and J3 are forward biased and J2 is reverse biased. So, the junction J2 behaves as a capacitor (of two conducting plates J1 and J3 with a dielectric J2) due to the space charges in the depletion region. The charging current of the capacitor is given as

I = C dv/ dt

where dv/dt is the rate of change of applied voltage and C is the junction capacitance. From the above equation, if the rate of change of the applied voltage is large, the charging current will be increased. So, the SCR becomes turned ON without a gate signal.

4. Light Triggering

An SCR turned ON by light radiation is called Light Activated SCR (LASCR). This type of triggering is employed for phase controlled converters in HVDC transmission systems. In this method, light rays with appropriate wave length and intensity are allowed to strike the junction J2.

These types of SCRs are consisting a niche in the inner p-layer. Therefore, when the light struck on this niche, electron-hole pairs are generated at the junction J2 which provides additional charge carriers at the junction leads to turn ON the SCR.

5. Gate Triggering

This is the most common and efficient method to turn ON the SCR. When the SCR is forward biased, a sufficient voltage at the gate terminal injects some electrons into the junction J2. This result to increase leakage current and hence the breakdown of junction J2 even at the anode voltage (V_A) lower than the V_{BO}.

Depends on the size of the SCR the gate current varies from a few milli-amps to 200 milli amps or more. If the gate current applied is more, then more electrons are injected into the junction J2 and results to come into the conduction state at much lower applied voltage.

Dynamic Turn ON Switching Characteristics:

The dynamic processes of the SCR are turn ON and turn OFF processes in which both voltage and currents of an SCR vary with time. The transition from one state to another takes finite time, but doesn't take place instantaneously.

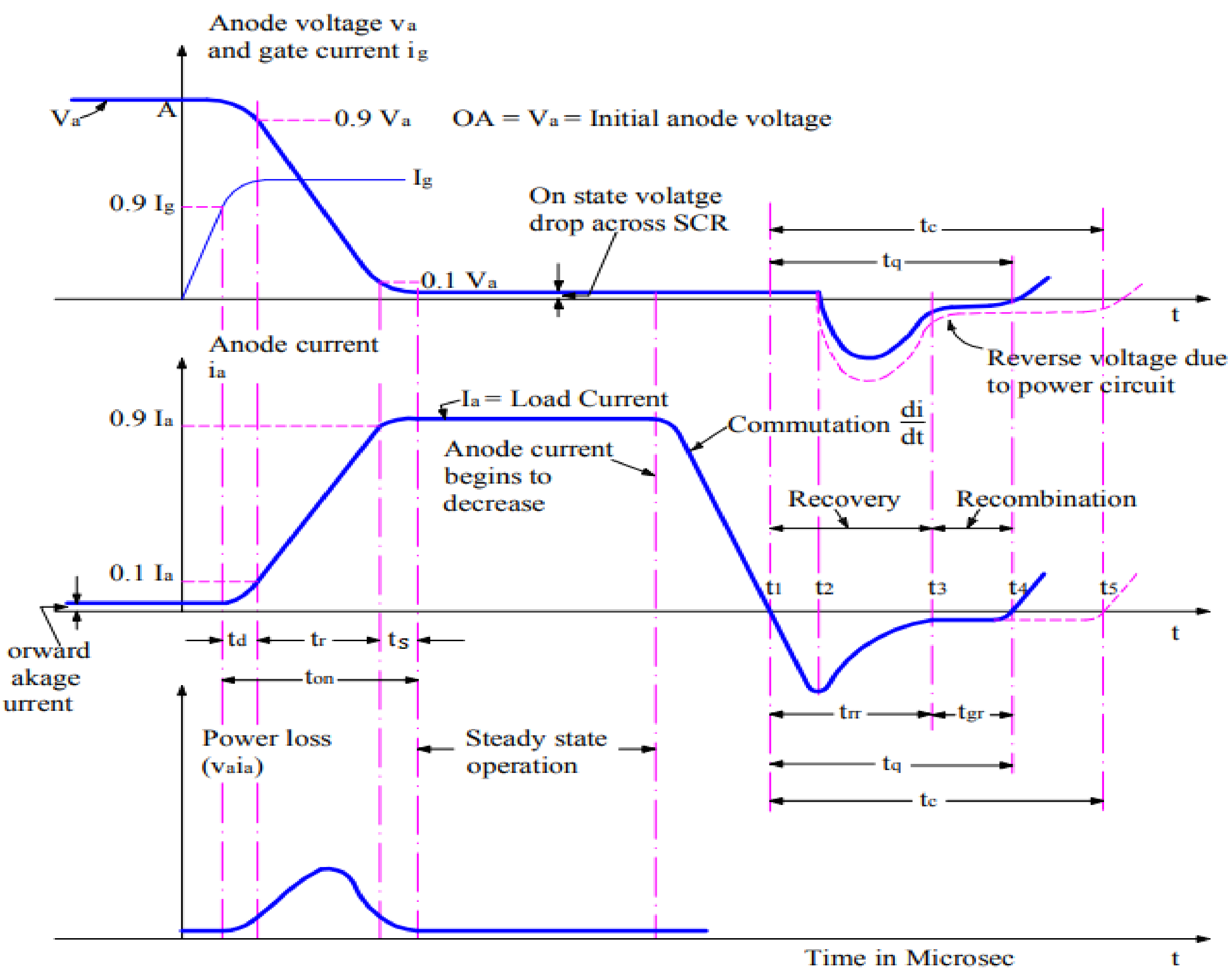
There will be a finite transition time that SCR takes to reach the forward conduction mode from blocking mode, which is termed as turn ON time of SCR. The turn ON time of the SCR (T_{on}) can be subdivided into three distinct intervals namely delay time t_d, rise time t_r, and spread time t_s.

$T_{on} = t_d + t_r + t_s$

T_d: from 0 to 0.1 I_A

T_r: from 0.1 I_A to 0.9 I_A

t_s: from 0.9 I_A to I_A



Dynamic Turn OFF Switching Characteristics:

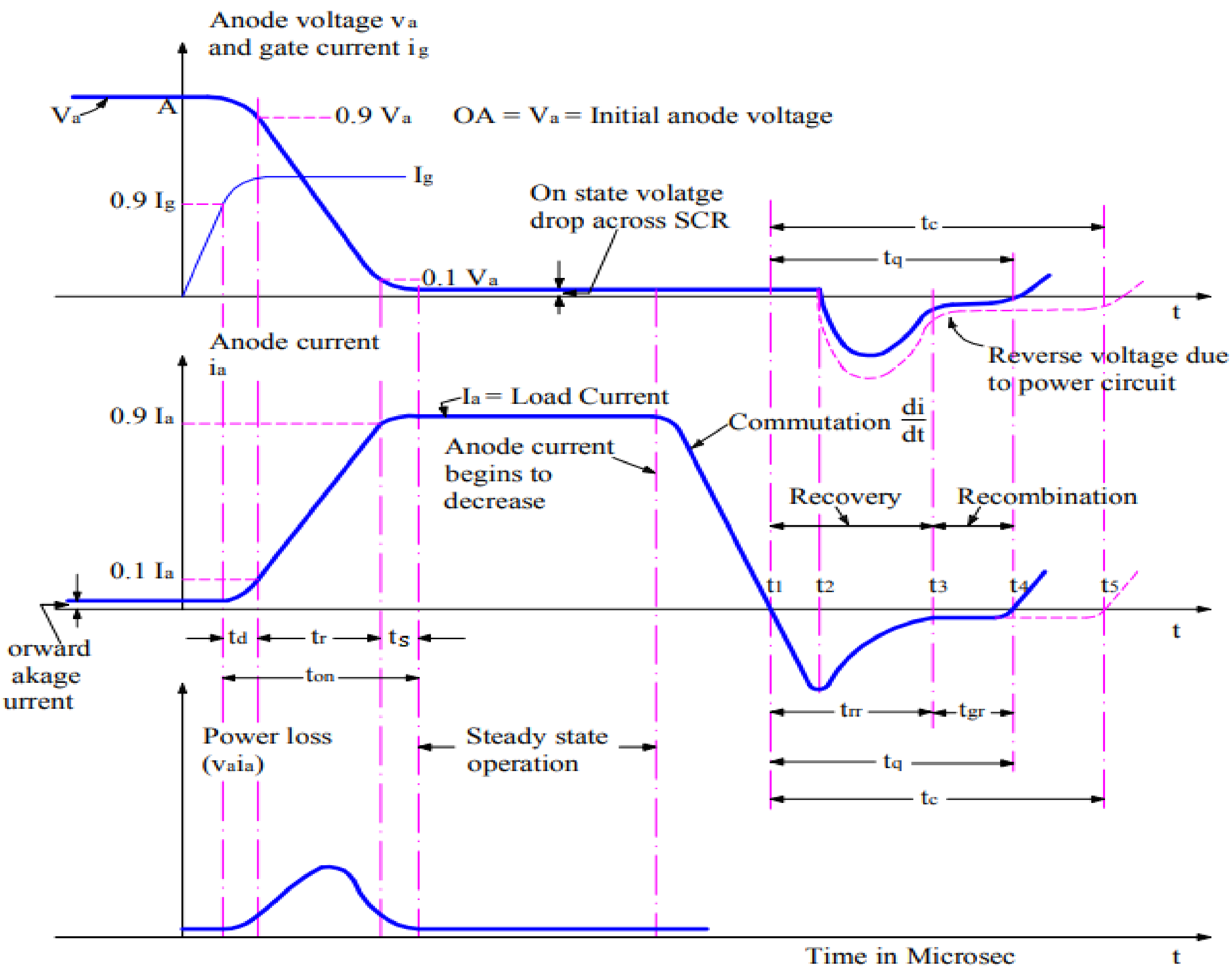
The transition of an SCR from forward conduction state to forward blocking state is called as turn OFF or commutation of SCR.

To turn OFF the SCR, the current must be reduced to a level below the holding current (I_h) of SCR. SCR turn OFF is achieved by reducing the forward current to zero. But if we apply the forward voltage immediately after the current zero of SCR, it starts conducting again even without gate triggering.

This is due to the presence of charge carriers in the four layers. Therefore, it is necessary to apply the reverse voltage, over a finite time across the SCR to remove the charge carriers.

This process takes place in two stages. In a first stage excess carriers from outer layers are removed and in second stage excess carriers in the inner two layers are to be removed. Hence, the total turn OFF time(t_{off}) is divided into two intervals; reverse recovery time t_{rr} and gate recovery time t_{gr}.

$T_{off} = t_{rr} + t_{gr}$



Thyristor's commutation methods

1. Natural (line) commutation

This is used to commutate the thyristor in AC circuits where the line voltage changes polarity two times each cycle, so the thyristor terminal voltage is reversed and switched – OFF each cycle (without any external helping circuit).

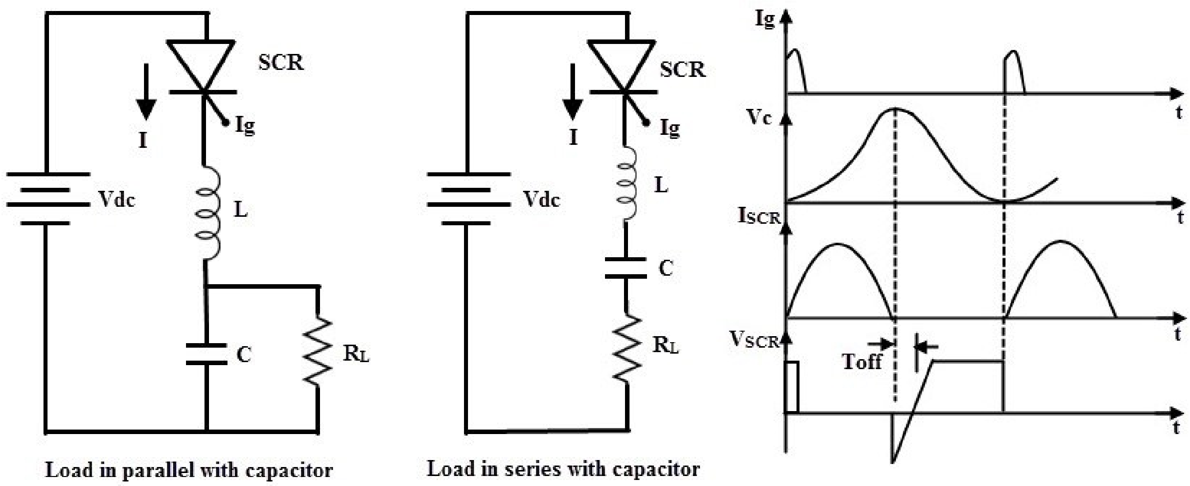
2. Forced commutation

This is used to commutate the thyristor in DC circuits. There are many types of this commutations:

A) Class A Commutation:

This is also known as self-commutation, or resonant commutation, or load commutation. In this commutation, the source of commutation voltage is in the load. This load must be an under damped R-L-C supplied with a DC supply so that natural zero is obtained.

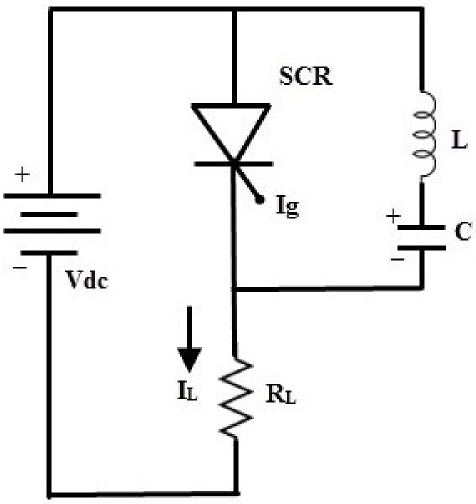
The commutating components L and C are connected either parallel or series with the load resistance R as shown below with waveforms of SCR current, voltage and capacitor voltage.

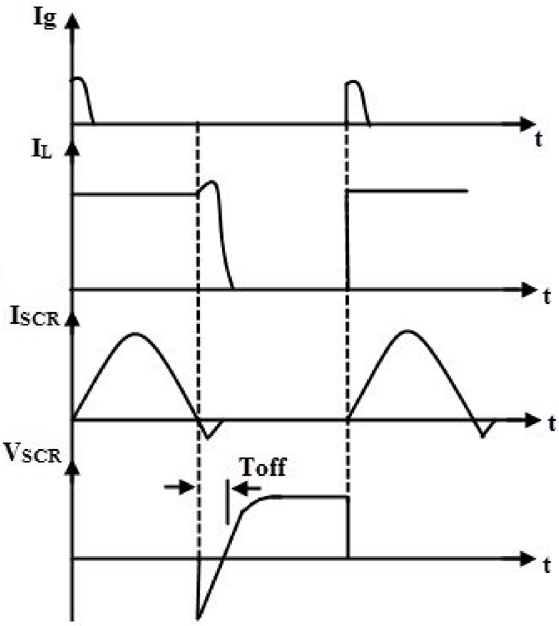


Load in parallel with capacitor   Load in series with capacitor

B) Class B Commutation:

This is also a self-commutation circuit in which commutation of SCR is achieved automatically by L and C components. The LC resonant circuit is connected across the SCR but not in series with load as in case of class A commutation and hence the L and C components do not carry the load current.

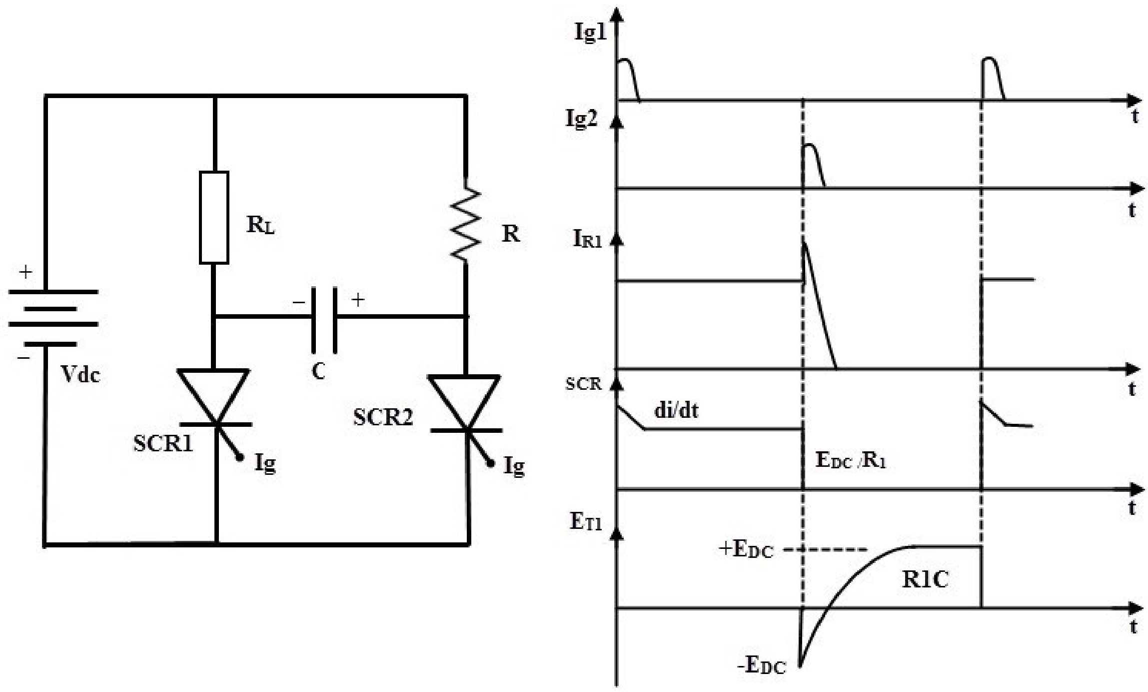




C) Class C Commutation:

In this commutation method, the main SCR is to be commutated is connected in series with the load and an additional or complementary SCR is connected in parallel with main SCR. This method is also called as complementary commutation.

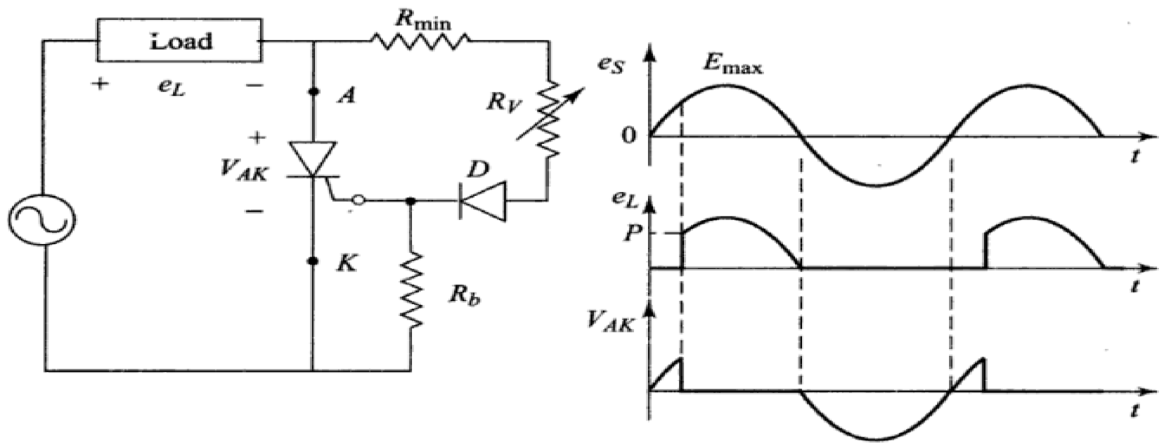
In this, SCR turns OFF with a reverse voltage of a charged capacitor. The figure below shows the complementary commutation with appropriate waveforms.



Thyristor triggering techniques

1- Resistance triggering:

The following circuit shows the resistance triggering.

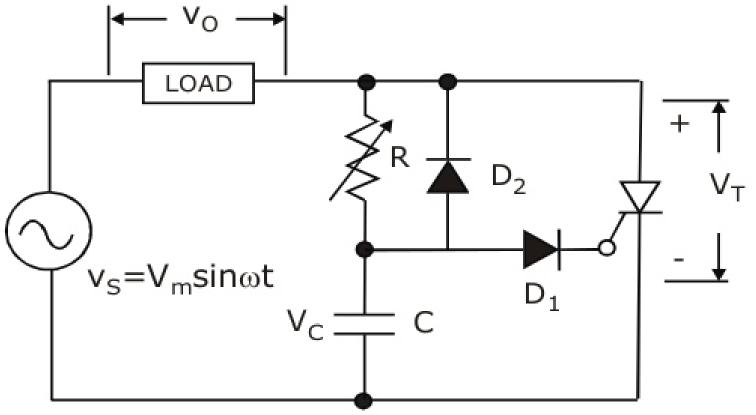


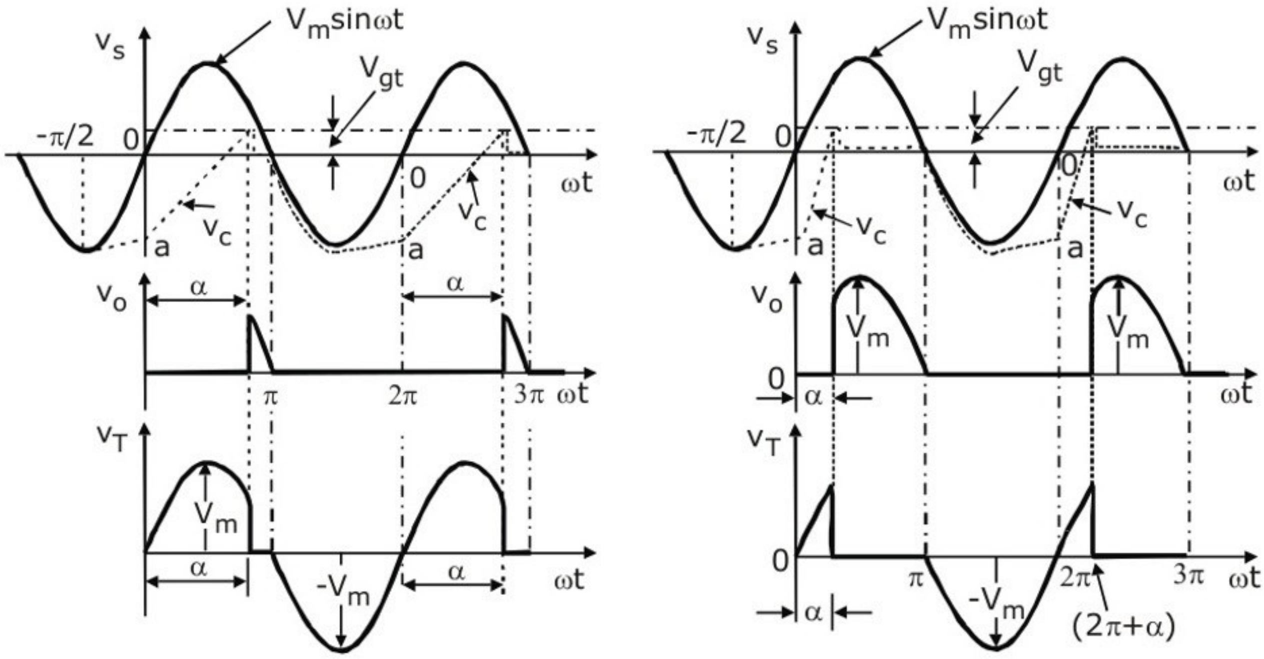
- In this method, the variable resistance R is used to control the gate current.
- Depending upon the value of R, when the magnitude of the gate current reaches the sufficient value (latching current of the device) the SCR starts to conduct.
- The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.
- By considering that the gate circuit is purely resistive, the gate current is in phase with the applied voltage.
- By using this method, we can achieve maximum firing angle up to 90°.

2- RC Triggering:

a) RC Half Wave Circuit

The following circuit shows the RC Half Wave Circuit triggering.

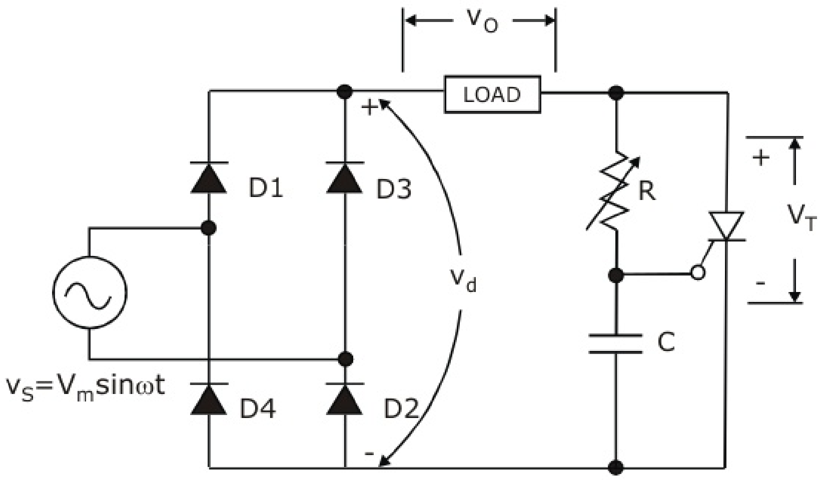


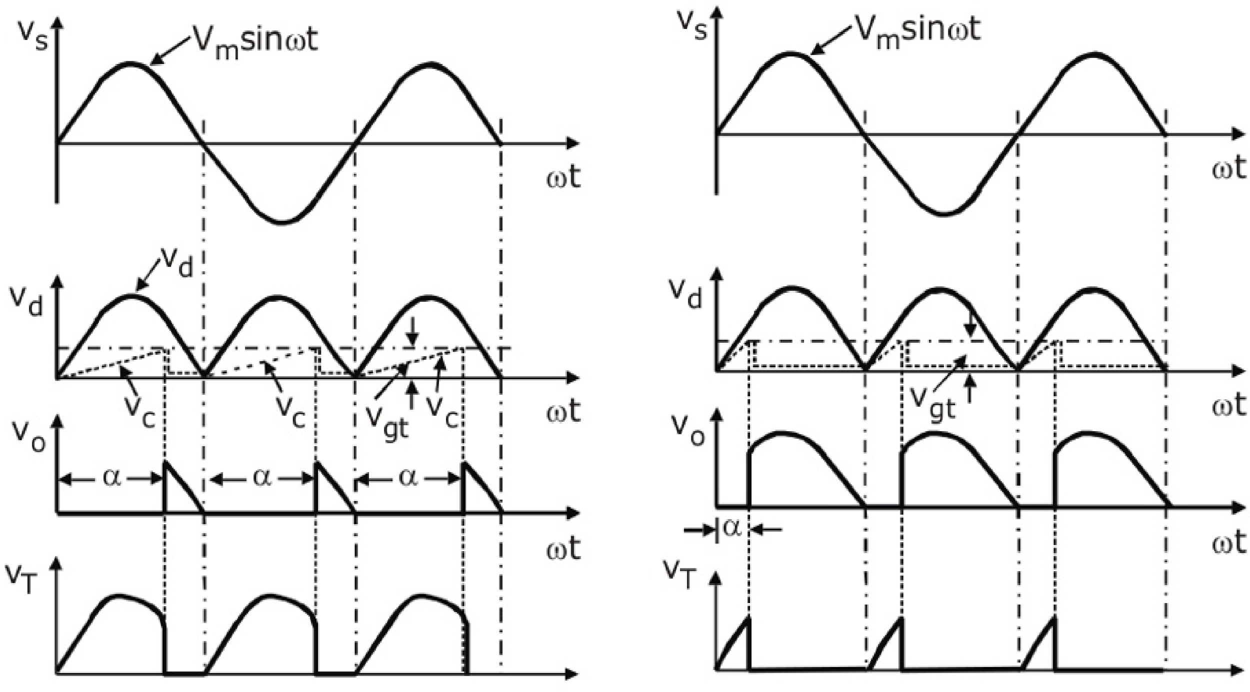


High Value of R **Low Value of R**

b) RC full Wave Circuit

The following circuit shows the RC full Wave Circuit triggering





High Value of R

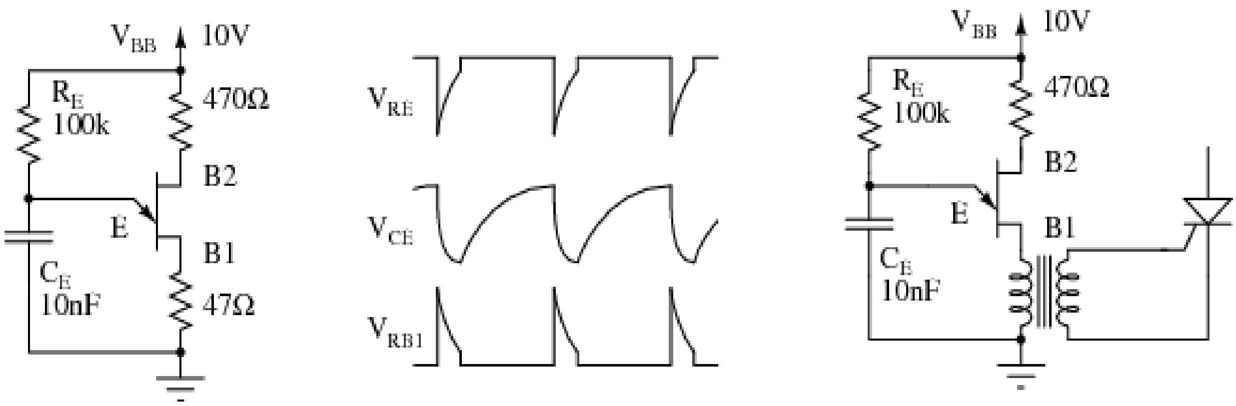
Low Value of R

- By using this method, we can achieve firing angle more than 90°.
- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peak value of the applied voltage.
- The variable resistor R controls the charging time of the capacitor.
- Depends upon the voltage across the capacitor, when sufficient amount of gate current will flow in the circuit, the SCR starts to conduct.
- In the negative half cycle, the capacitor C is charged up to the negative peak value.
- Diode D is used to prevent the reverse break down of the gate cathode junction in the negative half cycle.

3- Pulse Gate Triggering:

- In this method the gate drive consists of a single pulse appearing periodically (or) a sequence of high frequency pulses.
- A pulse transformer is used for isolation.
- The main advantage is that there is no need of applying continuous signals, so the gate losses are reduced.

UJT Triggering:

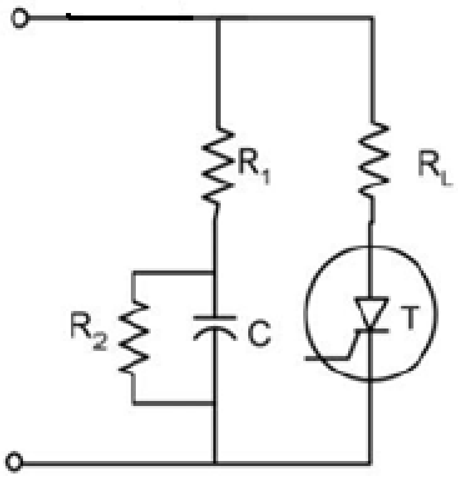


Advantages of pulse train triggering:

- Low gate dissipation at higher gate current.
- When the first trigger pulse fails to trigger the SCR, the following pulses can succeed in latching SCR. This important while triggering inductive circuits having back emf.

Thyristor protection

Protection against voltage:



protection against over voltage

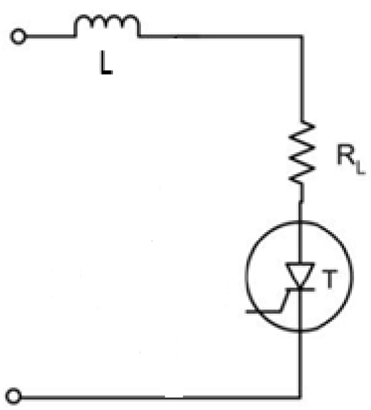
Protection over voltage take place

C charging

R_2 – used in discharging

R_1 – used for damping

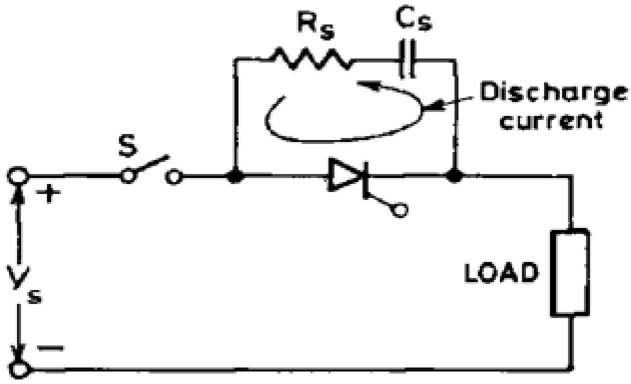
Protection against di / dt :



protection agansit di / dt

L is used to protection the scr from increasing in di / dt.

Protection against dv / dt (snubber-circuit):

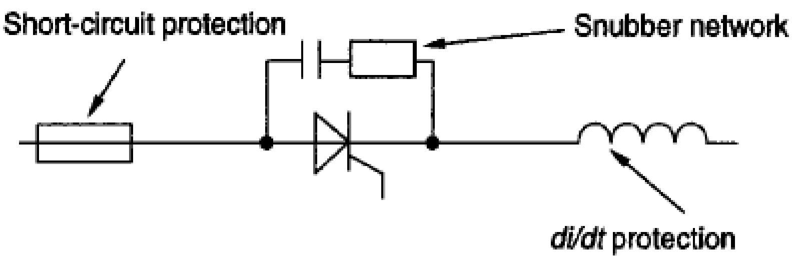


Snubber circuit across SCR.

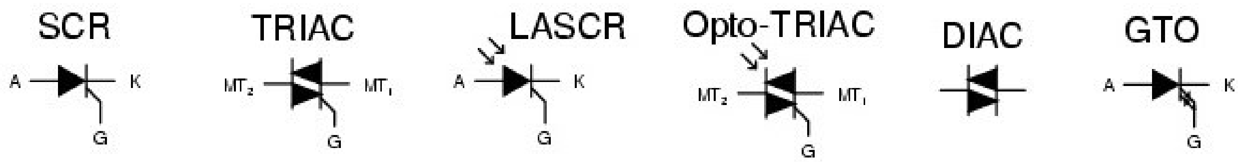
A snubber circuit consists of a series combination of resistance Rs and Capacitance Cs In parallel with the thyristor as shown in figure.

Capacitor Cs in parallel with device is sufficient to prevent unwanted dv/dt triggering of the SCR. When switch S is closed, a sudden voltage appears across the circuit , capacitor Cs behaves like a short circuit, therefore voltage across SCR is zero.

SCR protection

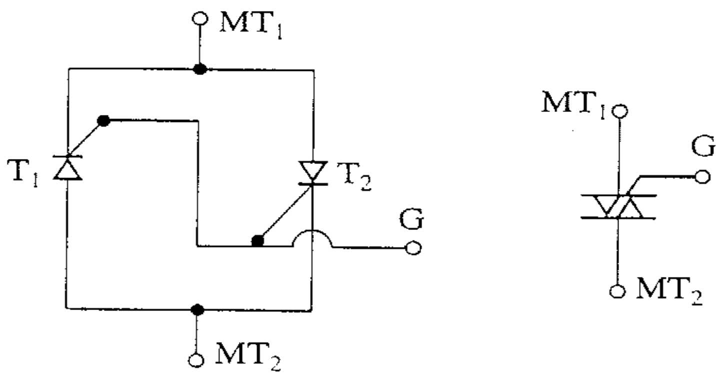


Thyristor Family

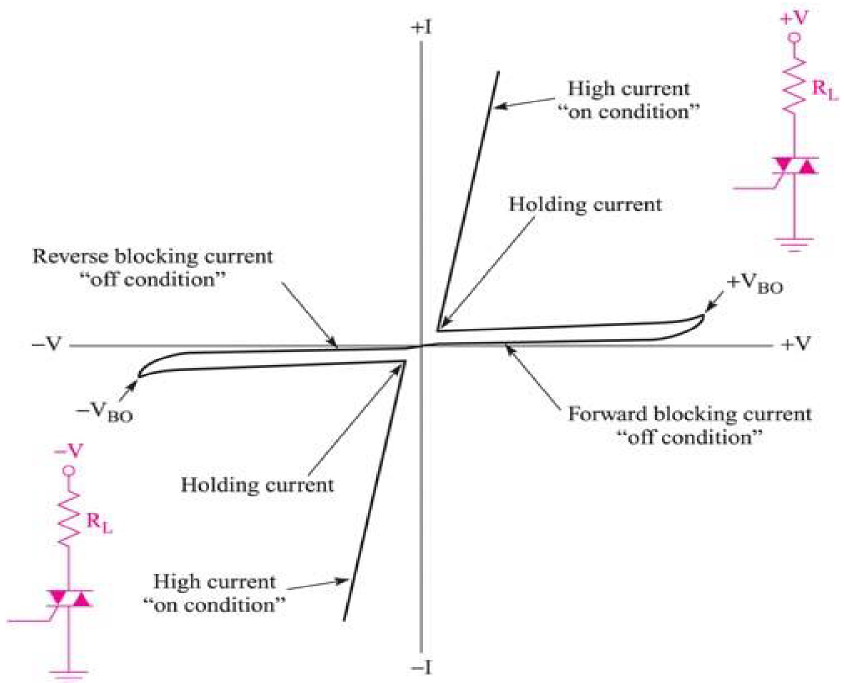


- SCR and LASCR and GTO are (Unidirectional).
- TRIAC, DIAC and Opto-TRIAC are (Bidirectional).

TRIAC (Bidirectional Thyristor):

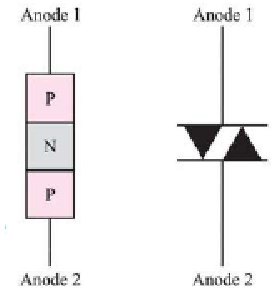


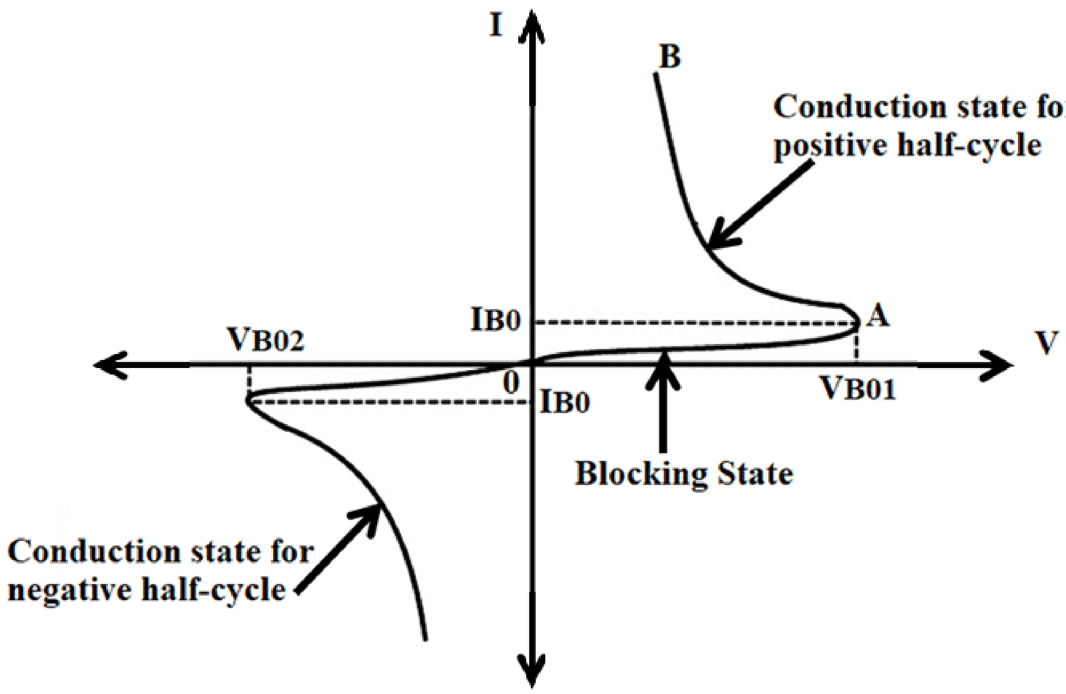
- TRIAC will remain off until the gate signal turns it on.
- MT_1 to MT_2 resistance drops very low.
- TRIAC conducts until current drops below holding current.



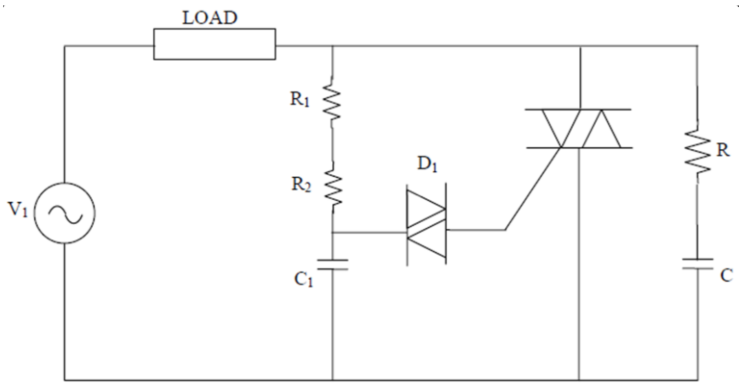
DIAC

- PNP 3-layer device
- Switching device
- Bilateral Diode
- Conducts both ways
- Typical Breakover voltage is about 32 V
- Remains off at low voltages.
- As voltage increases to the breakover voltage it conducts.
- Quick voltage drop results in a quick current spike.
- Useful for triggering signals.

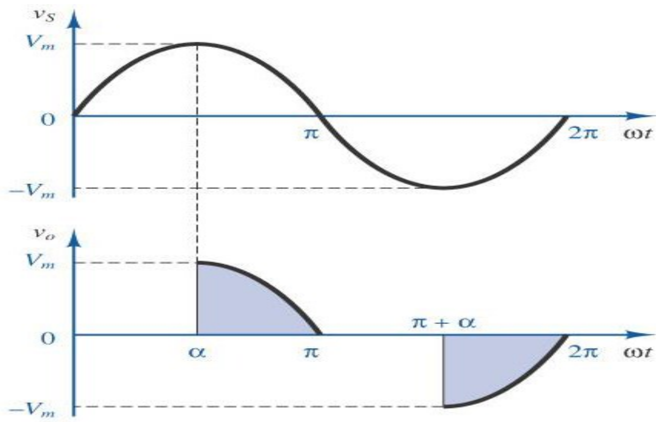




DIAC improves symmetry of control (bidirectional switch)



Triac triggering circuit using a diac.



TRIAC can be used as follows:

- As a high power lamp switch.
- Electronic changeover for transformer taps.
- Light dimmer.
- Speed controls for electric fans and other electric motors.

SCR		**TRIAC**
1	Operate in one direction	Operate in Bi-directions
2	Input AC & output DC	Input AC & output AC
3	Natural and forced commutation	Natural commutation

Gate Drive Circuits

The gating circuit is an integral part of a power converter that consists of power semiconductor devices. The output of a converter that depends on how the gating circuit drives the switching devices is a direct function of the switching. The design of gating circuit requires knowledge of gate characteristics and needs of power devices such as thyristors (SCR), bipolar junction transistor (BJT), metal oxide semiconductor field-effect transistor (MOSFET), and insulated-gate bipolar transistor (IGBT).

Because power electronics are increasingly used in application that require gate drive circuits with advance control, high speed, high efficiency, and compactness, gate drive integrated circuits (IC) are becoming commercially available.

There are various circuits that are used to drive the power switches, like:

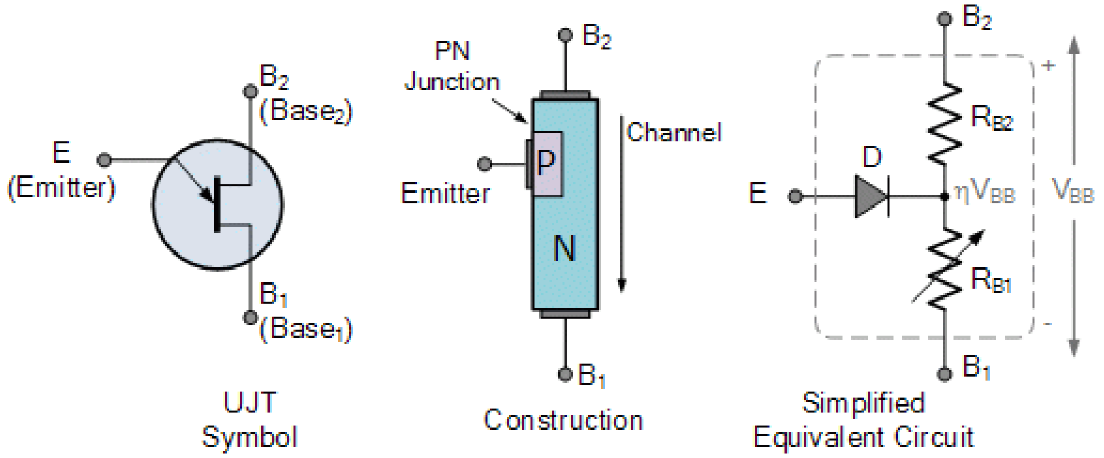
1- Unijunction Transistor (UJT).

2- Operational Amplifier (OP Amp).

Unijunction Transistor (UJT)

This device can trigger larger thyristors with a pulse at base B1. A unijunction transistor is composed of bar of N-type silicon having a P-type connection in the middle. The connections at the ends of the bar are known as bases B_1 and B_2; the P-type mid-point is the emit R_{BB} ranges from 4-12kΩ for different device types.

The stand-off ratio η is the ratio of R_{B1} to R_{BB}. It varies from 0.4 to 0.8 for different devices.



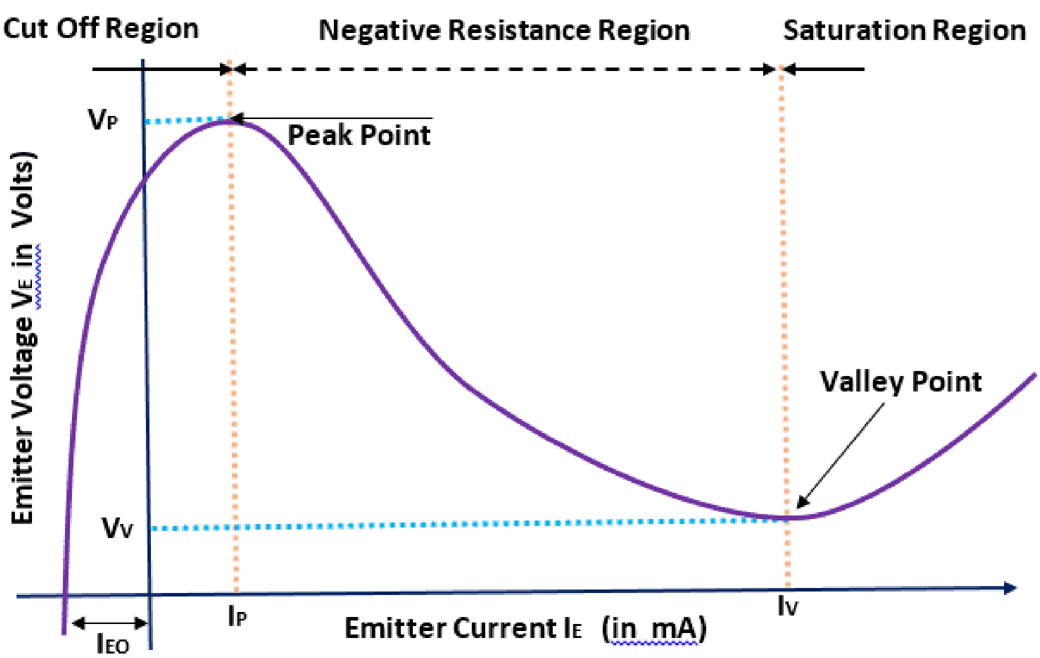
$$R_{BB} = R_{B1} + R_{B2}$$

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

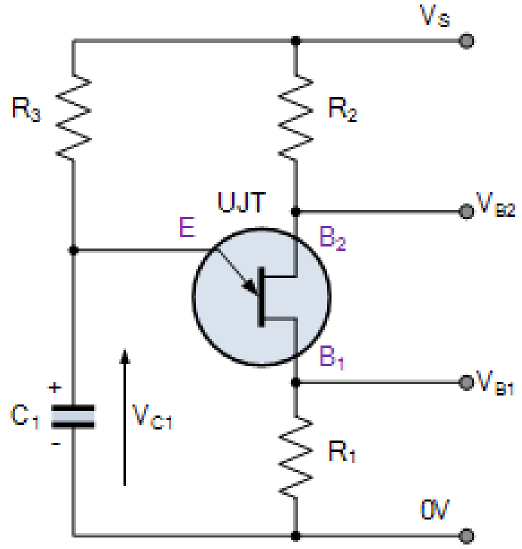
$$\eta = \frac{R_{B1}}{R_{BB}}$$

$$V_p = \eta \times V_{BB} + V_D$$

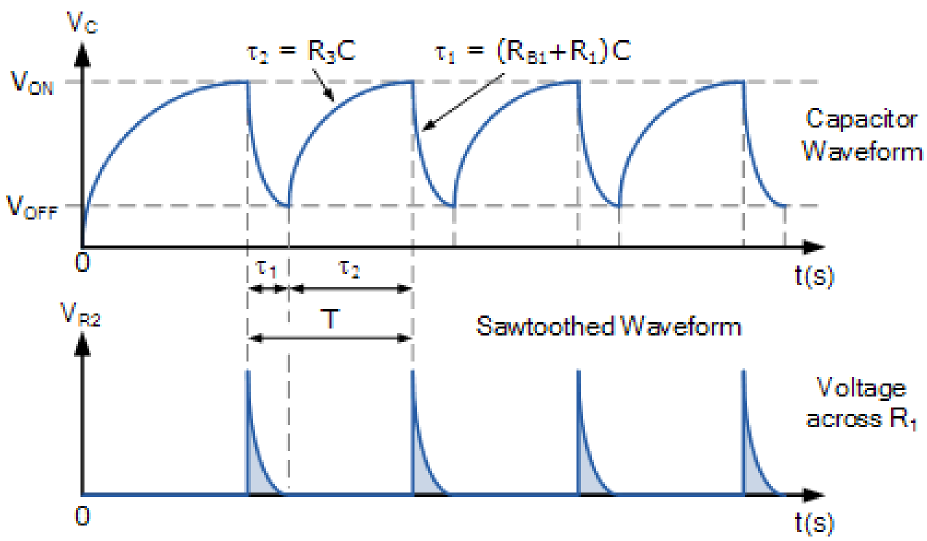
UJT Characteristics



UJT as relaxation oscillator



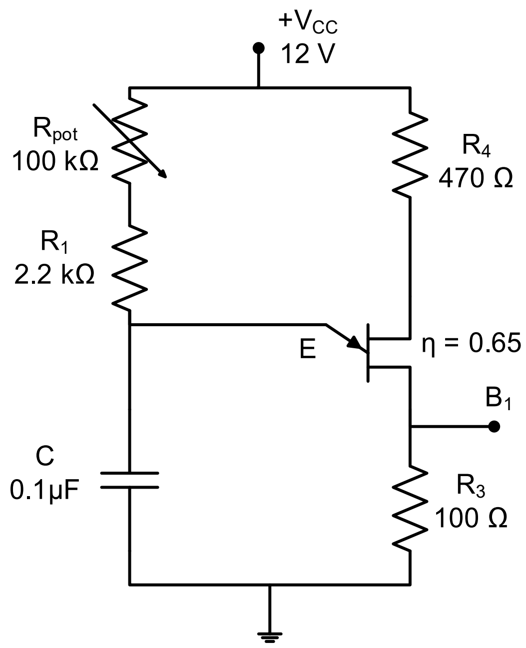
Circuit diagram



waveforms

$$T = RC \times ln\frac{1}{1-\eta}$$

Ex(6): For relaxation oscillator: calculate maximum and minimum frequencies, and calculate the maximum capacitance voltage, $\mathbf{V_D = 0.6\ V}$.



$$T = RC \times \ln\frac{1}{1-\eta}$$

$$R = R_1 + R_{pot}$$

$$R_{max} = 2.2k\Omega + 100k\Omega = 102.2\ k\Omega$$

$$T_{max} = 102 \times 10^3 \times 0.1 \times 10^{-6} \times \ln\frac{1}{1-0.65}$$

$$= 10.708\ ms$$

$$F_{min} = \frac{1}{T_{max}} = 93.38\ Hz$$

$$R_{min} = 2.2k\Omega + 0 = 2.2\ k\Omega$$

$$T_{min} = 2.2 \times 10^3 \times 0.1 \times 10^{-6} \times \ln\frac{1}{1-0.65} = 0.23\ ms$$

$$F_{max} = \frac{1}{T_{min}} = 4.329\ kHz$$

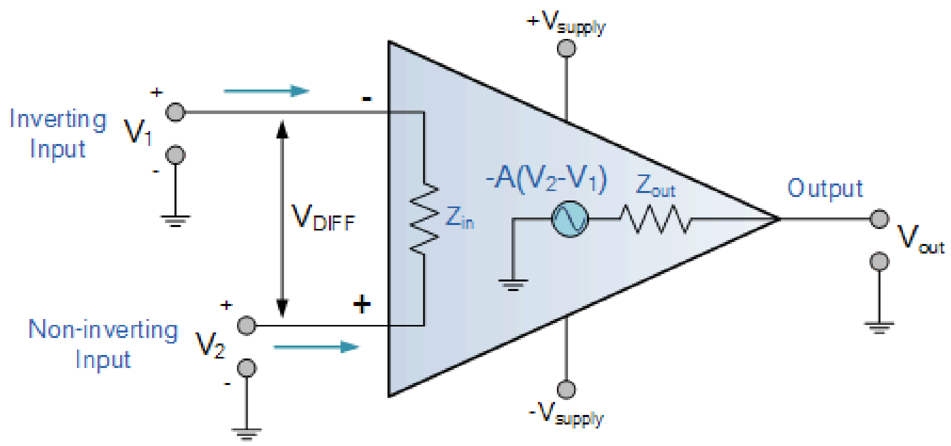
$$V_C = \eta \times V_{CC} + V_D = 0.65 \times 12 + 0.6 = 8.4\ V$$

H.W. (2): In relaxation oscillator circuit, calculate $\mathbf{F_{min}}$, $\mathbf{F_{max}}$ and $\mathbf{V_C}$, if: $\mathbf{V_D = 0.6}$ V, $\mathbf{R_1 = 3.3}$ **kΩ**, $\mathbf{R_{pot}}$ =95 **kΩ**, $\mathbf{\eta = 0.6}$, $\mathbf{C = 0.2}$ μF, $\mathbf{V_{CC} = 15}$ V.

Operational Amplifier

An integrated circuit (IC) DC amplifier with high open loop gain. It basically has 2 input terminals: Inverting input & Non inverting input (the inverting input inverts the input signal 180^0 phase shift) with one output terminal.

Equivalent Circuit of an Ideal Operational Amplifier



Op-amp Parameter and Idealized Characteristic

- **Open Loop Gain, (Avo):**

The ideal gain is infinite but typically real values ranged from 20,000 to 200,000.

- **Input impedance, (Z_{IN}):**

Input impedance is the ratio of input voltage to input current and is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry ($I_{IN} = 0$). Real op-amps have input leakage currents from a few pico-amps to a few milli-amps.

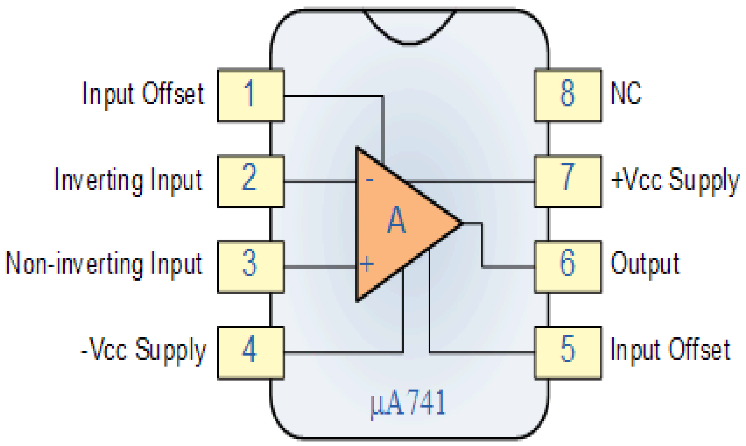
- **Output impedance, (Z_{OUT}):**

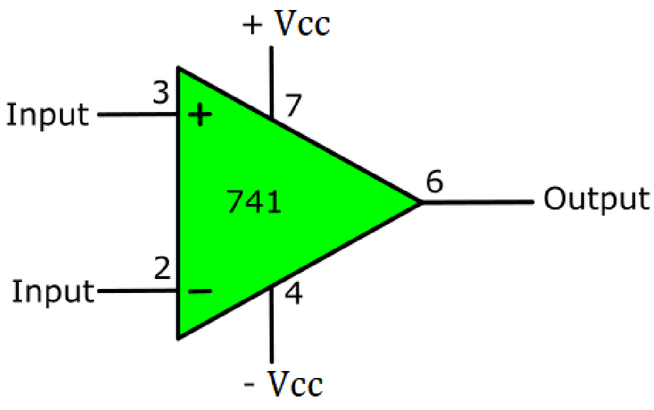
The output impedance of the ideal operational amplifier is assumed to be zero. Real op-amps have output impedances in the 100-20kΩ range.

IC 741 Op Amp (Operational Amplifier)

The 741 Op Amp IC is an integrated circuit, comprising of a general purpose Operational Amplifier. It was first manufactured by Fairchild semiconductors in the year 1963. The number 741 indicates that this operational amplifier IC has 7 functional pins, 4 pins capable of taking input and 1 output pin.

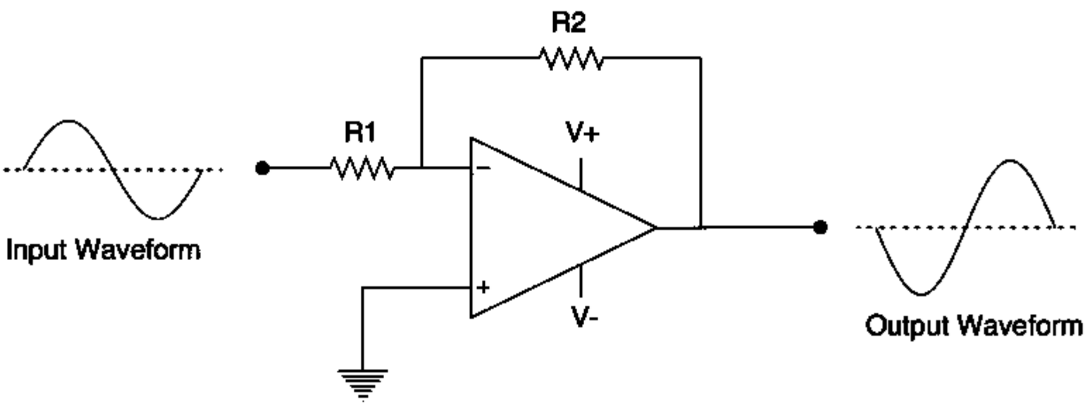
IC 741 Op Amp can provide high voltage gain and can be operated over a wide range of voltages, which makes it the best choice for use in integrators, summing amplifiers and general feedback applications.





741 Op-amp Symbol

a) Inverting Voltage Amplifier



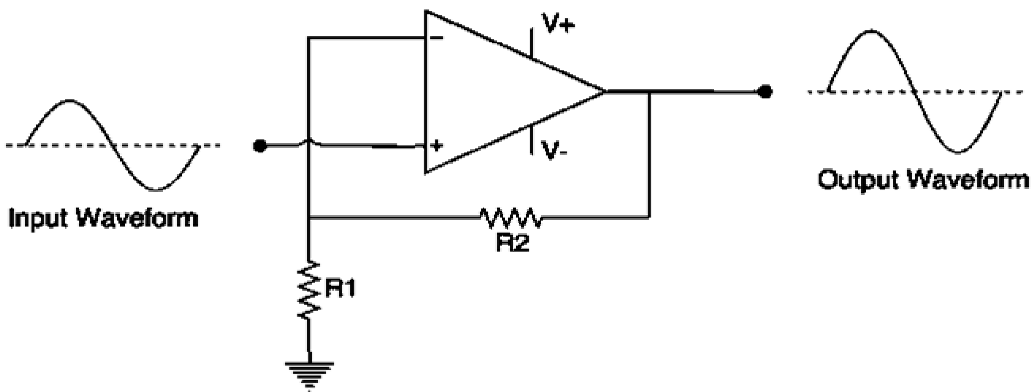
This arrangement is named as inverting because it amplifies and reverses the polarity of input signal (Observe the waveforms at the input and output). Resistor R2 is the feedback resistor. Gain of the amplifier is given by the formula:

$$Gain\ (A_V)\ =\ -(\frac{R_2}{R_1})$$

Negative sign indicates that the polarity of the output waveform is reversed. By adjusting the values of R1 and R2 desired amplification can be achieve

$$Gain\ (A_V) = \frac{V_{out}}{V_{in}} = -(\frac{R_f}{R_{in}})$$

b) Non-Inverting Voltage Amplifier



This arrangement is named as non-inverting because it amplifies the input signal, while retaining the same polarity. Gain of the amplifier is given by the formula:

$$Gain\ (A_V)\ =\ 1 + \frac{R_2}{R_1}$$

By adjusting the values of R_1 and R_2 desired amplification can be achieved. If the value of feedback resistor R_2 is made 0, the gain equals 1 and the Op-Amp configuration behaves as a “unity gain buffer” or a voltage follower.

$$Gain\ (A_V)\ =\ 1 + \frac{R_f}{R_{in}}$$

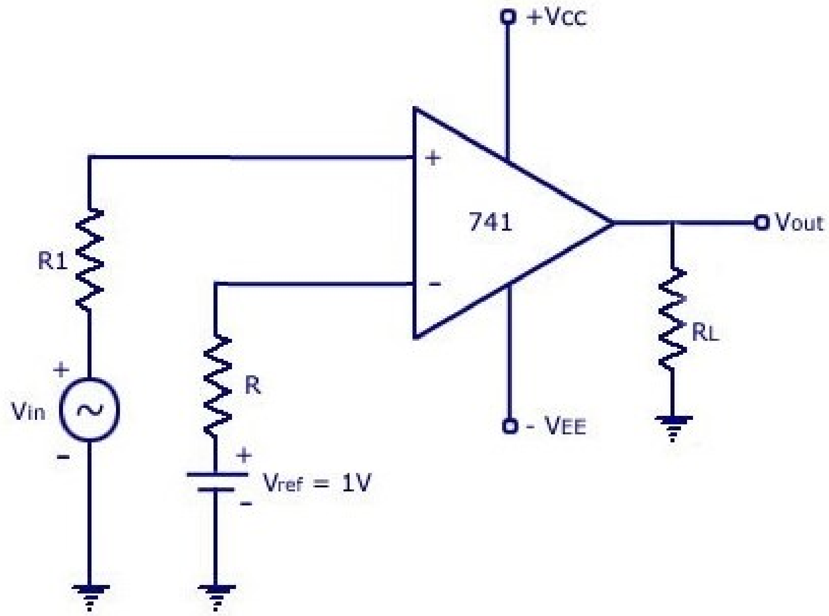
IC 741 Op Amp Applications

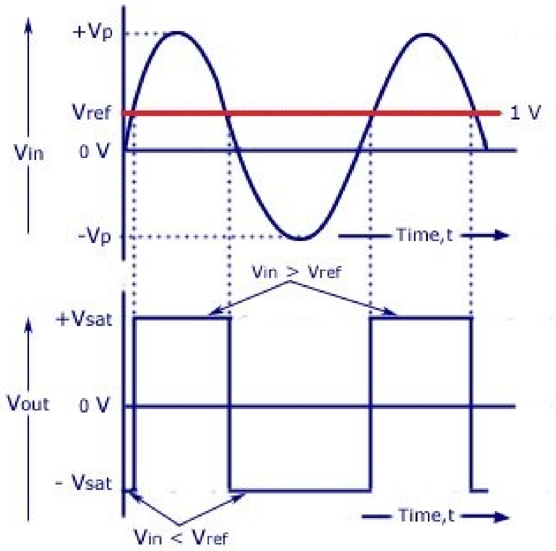
Below are the applications of IC 741 Op Amp across different use cases:

- Amplifiers: 741 IC is mostly used to amplify signals of varying frequencies ranging from DC to higher radio frequencies. It is also used in frequency selective amplifiers which filter out signals of unwanted frequencies.
- Computational: Many electronic circuits that perform mathematical operations like integration, differentiation, summers etc. use 741 Op-Amp.
- Oscillators: Op-Amp IC 741 is used as an oscillator in function generators to create different output waveforms like sinusoidal, square, triangular etc. It is also used in Pulse Width Modulators (PWM generators)
- Comparators: The 741 IC can be used to compare voltage signals and determine if they are almost of the same voltage. This can be used in voltage regulators and signal comparators.

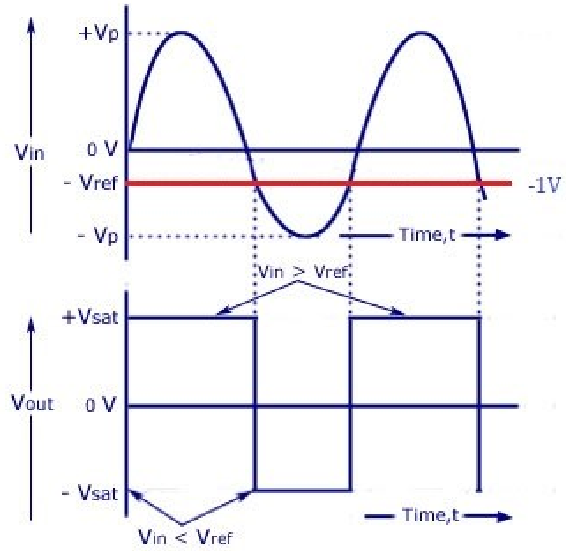
a) IC 741 Op-Amp as a Comparator

Non-inverting Comparator Circuit





Input and Output Waveforms
For Positive Vref

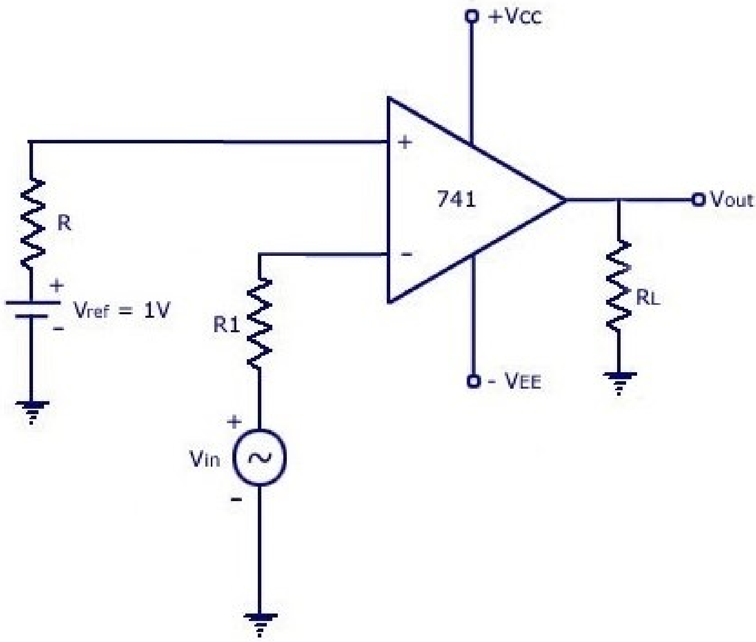


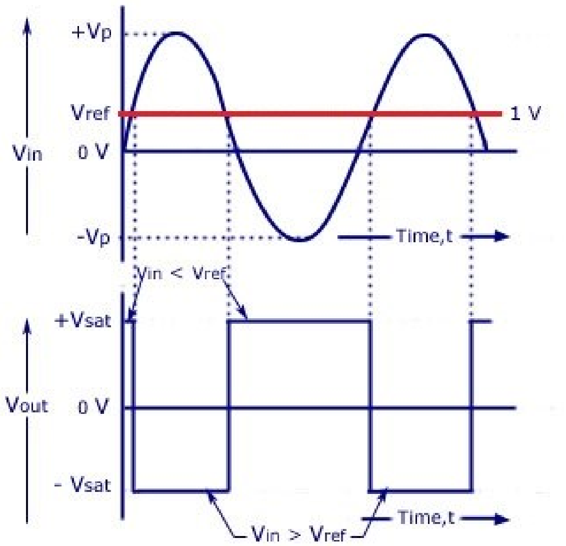
Input and Output Waveforms
For Negative Vref

$$V_{in} > V_{ref} \qquad V_{out} = +V_{sat}$$

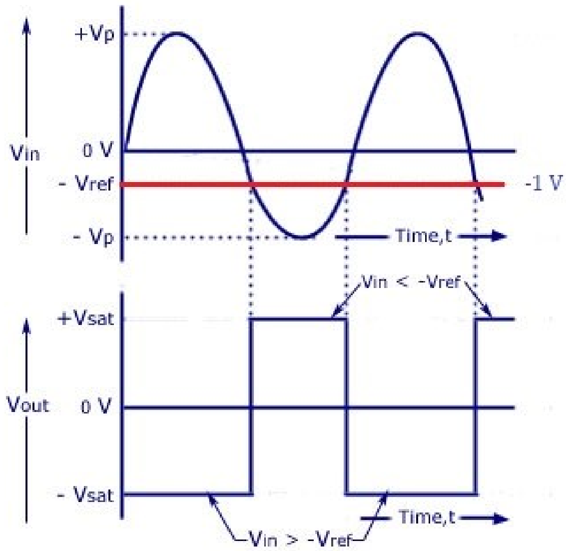
$$V_{in} < V_{ref} \qquad V_{out} = -V_{sat}$$

Inverting Comparator Circuit





Input and Output Waveforms
For Positive Vref



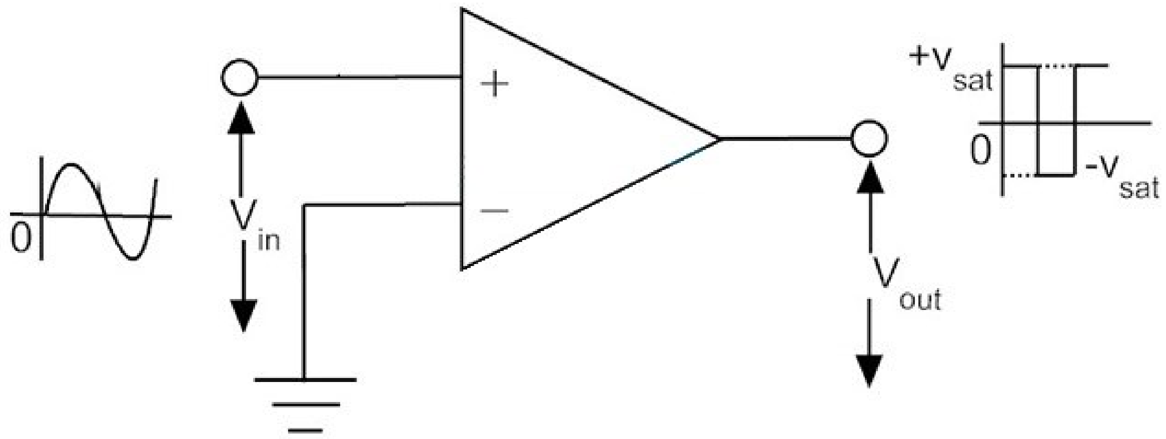
Input and Output Waveforms
For Negative Vref

$V_{in} > V_{ref}$ $\quad V_{out} = -V_{CC}$

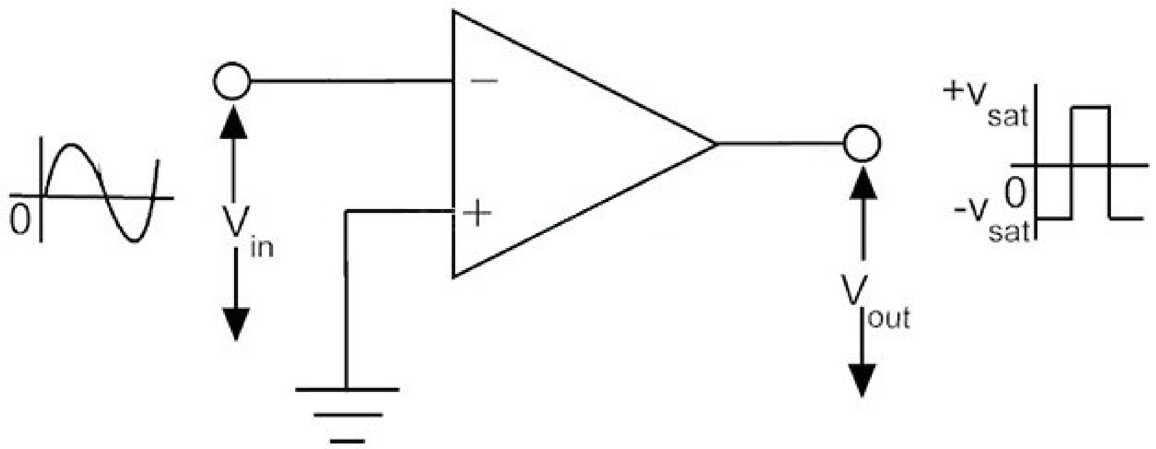
$V_{in} < V_{ref}$ $\quad V_{out} = +V_{CC}$

b) IC 741 Op-Amp as a Zero crossing detector

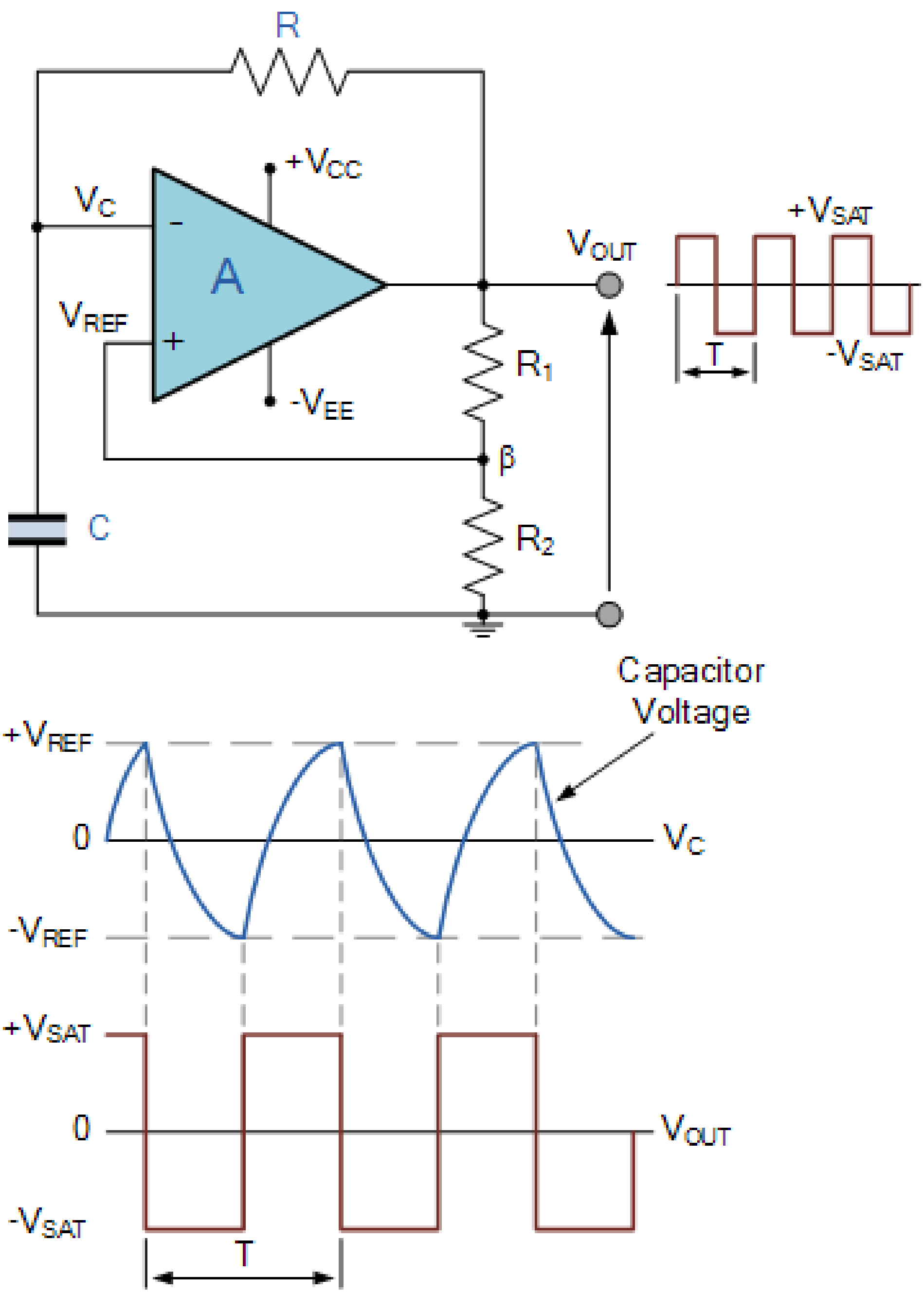
Non-Inverting Zero Crossing Detector



Inverting Zero Crossing Detector



c) IC 741 Op-Amp as an Astable Multivibrator (signal generator)



Once the op-amps inverting terminal reaches the new negative reference voltage, ($-V_{ref}$) at the non-inverting terminal, the op-amp once again changes state and the output is driven to the opposing supply rail voltage, ($+V_{sat}$). The capacitor now sees a positive voltage across its plates and the charging cycle begins again. Thus, the capacitor is constantly charging and discharging creating an astable op-amp multivibrator output.

The period of the output waveform is determined by the RC time constant of the two timing components and the feedback ratio established by the R_1, R_2 voltage divider network which sets the reference voltage level. If the positive and negative values of the amplifier's saturation voltage have the same magnitude, then ($t_1 = t_2$) and the expression to give the period of oscillation becomes:

$$\beta = \frac{R_2}{R_1 + R_2}$$

$$T = 2RC\, ln\left(\frac{1+\beta}{1-\beta}\right)$$

Ex (7): An op-amp multivibrator circuit is constructed using the following components. R_1 = 35 kΩ, R_2 = 30 kΩ, R = 50 kΩ and C = 0.01 μF. Calculate the circuits frequency of oscillation.

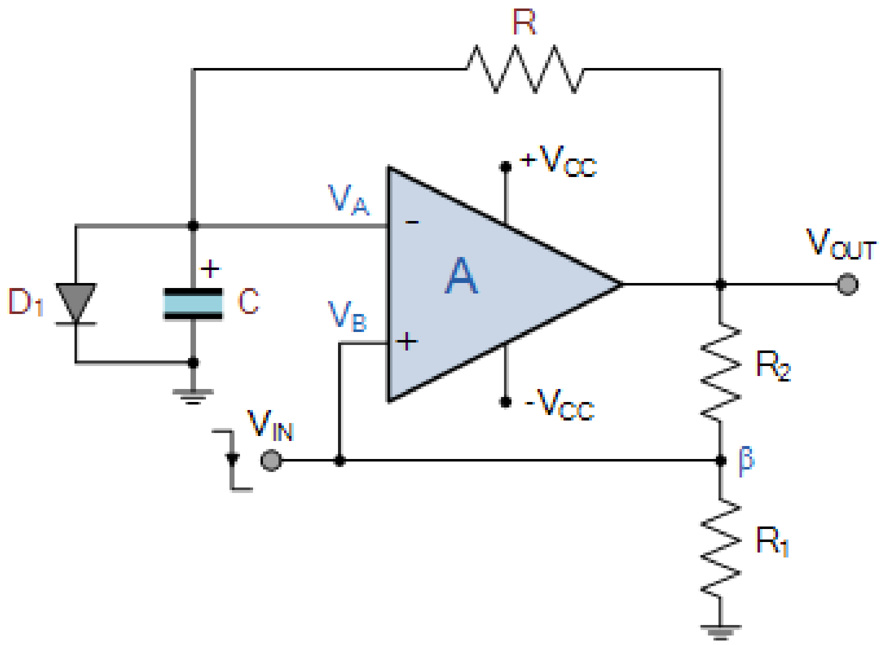
$$\beta = \frac{R_2}{R_1 + R_2} = \frac{30 * 10^3}{35 * 10^3 + 30 * 10^3} = 0.462$$

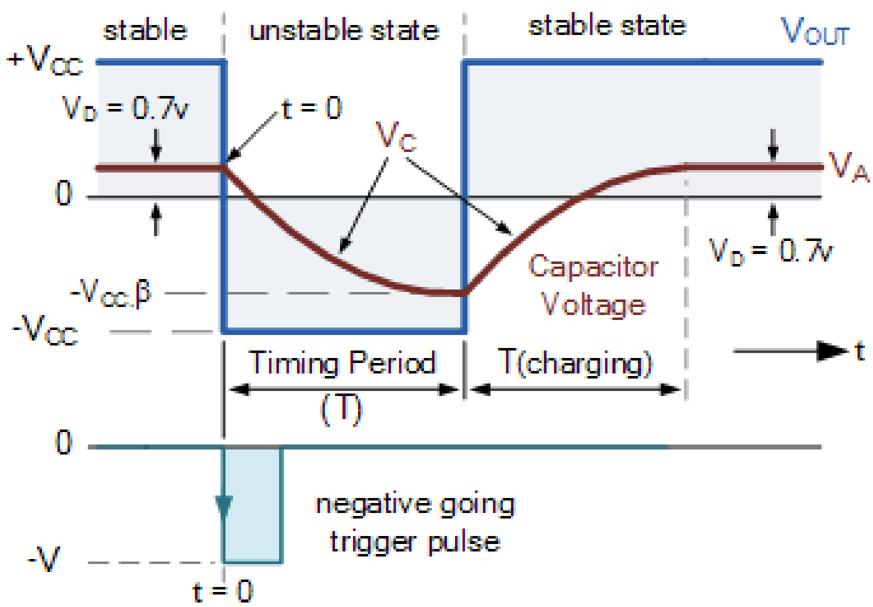
$$T = 2RC\, ln\left(\frac{1+\beta}{1-\beta}\right) = 2 * 50 * 10^3 * 0.01 * 10^{-6} * ln\left(\frac{1+0.462}{1-0.462}\right)$$

$$T = 2 * 50 * 10^3 * 0.01 * 10^{-6} * ln(2.717) = 0.001\, Sec\ or\ 1\, mSec$$

$$F = \frac{1}{T} = \frac{1}{0.001} = 1000\, Hz\ \ or\ 1\, kHz$$

d) IC 741 Op-Amp as a Monostable Multivibrator (one shot)





At initial power on (that is t = 0), the output (V_{OUT}) will saturate towards either the positive rail ($+V_{cc}$), or to the negative rail ($-V_{cc}$), since these are the only two stable states allowed by the op-amp. Let's assume for now that the output has swung towards the positive supply rail, ($+V_{cc}$). Then the voltage at the non-inverting input, (V_B) will be equal to **($+Vcc * \beta$)** where β is the feedback fraction.

The inverting input is held at 0.7 volts which is the forward volt drop of diode D_1, preventing it from going any more positive. Thus, the potential at V_A is much less than that at V_B and the output remains stable at ($+V_{cc}$). At the same time, the capacitor (C) charges up to the same 0.7 volts potential and is held there by the forward-biased voltage drop of the diode.

This temporary meta-stable state causes the capacitor to charge up exponentially in the opposite direction through the feedback resistor (R) from (+0.7 volts) down to the saturated output which it has just switched to ($-V_{cc}$). Diode (D_1) becomes reverse-biased so has no effect. The capacitor (C) will discharge at a time constant ($\tau = RC$).

As soon as the capacitor voltage at V_A reaches the same potential as V_B, that is **(** $-Vcc * \beta$ **)**, the op-amp switches back to its original permanent stable state with the output saturated once again at ($+V_{cc}$).

Then we can see that a negative-going trigger input, will switch the op-amp monostable circuit into its temporary unstable state. After a time delay (T) while the capacitor (C) charges up through the feedback resistor (R), the circuit switches back to its normal stable state once the capacitor voltage reaches the required potential.

This time delay period (T) of the rectangular pulse at the output (the unstable state time) is given as:

H.W. (3): An op-amp multivibrator circuit is constructed using the following components. $R_1 = 10\ k\Omega$, $R_2 = 10\ k\Omega$, $R = 10\ k\Omega$ and $C = 0.1\ \mu F$. Calculate the circuits frequency of oscillation.