GANDHI ACADEMY OF Technology & Engineering
GOLANTHARA, BERHAMPUR

*Lecture Notes on*

# Power Electronics and PLC

## For 5th Semester

## Electrical Engineering (Diploma)

## As per SCTE&VT Syllabus

PREPARED BY: SOUMYA SHYMALAI MAHAPATRA

# TH.5 POWER ELECTRONICS AND PLC

| **Name of the Course:** Diploma in Electrical Engineering | | | |
|---|---|---|---|
| **Course code:** | Th.5 | **Semester:** | 5 th |
| **Total Period:** | 60 Periods | **Examination:** | 3 Hrs |
| **Theory periods:** | 4 P / Week | **Internal Assessment:** | 20 |
| **Tutorial:** | - | **End Semester Examination:** | 80 |
| **Maximum marks:** | 100 | | |

**A. Rationale:**

The development of high power semiconductor devices has facilitated electronic control techniques for electrical power control in a simple, economic and efficient manner. Thus a new area of power electronics has now emerged which replaced the old and bulky method of power control through the use of small electronic devices. Power electronics application has occupied an indispensible position in industrial applications like heating, welding, uninterrupted power supply, battery charging etc. Industrial drives, lighting control are most efficiently controlled by power electronics devices to achieve optimum performance. The objective of this paper is to familiar students with the principles and operations of Power electronics devices in Industrial applications with drives control.

**B. Objectives:**

After completion of this subject the student will be able to:

1. Understand construction, working principle & application of various power electronics devices.
2. Know different gate triggering circuits and commutation methods.
3. Understand working principle of phase controlled rectifier.
4. Know the types and working principle of inverter.
5. Understand working principle and voltage control of chopper.
6. Understand frequency variation using Cyclo-converter.
7. Understand control principle of AC & DC industrial drive.
8. Know different application of SCR / Thyristor.
9. Concept in PLC & its Programming

**C. TOPIC WISE DISTRIBUTION OF PERIODS**

| Sl. No | Topics | Periods |
|---|---|---|
| 1 | Understand The Construction And Working Of Power Electronic Devices | 18 |
| 2 | Understand The Working Of Converters, Ac Regulators And Choppers. | 12 |
| 3 | Understand The Inverters And Cyclo-Converters | 08 |
| 4 | Understand Applications Of Power Electronic Circuits | 10 |
| 5 | PLC And Its Applications | 12 |
| | Total | 60 |

**COURSE CONTENT:**

**1. UNDERSTAND THE CONSTRUCTION AND WORKING OF POWER ELECTRONIC DEVICES**

Construction, Operation, V-I characteristics & application of power diode, SCR, DIAC,TRIAC, Power MOSFET, GTO &IGBT

Two transistor analogy of SCR.

Gate characteristics of SCR.

Switching characteristic of SCR during turn on and turn off.

Turn on methods of SCR.

Turn off methods of SCR (Line commutation and Forced commutation)

Load Commutation

Resonant pulse commutation

Voltage and Current ratings of SCR.

Protection of SCR

Over voltage protection

Over current protection

Gate protection

Firing Circuits

General layout diagram of firing circuit

R firing circuits

R-C firing circuit

UJT pulse trigger circuit

Synchronous triggering (Ramp Triggering )

Design of Snubber Circuits

**2. UNDERSTAND THE WORKING OF CONVERTERS, AC REGULATORS AND CHOPPERS.**

Controlled rectifiers Techniques(Phase Angle, Extinction Angle control), Single quadrantsemi converter, two quadrant full converter and dual Converter

Working of single-phase half wave controlled converter with Resistive and R-L loads.

Understand need of freewheeling diode.

Working of single phase fully controlled converter with resistive and R- L loads.

Working of three-phase half wave controlled converter with Resistive load

Working of three phase fully controlled converter with resistive load.

Working of single phase AC regulator.

Working principle of step up & step down chopper.

Control modes of chopper

Operation of chopper in all four quadrants.

**3. UNDERSTAND THE INVERTERS AND CYCLO-CONVERTERS**

Classify inverters.

Explain the working of series inverter.

Explain the working of parallel inverter
Explain the working of single-phase bridge inverter
Explain the basic principle of Cyclo-converter.
Explain the working of single-phase step up & step down Cyclo-converter.
Applications of Cyclo-converter.

**4. UNDERSTAND APPLICATIONS OF POWER ELECTRONIC CIRCUITS**

List applications of power electronic circuits.
List the factors affecting the speed of DC Motors.
Speed control for DC Shunt motor using converter.
Speed control for DC Shunt motor using chopper.
List the factors affecting speed of the AC Motors.
Speed control of Induction Motor by using AC voltage regulator.
Speed control of induction motor by using converters and inverters (V/F control).
Working of UPS with block diagram.
Battery charger circuit using SCR with the help of a diagram.
Basic Switched mode power supply (SMPS) - explain its working & applications

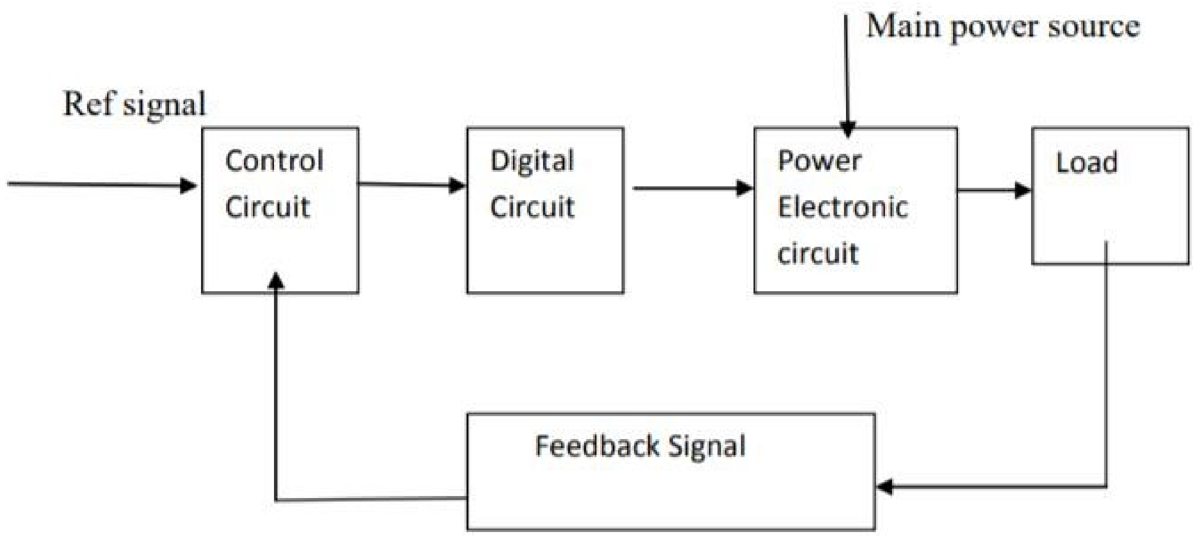
**5. PLC AND ITS APPLICATIONS**

Introduction of Programmable Logic Controller (PLC)
Advantages of PLC
Different parts of PLC by drawing the Block diagram and purpose of each part of PLC.
Applications of PLC
Ladder diagram
Description of contacts and coils in the following states
i)Normally open
ii) Normally closed
iii) Energized output
iv) latched Output
v) Branching
Ladder diagrams for i) AND gate ii) OR gate and iii) NOT gate.
Ladder diagrams for combination circuits using NAND, NOR, AND, OR and NOT
Timers-i)T ON ii) T OFF and iii)Retentive timer
Counters-CTU, CTD
Ladder diagrams using Timers and counters
PLC Instruction set
Ladder diagrams for following (i) DOL starter and STAR-DELTA starter (ii) Stair caselighting (iii) Traffic light Control (iv) Temperature Controller
Special control systems- Basics DCS & SCADA systems
Computer Control–Data Acquisition, Direct Digital Control System (Basics only)

POWER ELECTRONICS

## INTRODUCTION

Power electronics may be defined as the application of solid state electronics for the control and conversion of electrical power. The inter relationship of power electronics with power, electronics and control is shown in the fig




Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices have been improved tremendously.

Advantages of power electronics

- High efficiency due to low loss in power semiconductor devices.
- High reliability of power electronic converter system.
- Long life and less maintenance due to absence of any moving parts.
- Flexibility in operation
- Fast dynamic response compared to electromechanical converter system.
- Small size and less weight, thus low installation cost.

**Application of power electronics**

- Our Daily Life: fan regulator, light dimmer, air-conditioning, induction cooking, emergency lights, personal computers, vacuum cleaners, UPS (uninterrupted power system), battery charges, etc.
- Automotives and Traction: Subways, hybrid electric vehicles, trolley, fork-lifts, and many more. A modern car itself has so many components where power electronic is used such as ignition switch, windshield wiper control, adaptive front lighting, interior

lighting, electric power steering and so on. Besides power electronics are extensively used in modern traction systems and ships.

- Industries: Almost all the motors employed in the industries are controlled by power electronic drives, for eg. Rolling mills, textile mills, cement mills, compressors, pumps, fans, blowers, elevators, rotary kilns etc. Other applications include welding, arc furnace, cranes, heating applications, emergency power systems, construction machinery, excavators etc.
- Defense and Aerospace: Power supplies in aircraft, satellites, space shuttles, advance control in missiles, unmanned vehicles and other defense equipments.
- Renewable Energy: Generation systems such as solar, wind etc. needs power conditioning systems, storage systems and conversion systems in order to become usable. For example solar cells generate DC power and for general application we need AC power and hence power electronic converter is used.
- Utility System: HVDC transmission, VAR compensation (SVC), static circuit breakers, generator excitation systems, FACTS, smart grids, etc.

## CONSTRUCTION, OPERATION, V-I CHARACTERISTICS & APPLICATION OF POWER DIODE, SCR, DIAC, TRIAC, POWER MOSFET, GTO &IGBT

### POWER DIODE

Definition: A diode that has two terminals like anode & cathode and two layers like P & N, used in the power electronics circuits is known as power diode. This diode is more complex in construction as well as in operation because low power device has to change to make them appropriate in high power applications.

In power electronic circuits, this diode plays an essential role. It can be used as a rectifier in converter circuits, voltage regulation circuits, flyback / freewheeling diode, reverse voltage protection, etc.

These diodes are related to signal diodes except for a slight disparity in its construction. The doping level in signal diode for both P-layer & N-layer is the same whereas, in power diodes, the junction can be formed among a heavily doped P+ layer & lightly doped N– layer.

**CONSTRUCTION**

The construction of this diode includes three layers like the P+ layer, n– layer and n+ layer. Here the top layer is the P+ layer, it is heavily doped. The middle layer is n– layer, it is lightly doped and the last layer is n+ layer, and it is heavily doped.

Here p+ layer acts as an anode, the thickness of this layer is 10 µm. The n+ layer acts as a cathode, the thickness of this layer is 250-300 µm. The n- layer acts as a middle layer/drift layer, increases then breakdown voltage will be increased.

**WORKING PRINCIPLE OF POWER DIODE**

The working principle of this diode is similar to the normal PN junction diode. When the voltage of the anode terminal is high than the voltage of the cathode terminal, the diode conducts. The range of forwarding voltage drop in this diode is very small approximately 0.5V – 1.2V. In this mode, the diode works as a forward characteristic.

If the voltage of the cathode is high than the voltage of anode, the diode performs as blocking mode. In this mode, the diode performs like the reverse characteristic.

**TYPES OF POWER DIODE**

The power diodes depending on the reverse recovery time as well as the process of manufacturing are classified into three types such as

General Purpose Diodes

Fast Recovery Diodes

Schottky Diodes

**APPLICATION OF POWER DIODE**

Rectifiers

Clipper Circuits

Clamping Circuits

Reverse Current Protection Circuits

In Logic Gates

**V-I CHARACTERISTICS OF POWER DIODES**

The figure below shows the v-i characteristics of a power diode which is almost similar to that of a signal diode.

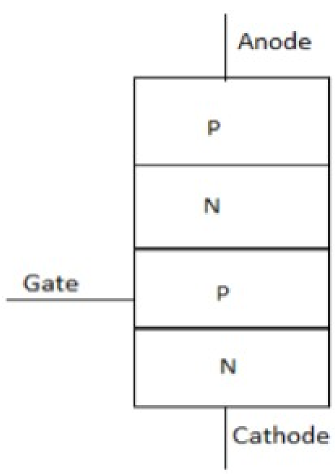
In signal diodes for forward biased region the current increases exponentially however in power diodes high forward current leads to high ohmic drop which dominates the exponential growth and the curve increases almost linearly. The maximum reverse voltage that the diode can withstand is depicted by $V_{RRM}$, i.e. peak reverse repetitive voltage. Above this voltage the reverse current becomes very high abruptly and as the diode is not designed to dissipate such high amount of heat, it may get destroyed. This voltage may also be called as peak inverse voltage (PIV).

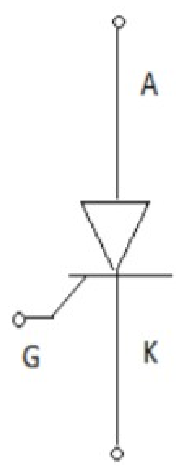
**SCR/THYRISTOR**

Thyristor is a four layer three junction pnpn semiconductor switching device. It has 3 terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact, possess high reliability and have low loss.

**CONSTRUCTION**

An SCR is constructed with the four layers that consist of the P-type and the N-type semiconductor material. These are layered in such a way that it tends to form three junctions that are J1, J2, and J3. The three terminals that are attached to it are known as anode, cathode and the gate. The anode is the basic terminal through which the current flows or enters into the device. Where the cathode is the terminal through which the entered current leaves the device.
The current entering terminal is of positive polarity and the terminal through which the current is leaving is of negative polarity. In between the flow of current among the terminals, there must be a terminal that can provide the control. This can be provided by the terminal gate. This terminal is sometimes also referred to as the terminal of control.



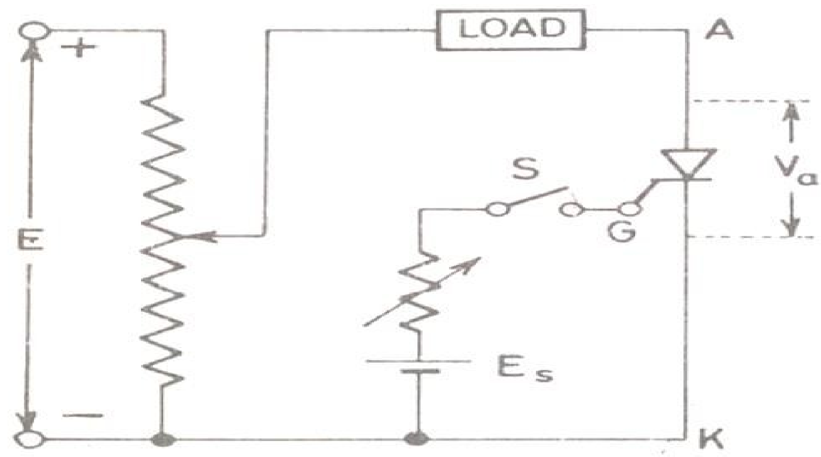




**PRINCIPLE OF OPERATION**

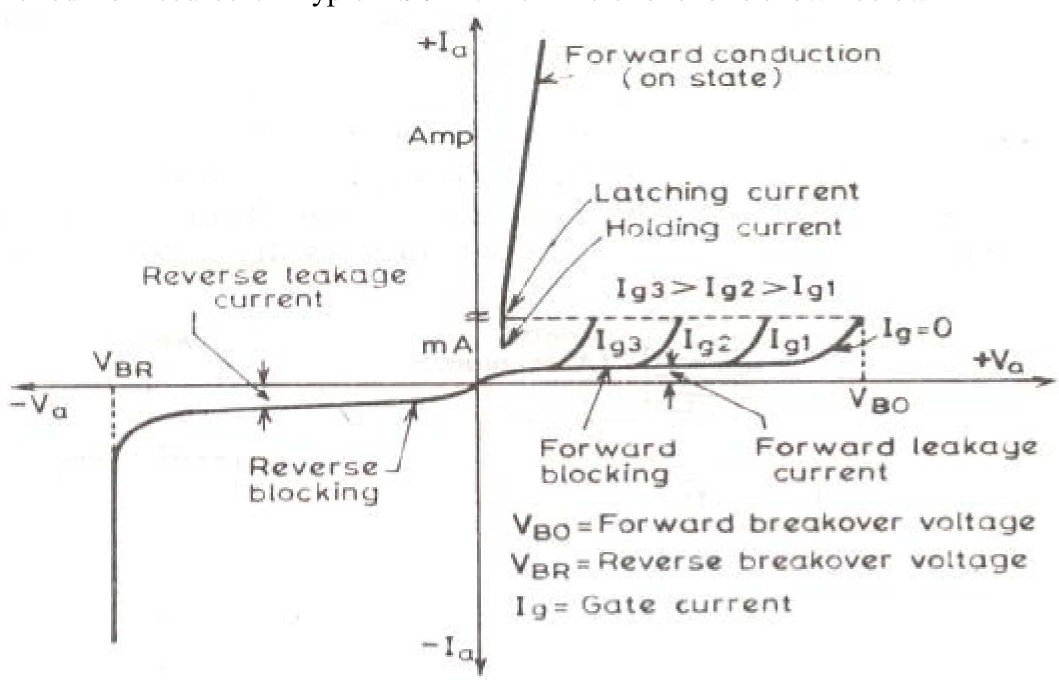
SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forward direction and high resistance in the reverse direction. It is a unidirectional device.

The anode to cathode is connected in series with the load circuit. Essentially the device is a switch. Ideally it remains off (voltage blocking state), or appears to have an infinite impedance until both the anode and gate terminals have suitable positive voltages with respect to the cathode terminal. The thyristor then switches on and current flows and continues to conduct without further gate signals. Ideally the thyristor has zero impedance in conduction state. For switching off or reverting to the blocking state, there must be no gate signal and the anode current must be reduced to zero. Current can flow only in one direction.

The circuit diagram for obtaining static V-I characteristics is as shown




Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source . A typical SCR V-I characteristic is as shown below




$VBO$=Forward breakover voltage

$VBR$=Reverse breakover voltage

$Ig$=Gate current
$Va$=Anode voltage across the thyristor terminal A,K.
$Ia$=Anode current
It can be inferred from the static V-I characteristic of SCR. SCR have 3 modes of operation:
1. Reverse blocking mode
2. Forward blocking mode ( off state)
3. Forward conduction mode (on state)

1. Reverse Blocking Mode
When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions $J1$ and $J2$ are reverse biased where junction $J2$ is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them. A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.
Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage $VBR$, an avalanche occurs at $J1$ and $J3$ and the reverse current increases rapidly. As a large current associated with $VBR$ and hence more losses to the SCR. This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

2. Forward Blocking Mode
When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased.
Thus junction $J1$ and $J3$ are forward biased and $J2$ is reverse biased. As the forward voltage is increases junction $J2$ will have an avalanche breakdown at a voltage called forward breakover voltage$VBO$. When forward voltage is less then $VBO$ thyristor offers high impedance. Thus a thyristor acts as an open switch in forward blocking mode.

3. Forward Conduction Mode
Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:
1. By exceeding the forward breakover voltage.
2. By applying a gate pulse between gate and cathode.
During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2V. This small voltage drop is due to ohmic drop across the four layers of the device.

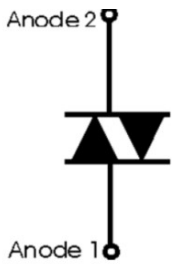
**LIST APPLICATIONS OF SCR**
Due to the wide variety of advantages, like ability to turn ON from OFF state in response to a low gate current and also able to switch high voltages, makes the SCR or thyristor to be used in a variety of applications.

These applications include switching, rectification, regulation, protection, etc. The SCRs are used for home appliance control include lighting, temperature control, fan speed regulation, heating, and alarm activation.

For industrial applications, SCRs are used to control the motor speed, battery charging and power conversions.

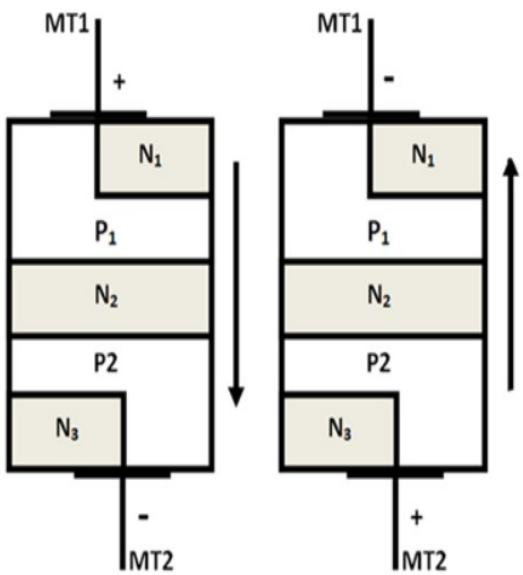
**DIAC**

The DIAC is a bi-directional semiconductor switch that can be switched on in both polarities. The full form of the name DIAC is diode alternating current.




**CONSTRUCTION AND OPERATION OF DIAC**

The basic construction of DIAC consist of two terminals namely MT1 and MT2. When the MT1 terminal is designed +Ve with respect to the terminal MT2, the transmission will take place to the p-n-p-n structure. The diac works in both the direction.



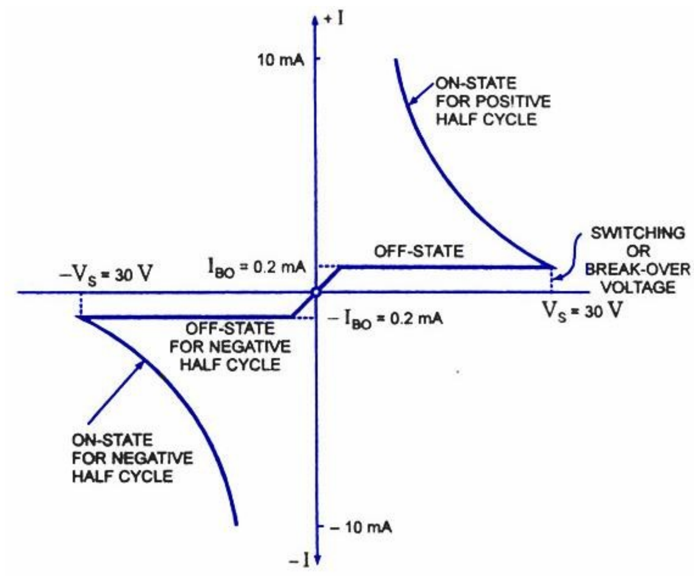

The DIAC is basically a diode that conducts after a 'break-over' voltage, selected VBO, and is exceeded. When the diode surpasses the break-over voltage, then it goes into the negative dynamic resistance of region. This causes in a reduce in the voltage drop across the diode with rising voltage. So there is a quick increase in the current level that is mannered by the device.

The diode leftovers in its transmission state until the current through it falls below, what is termed the holding current, which is usually chosen by the letters IH. Below the holding current, the DIAC reverts to its non-conducting state. Its behavior is bidirectional and thus its function takes place on both halves of an alternating cycle.

**CHARACTERISTICS OF DIAC**

V-I characteristics of a diac is shown below

The diac performs like an open-circuit until its switching is exceeded. At that position the diac performs until its current decreases toward zero. Because of its abnormal construction, doesn't switch sharply into a low voltage condition at a low current level like the Triac or SCR, once it goes into transmission, the diac preserves an almost continuous –Ve resistance characteristic, that means, voltage reduces with the enlarge in current. This means that, unlike the Triac and the SCR, the diac cannot be estimated to maintain a low voltage drop until its current falls below the level of holding current.




*V-I Characteristic of a Diac*

**LIST APPLICATION OF DIAC**

The main application of a DIAC is its use in a TRIAC triggering circuit. The DIAC is connected to the gate terminal of the TRIAC. When the voltage across the gate decreases below a predetermined value, the gate voltage will be zero and hence the TRIAC will be turned off. Some other applications of a DIAC include:

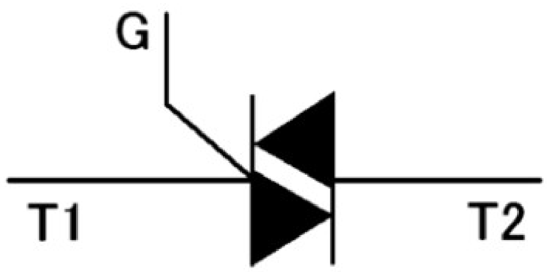
It can be used in the lamp dimmer circuit

It is used in a heat control circuit

It is used in the speed control of a universal motor

**TRIAC**

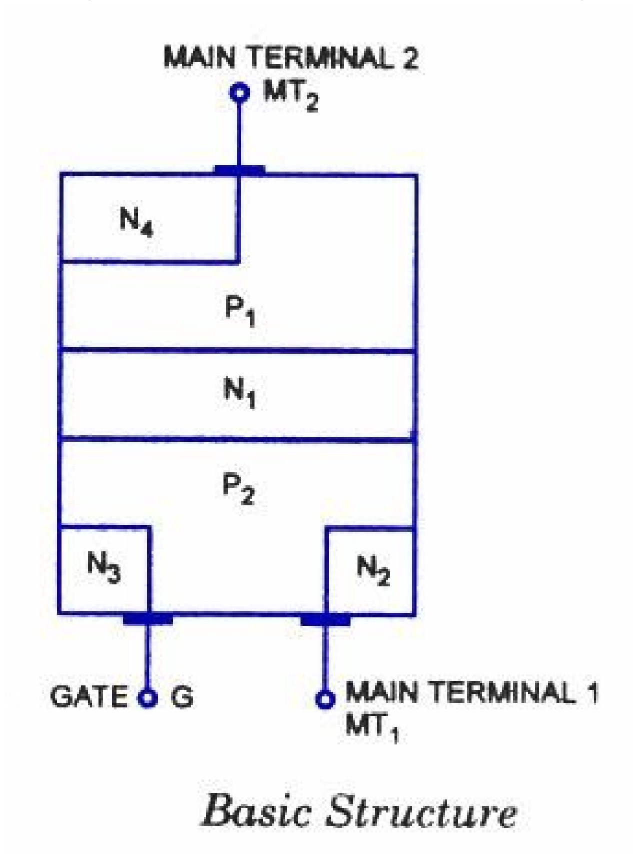
A Triac device comprises of two thyristors that are connected in opposite direction but in parallel but, it is controlled by the same gate. Triac is a 2-dimensional thyristor which is activated on both halves of the i/p AC cycle using + Ve or -Ve gate pulses. The three terminals of the Triac are MT1; MT2 & gate terminal (G). Generating pulses are applied between MT1 and gate terminals. The 'G' current to switch 100A from triac is not more than 50mA or so.

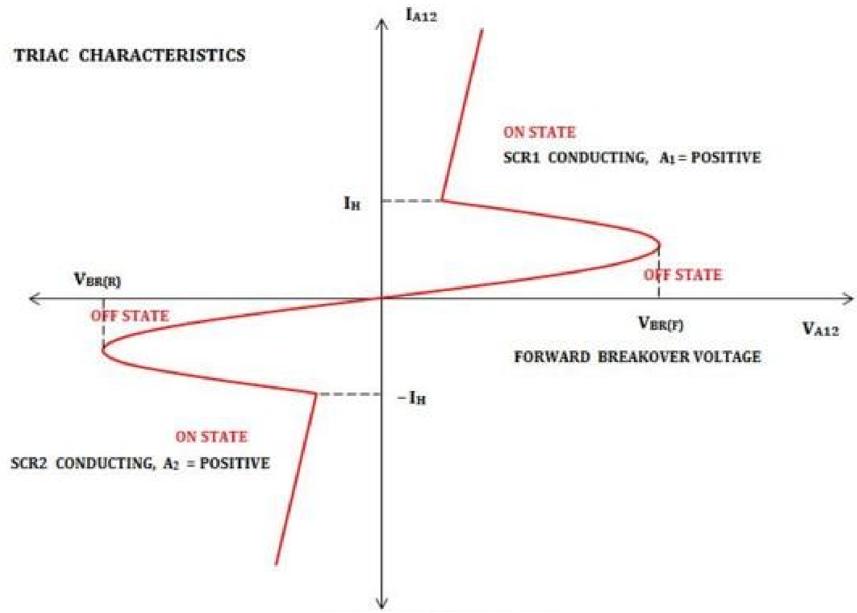



TRIAC

**CONSTRUCTION AND OPERATION OF TRIAC**

TRIAC is equivalent to two SCRs connected in inverse parallel with the gates connected together. As a result, the TRIAC functions as a Bidirectional switch to pass the current in both directions once the gate is triggered. TRIAC is a three terminal device with a Main terminal1 (MT1), Main terminal 2(MT2) and a Gate. The MT1 and MT2 terminals are used to connect the Phase and Neutral lines while the Gate is used to feed the triggering pulse. The Gate can be triggered either by a positive voltage or negative voltage. When the MT2 terminal gets a positive voltage with respect to the MT1 terminal and the Gate gets a positive trigger, then the left SCR of the TRIAC triggers and circuit completes. But if the polarity of the voltage at the MT2 and MT1 terminals is reversed and a negative pulse is applied to the Gate, then the right SCR of Triac conducts. When the Gate current is removed, the TRIAC switches off. So a minimum holding current Ih must be maintained at the gate to keep the TRIAC conducting.






**CHARACTERISTICS OF TRIAC**

The V-I characteristics of TRIAC are discussed below

The triac is designed with two SCRs which are fabricated in the opposite direction in a crystal. Operating characteristics of triac in the 1st and 3rd quadrants are similar but for the direction of flow of current and applied voltage.

The V-I characteristics of triac in the first and third quadrants are basically equal to those of an SCR in the first quadrant.

It can be functioned with either +Ve or –Ve gate control voltage but in typical operation generally the gate voltage is +Ve in first quadrant and -Ve in third quadrant.

The supply voltage of the triac to switch ON depends upon the gate current. This allows utilizing a triac to regulate AC power in a load from zero to full power in a smooth and permanent manner with no loss in the device control.

**MODES OF OPERATION OF TRIAC AND MENTION THE PREFERRED MODES**

It is possible to connect various combinations of negative and positive voltages to the triac terminals because it is a bidirectional device. The four possible electrode potential combinations which make the triac to operate four different operating quadrants or modes are given as.

MT2 is positive with respect to MT1 with a gate polarity positive with respect to MT1.

MT2 is positive with respect to MT1 with a gate polarity negative with respect to MT1.

MT2 is negative with respect to MT1 with a gate polarity negative with respect to MT1.

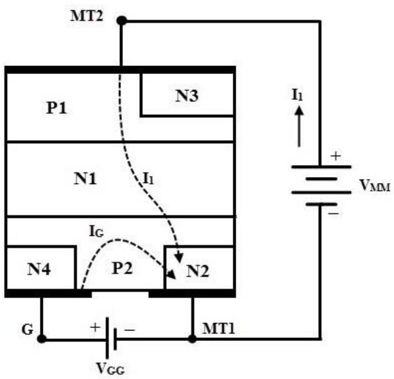
MT2 is negative with respect to MT1 with a gate polarity positive with respect to MT1.

Mode 1: MT2 is Positive, Positive Gate Current

When the gate terminal is made positive with respect to MT1, gate current flows through the P2 and N2 junction. When this current flows, the P2 layer is flooded with electrons and further these electrons are diffused to the edge of junction J2 (or P2-N1 junction).

These electrons collected by the N1 layer builds a space charge on the N1 layer. Therefore, more holes from the P1 region are diffused into the N1 region to neutralize the negative space charges. These holes arrive at the junction J2 and produce the positive space charge in the P2 region, which causes more electrons to inject into P2 from N2.

This results a positive regeneration and finally the main current flows from MT2 to MT1 through the regions P1- N1 – P2 – N2.

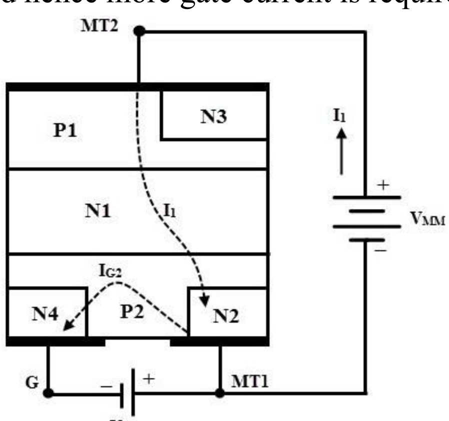



Mode 2: MT2 is Positive, Negative Gate Current

When MT2 is positive and the gate terminal is negative with respect to MT1, gate current flows through the P2-N4 junction. This gate current forward biases the P2-N4 junction for auxiliary P1N1P2N4 structure. This results the triac to conduct initially through the P1N1P2N4 layers.

This further raises the potential between P2N2 towards the potential of MT2. This causes the current to establish from left to right in the P2 layer which forward biases the junction P2N2. And hence the main structure P1N1P2N2 begins to conduct.

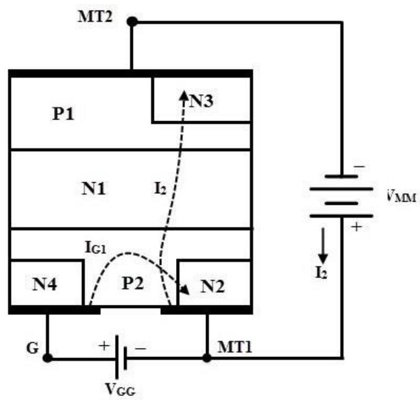
Initially conducted auxiliary structure P1N1P2N4 is considered as a pilot SCR while later conducted structure P1N1P2N2 is considered as main SCR. Hence the anode current of pilot SCR serves as gate current to the main SCR. The sensitivity to gate current is less in this mode and hence more gate current is required to turn the triac.



Mode 3: MT2 is Negative, Positive Gate Current

In this mode, MT2 is made negative with respect to MT1 and the device is turned ON by applying a positive voltage between the gate and MT1 terminal. The turn ON is initiated by N2 which acts as a remote gate control and the structure leads to turn ON the triac is P2N1P1N3.

The external gate current forward biases the junction P2-N2. N2 layer injects the electrons into the P2 layer which are then collected by junction P2N1. This result to increases the current flow through P2N1 junction.




The holes injected from layer P2 diffuse through the N1 region. This builds a positive space charge in the P region. Therefore, more electrons from N3 are diffused into P1 to neutralize the positive space charges.

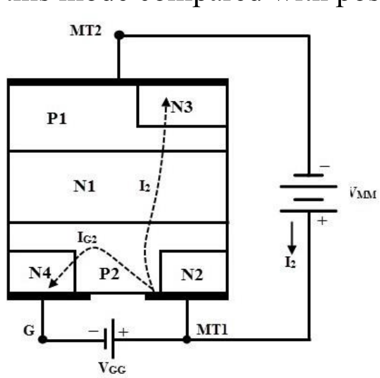
Hence, these electrons arrive at junction J2 and produce a negative space charge in the N1region which results to inject more holes from the P2 into the region N1. This regenerative process continues till the structure P2N1P1N3 turns ON the triac and conducts the external current.

As the triac is turned ON by the remote gate N2, the device is less sensitive to the positive gate current in this mode.

Mode 4: MT2 is Negative, Negative Gate Current

In this mode N4 acts as a remote gate and injects the electrons into the P2 region. The external gate current forward biases the junction P2N4. The electrons from the N4 region are collected by the P2N1 junction increase the current across P1N1 junction.

Hence the structure P2N1P1N3 turns ON by the regenerative action. The triac is more sensitive in this mode compared with positive gate current in mode 3.



From the above discussion, it is concluded that the modes 2 and 3 are less sensitive configuration which needs more gate current to trigger the triac, whereas more common triggering modes of triac are 1 and 4 which have greater sensitivity. In practice the more sensitive mode of operation is selected such that the polarity of the gate is to match with the polarity of the terminal MT2.

**APPLICATIONS OF TRIAC:**

TRIACs are used in numerous applications such as light dimmers, speed controls for electric fans and other electric motors and in the modern computerized control circuits of numerous household small and major appliances. They can be used both into AC and DC circuits however the original design was to replace the utilization of two SCRs in AC circuits. There are two families of TRIACs, which are mainly used for application purpose, they are BT136, BT139.

**POWER MOSFET**

The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) transistor is a semiconductor device that is widely used for switching purposes and for the amplification of electronic signals in electronic devices.

The constructional details of high power MOSFET are shown in below figure. In this figure is shown a planar diffused metal-oxide-semiconductor (DMOS) structure for n -channel which is quite common for power MOSFETs. On n+ substrate, high resistivity n− layer is epitaxially grown. The thickness of n− layer determines the voltage blocking capability of the device.

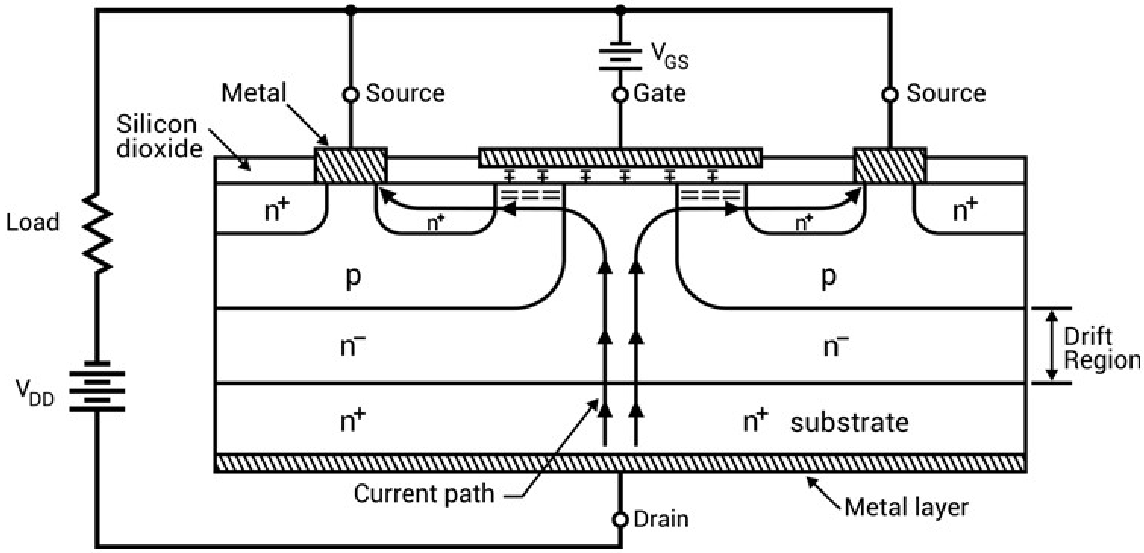
On the other side of n+ substrate, a metal layer is deposited to form the drain terminal. Now p− regions are diffused in the epitaxially grown n− layer. Further, n+ regions are diffused in p regions as shown. As before, Si02 layer is added, which is then etched so as to fit metallic source and gate terminals.

A power MOSFET actually consists of a parallel connection of thousands of basic MOSFET cells on the same single chip of silicon.

When gate circuit voltage is zero, and VDD is present, n−p junctions are reverse biased and no current flows from drain to source. When gate terminal is made positive with respect to source, an electric field is established and electrons form n-channel in the p regions as shown. So a current from drain to source is established as indicated by arrows.

With gate voltage increased current ID also increases as expected. Length of n-channel can be controlled and therefore on-resistance can be made low if short length is used for the channel.

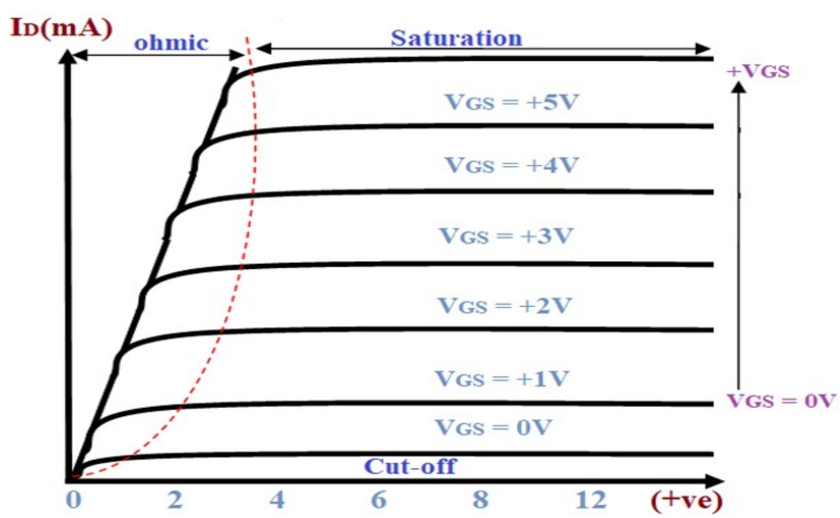
Power MOSFET conduction is due to majority carriers; therefore, time delays caused by removal or recombination of minority carriers are eliminated. Thus, power MOSFET can work at switching frequencies in the megahertz range.




*Basic structure of a n-channel DMOS power MOSFET*

**VI Characteristics:**

**VI characteristics of the enhancement-mode MOSFET** are drawn between the drain current ($I_D$) and the drain-source voltage ($V_{DS}$). The VI characteristics are partitioned into three different regions, namely ohmic, saturation, and cut-off regions. The cutoff region is the region where the MOSFET will be in the OFF state where the applied bias voltage is zero. When the bias voltage is applied, the MOSFET slowly moves towards conduction mode, and the slow increase in conductivity takes place in the ohmic region. Finally, the saturation region is where the positive voltage is applied constantly and the MOSFET will be staying in the conduction state.

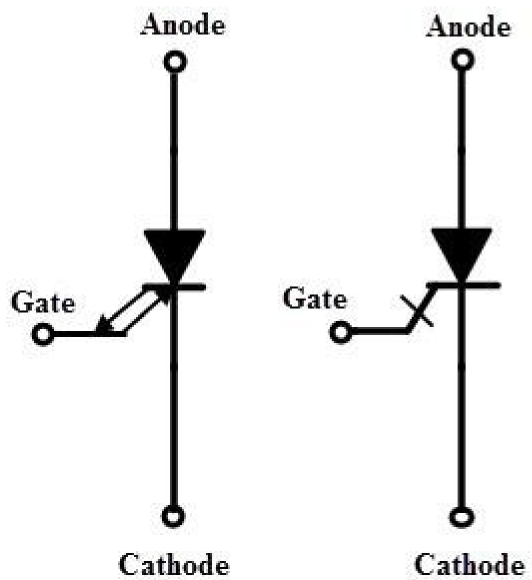


**APPLICATIONS OF MOSFET**

- MOSFET amplifiers are extensively used in radio frequency applications.
- It acts as a passive element like resistor, capacitor and inductor.
- DC motors can be regulated by power MOSFETs.
- High switching speed of MOSFETs makes it an ideal choice in designing chopper circuits.

**GTO**

A Gate Turn off Thyristor or GTO is a three terminal, bipolar (current controlled minority carrier) semiconductor switching device. Similar to conventional thyristor, the terminals are anode, cathode and gate as shown in figure below. As the name indicates, it has gate turn off capability. These are capable not only to turn ON the main current with a gate drive circuit, but also to turn it OFF.

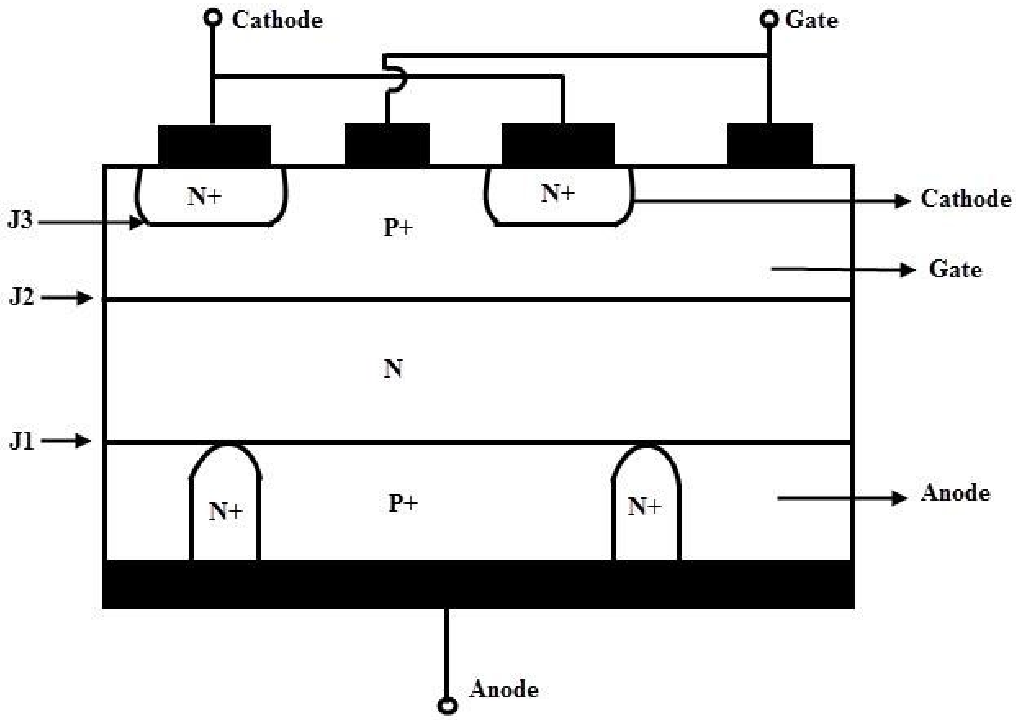



**Gate Turn-Off Thyristor Symbols**

**CONSTRUCTION**

Consider the below structure of GTO, which is almost similar to the thyristor. It is also a four layer, three junction P-N-P-N device like a standard thyristor. In this, the n+ layer at the cathode end is highly doped to obtain high emitter efficiency. This result the breakdown voltage of the junction J3 is low which is typically in the range of 20 to 40 volts.

The doping level of the p type gate is highly graded because the doping level should be low to maintain high emitter efficiency, whereas for having a good turn OFF properties, doping of this region should be high. In addition, gate and cathodes should be highly interdigited with various geometric forms to optimize the current turn off capability.




The junction between the P+ anode and N base is called anode junction. A heavily doped P+ anode region is required to obtain the higher efficiency anode junction so that a good turn ON properties is achieved. However, the turn OFF capabilities are affected with such GTOs.

This problem can be solved by introducing heavily doped N+ layers at regular intervals in P+ anode layer as shown in figure. So this N+ layer makes a direct contact with N layer at junction J1. This cause the electrons to travel from base N region directly to anode metal contact without causing hole injection from P+ anode. This is called as a anode shorted GTO structure.

Due to these anode shorts, the reverse blocking capacity of the GTO is reduced to the reverse breakdown voltage of junction j3 and hence speeds up the turn OFF mechanism.

However, with a large number of anode shorts, the efficiency of the anode junction reduces and hence the turn ON performance of the GTO degrades. Therefore, careful considerations have to be taken about the density of these anode shorts for a good turn ON and OFF performance.

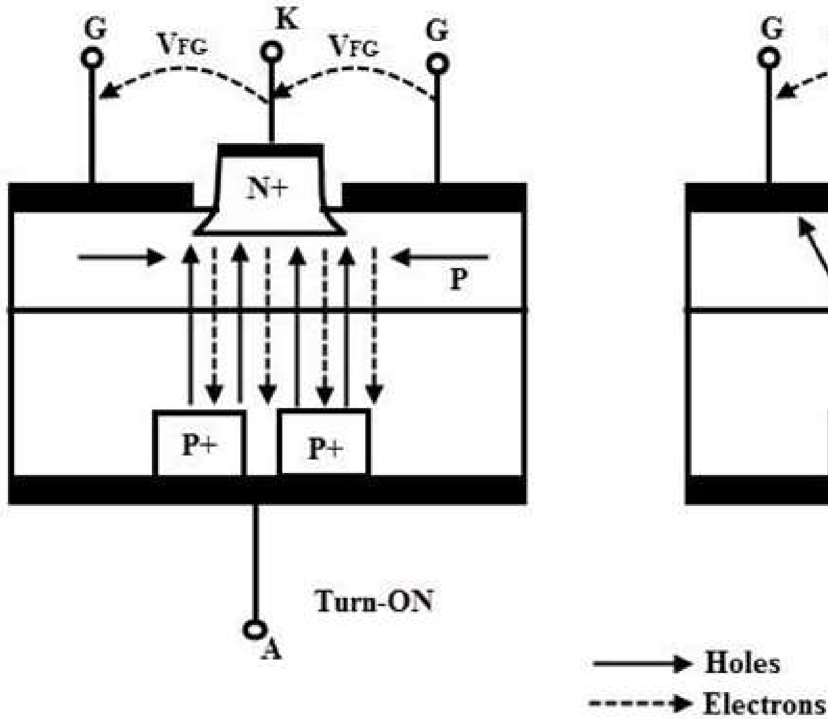
**PRINCIPLE OF OPERATION**

The turn ON operation of GTO is similar to a conventional thyristor. When the anode terminal is made positive with respect to cathode by applying a positive gate current, the hole current injection from gate forward bias the cathode p-base junction.

This results in the emission of electrons from the cathode towards the anode terminal. This induces the hole injection from the anode terminal into the base region. This injection of holes and electrons continuous till the GTO comes into the conduction state.

In case of thyristor, the conduction starts initially by turning ON the area of cathode adjacent to the gate terminal. And thus, by plasma spreading the remaining area comes into the conduction.

Unlike a thyristor, GTO consists of narrow cathode elements which are heavily interdigitated with gate terminal, thereby initial turned ON area is very large and plasma spreading is small. Hence the GTO comes into the conduction state very quickly.




To turn OFF a conducting GTO, a reverse bias is applied at the gate by making the gate negative with respect to cathode. A part of the holes from the P base layer is extracted through the gate which suppress the injection of electrons from the cathode.

In response to this, more hole current is extracted through the gate results more suppression of electrons from the cathode. Eventually, the voltage drop across the p base junction causes to reverse bias the gate cathode junction and hence the GTO is turned OFF.

During the hole extraction process, the p-base region is gradually depleted so that the conduction area squeezed. As this process continuous, the anode current flows through remote areas forming high current density filaments. This causes local hot spots which can damage the device unless these filaments are extinguished quickly.

By the application of high negative gate voltage these filaments are extinguished rapidly. Due to the N base region stored charge, the anode to gate current continues to flow even though the cathode current is ceased. This is called a tail current which decays exponentially as the excess charge carriers are reduced by the recombination process. Once the tail current reduced to a leakage current level, the device retains its forward blocking characteristics.

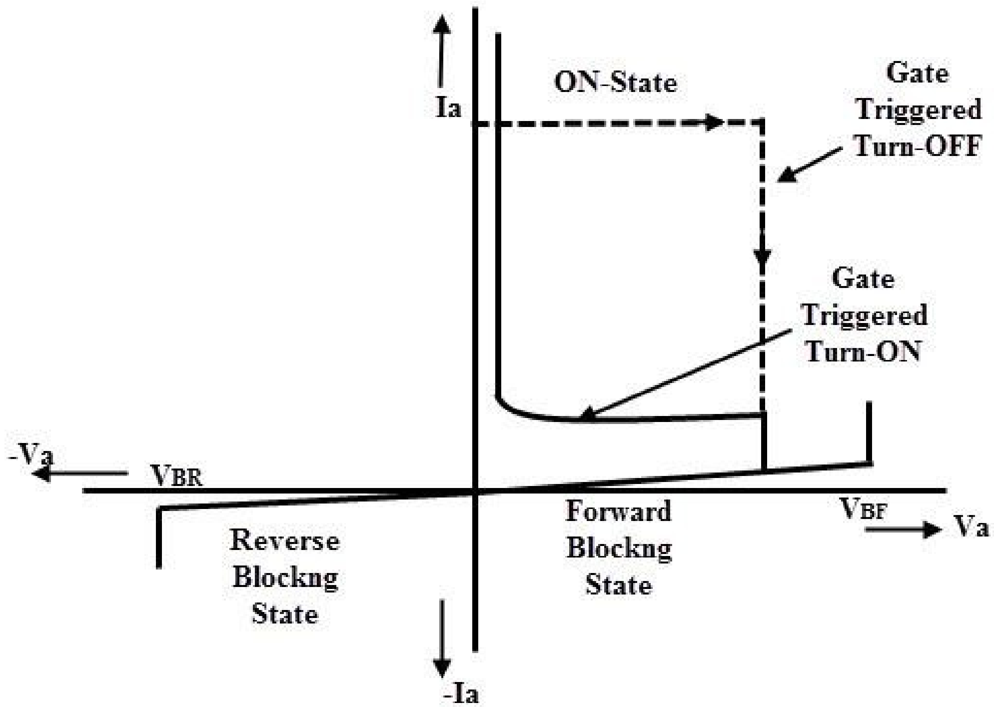
**V-I CHARACTERISTICS**

During the turn ON, GTO is similar to thyristor in its operates.So the first quadrant characteristics are similar to the thyristor. When the anode is made positive with respect to cathode, the device operates in forward blocking mode. By the application of positive gate signal triggers the GTO into conduction state.

The latching current and forward leakage currents are considerably higher in GTO compared to the thyristor as shown in figure. The gate drive can be removed if the anode current is above the holding current level.

But it is recommended not to remove the positive gate drive during conduction and to hold at value more than the maximum critical gate current. This is because the cathode is subdivided into small finger elements as discussed above to assist the turn OFF process.

This causes the anode current dips below the holding current level transiently, which forces a high anode current at a high rate back into the GTO. This can be potentially destructive. Therefore, some manufacturers recommend the continuous gate signal during the conduction state.




The GTO can be turned OFF by the application of reverse gate current which can be either step or ramp drive. The GTO can be turned OFF without reversing anode voltage. The dashed line in the figure shows i-v trajectory during the turn OFF for an inductive load. It should be noted that during the turn OFF, GTO can block a rated forward voltage only.

To avoid dv/dt triggering and protect the device during turn OFF, either a recommended value of resistance must be connected between the gate and cathode or a small reverse bias voltage (typically -2V) must be maintained on the gate terminal. This prevents the gate cathode junction to become forward biased and hence the GTO sustains during the turn OFF state.

In reverse biased condition of GTO, the blocking capability is depends on the type of GTO. A symmetric GTO has a high reverse blocking capability while asymmetric GTO has a small reverse blocking capability as shown in figure.

It is observed that, during reverse biased condition, after a small reverse voltage (20 to 30 V) GTO starts conducting in reverse direction due to the anode short structure. This mode of operation does not destroy the device provided that the gate is negatively biased and the time of this operation should be small.

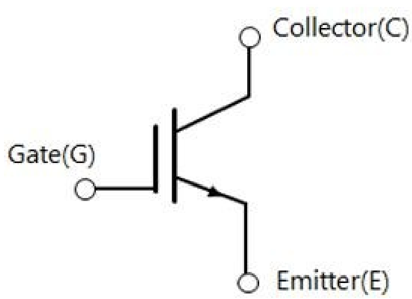
**LIST APPLICATION OF GTO**

Due to the advantages like excellent switching characteristics, no need of commutation circuit, maintenance-free operation, etc makes the GTO usage predominant over thyristor in many applications. It is used as a main control device in choppers and inverters. Some of these applications are

- AC drives
- DC drives or DC choppers
- AC stabilizing power supplies
- DC circuit breakers
- Induction heating
- And other low power applications

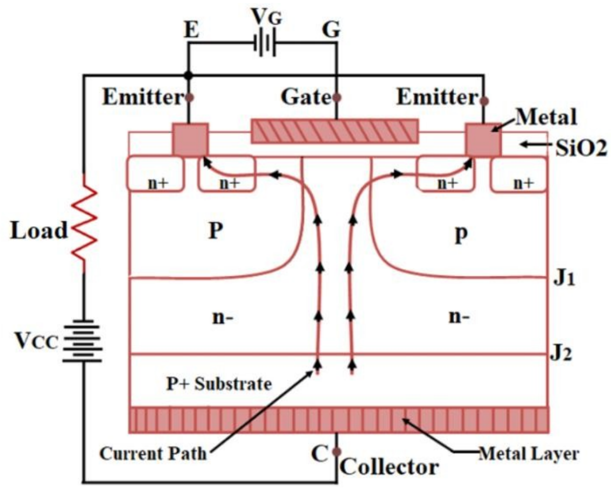
**IGBT**

IGBT is the short form of Insulated Gate Bipolar Transistor. It is a three-terminal semiconductor switching device that can be used for fast switching with high efficiency in many types of electronic devices. These devices are mostly used in amplifiers for switching/processing complex wave patters with pulse width modulation (PWM). The typical symbol of IGBT along with its image is shown below.



**WORKING OF IGBT**

IGBT has three terminals attached to three different metal layers, the metal layer of the gate terminal is insulated from the semiconductors by a layer of silicon dioxide (SIO2). IGBT is constructed with 4 layers of semiconductor sandwiched together. The layer closer to the collector is the p+ substrate layer above that is the n- layer, another p layer is kept closer to the emitter and inside the p layer, we have the n+ layers. The junction between the p+ layer and n- layer is called the junction J2 and the junction between the n- layer and the p layer is called the junction J1. The structure of IGBT is shown in the figure below.

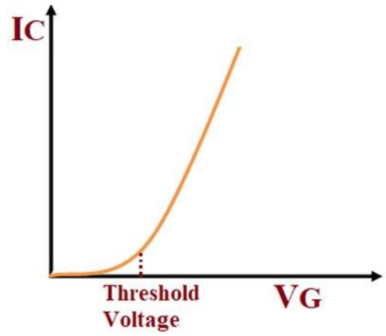



To understand the working of the IGBT, consider a voltage source VG connected positively to the Gate terminal with respect to the Emitter. Consider other voltage source VCC connected across The Emitter and the Collector, where Collector is kept positive with respect to the Emitter. Due to the voltage source VCC the junction J1 will be forward-biased whereas the junction J2 will be reverse biased. Since J2 is in reverse bias there will not be any current flow inside the IGBT (from collector to emitter).

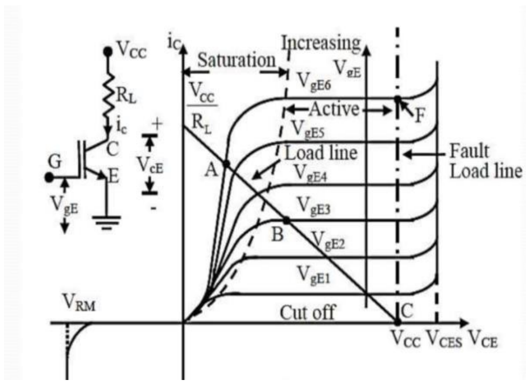
Initially, consider that there is no voltage applied to the Gate terminal, at this stage the IGBT will be in a non-conductive state. Now if we increase the applied gate voltage, due to the capacitance effect on the SiO2 layer the negative ions will get accumulated on the upper side of the layer and the positive ions will get accumulated on the lower side of the SiO2 layer. This will cause the insertion of negative charge carriers in the p region, higher the applied voltage VG greater the insertion of negatively charged carriers. This will lead to a formation of the channel between the J2 junctions which allow the flow of current from collector to emitter. The flow of current is represented as the current path in the picture, when the applied Gate voltage VG increases the amount of current flow from the collector to the emitter also increases.

**INPUT CHARACTERICTCS OF IGBT**

The input characteristics of IGBT can be understood from the graph below. Initially, when no voltage is applied to the gate pin the IGBT is in turn off condition and no current flows through the collector pin. When the voltage applied to the gate pin exceeds the threshold voltage, the IGBT starts conducting and the collector current IG starts to flow between the collector and emitter terminals. The collector current increases with respect to the gate voltage as shown in the graph below.




**VI CHARACTRSTICS OF IGBT**




The output characteristics of IGBT

The output characteristics of IGBT have three stages, initially, when the Gate Voltage $V_{GE}$ **is** zero the device is in the off state, this is called the cutoff region**.** When $V_{GE}$ is increased and if it is less than the threshold voltage then there will be a small leakage current flowing through the device, but the device will still be in the cutoff region. When the $V_{GE}$ is increased beyond the threshold voltage the device goes into the active region and the current starts flowing through the device. The flow of current will increases with an increase in the voltage $V_{GE}$ as shown in the graph above. The output characteristics of IGBT have three stages, initially, when the Gate Voltage VGE is zero the device is in the off state, this is called the cutoff region. When VGE is increased and if it is less than the threshold voltage then there will be a small leakage current flowing through the device, but the device will still be in the cutoff region. When the VGE is increased beyond the threshold voltage the device goes into the active region and the current starts flowing through the device. The flow of current will increases with an increase in the voltage VGE as shown in the graph above.

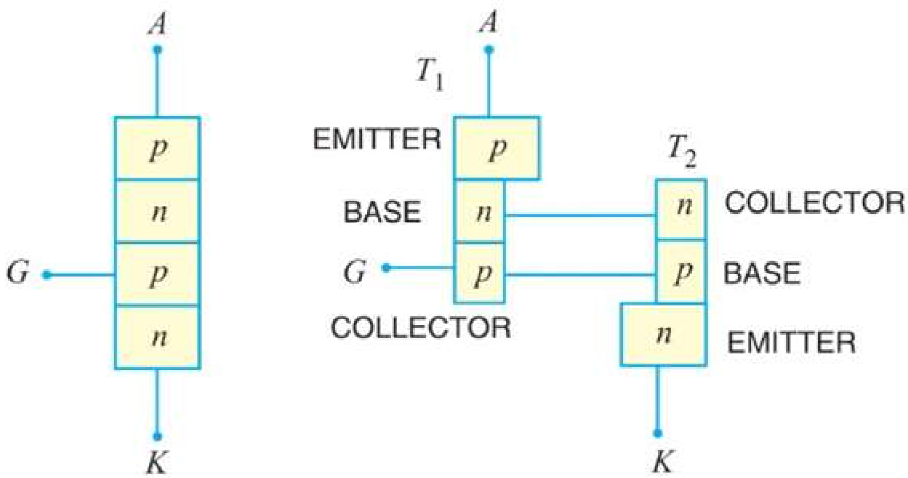
**APPLICATIONS OF IGBT**

IGBTs are used in various applications such as AC and DC motor drives, Unregulated Power Supply (UPS), Switch Mode Power Supplies (SMPS), traction motor control and induction heating, inverters, used to combine an isolated-gate FET for the control input and a bipolar power transistor as a switch in a single device, etc.

**TWO TRANSISTOR ANALOGY OF SCR.**

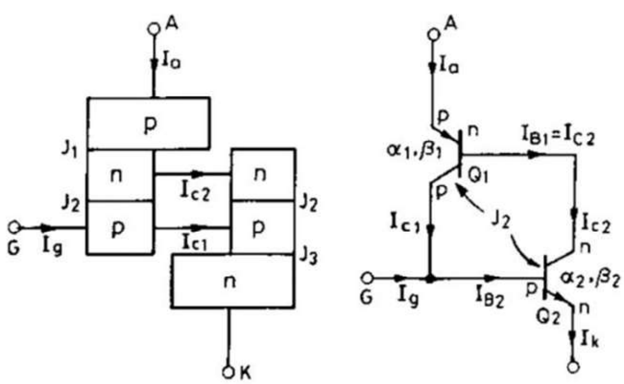
Two transistor analogy of SCR is a method of representing SCR in the form of two transistor model. This represents SCR is the combination of PNP and NPN transistor.

SCR or thyristor is a three terminal semiconductor device which having P-N-P-N structure. The basic operating principle of SCR can understand by two transistor method of SCR.




As per figure you can see **two transistors equivalent circuit of SCR**. From the figure, you can see the base of the transistor T1 is work as the collector of the transistor T2 and collector of the transistor T1 work as the base of the transistor T2.

Now here we find the expression for anode current of SCR.




As per transistor leakage current equation,

Collector current is expressed as,

$$I_C = \alpha I_E + I_{CBO}$$

Where α is the current gain of transistor and Icbo is the leakage current of the common base transistor.

For transistor T1 emitter current = anode current Ia and collector current Ic = Ic1

$$I_{C1} = \alpha_1 I_a + I_{CBO1}$$

Where $\alpha 1$ is the current gain of transistor T1.

Similarly, for transistor T2

$$I_{C2} = \alpha_2 I_k + I_{CBO2}$$

Where $\alpha 2$ is the current gain of transistor T2. And emitter current of transistor T2 = cathode current Ik.

Hereby figure, you can see anode current Ia is the sum of two collector current: Ic1 and Ic2.

$$\therefore \quad I_a = I_{C1} + I_{C2}$$
$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2}$$

By putting Ik = Ia + Ig, anode current Ia will be,

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$$
$$I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

From this relation we can assure that with increasing the value of $(\alpha_1 + \alpha_2)$towards unity, corresponding anode current will increase.

## GATE CHARACTERISTICS OF THYRISTOR

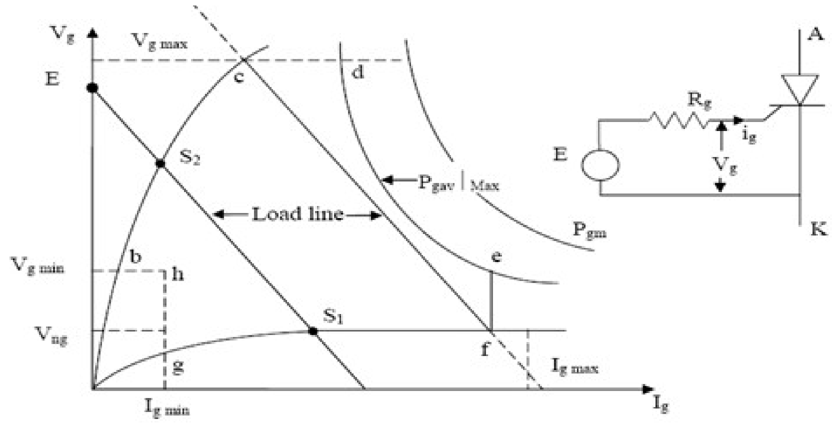
The gate circuit of a thyristor behaves like a poor quality diode with high on state voltage drop and low reverse break down voltage. This characteristic usually is not unique even within the same family of devices and shows considerable variation from device to device.

Therefore, manufacturer's data sheet provides the upper and lower limit of this characteristic as shown in figure below. Each thyristor has maximum gate voltage limit (Vgmax), gate current limit (Igmax) and maximum average gate power dissipation limit (PGav/Max). These limits should not be exceeded in order to avoid permanent damage to the gate cathode junction.

There are also minimum limits of Vg (Vgmin) and Ig (Igmin) for reliable turn on of the thyristor. A gate non triggering voltage (Vng) is also specified by the manufacturers of Thyristors.

All spurious noise signals should be less than this voltage Vng in order to prevent unwanted turn on of the thyristor.

Referring to the gate drive circuit in the inset the equation of the load line is given by Vg = E – Rgig




**Gate Drive Requirements**

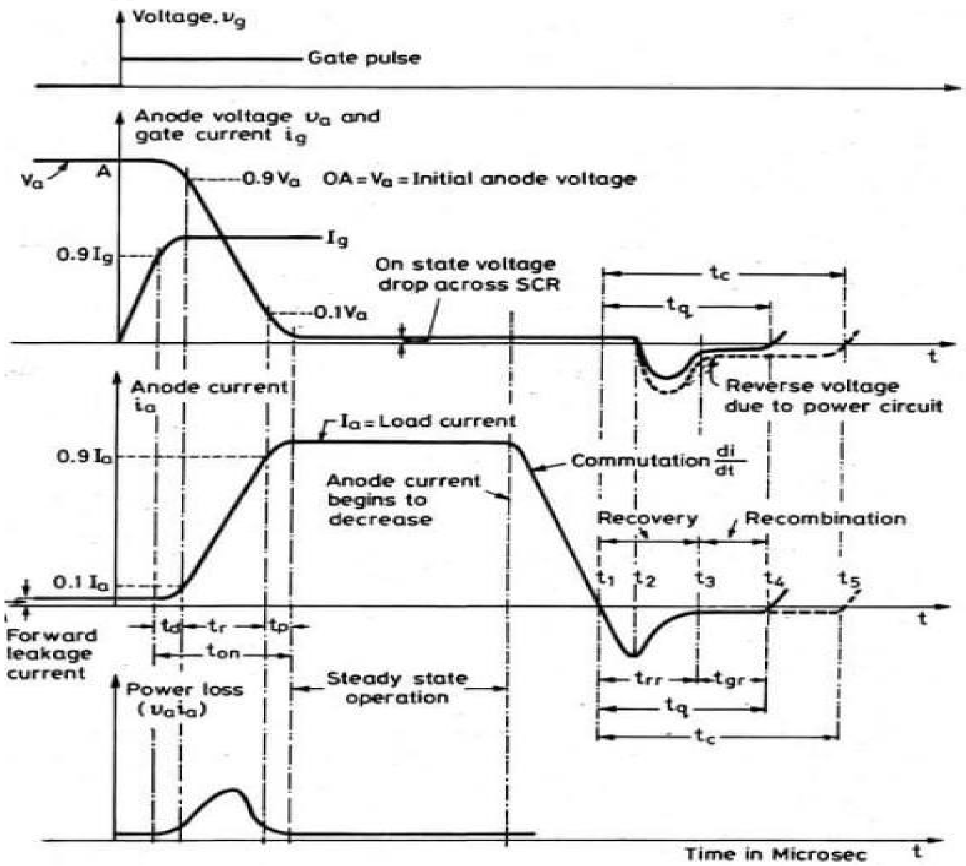
- Positive gate voltage or gate current
- Maximum Permissible gate power dissipation $P_{GM}$
- There are maximum and minimum limits for gate voltage and gate current to prevent the permanent destruction of junction J3 and to provide the realizable triggering.
- The gate signal can be ac or dc or a sequence of high frequency pulses.

**SWITCHING CHARACTERISTIC OF SCR DURING TURN ON AND TURN OFF.** The device's switching characteristics tells us about the switching losses, which is veryimportant parameter to decide the selection of device.

- When a positive gate signal is applied to a forward biased SCR, the transition of SCR from blocking state to conducting state is called as turn ON mechanism.
- The time taken for SCR to traverse from the blocking state to conducting state is called as turn on time.
- Turn on time is divided into 3 periods.
- tON = td + tr + tp
- td = delay time, tp or ts = peak time (or) spread time
- when the gate current reaches 0.9IG the anode current IA starts increasing and reaches 0.1IA (10% of its max value)
- The time taken for anode current to reach 0.1IA is called as delay time (td).
- In other words, it is the time taken for anode voltage to fall from VA to 0.9VA
- The anode current further increases and reaches 0.9IA.
- The time taken by the anode current to increases from 0.1IA to 0.9IA is called as rise time (tr).
- In other words, it is the time taken by the anode voltage to fall from 0.9VA to 0.1VA
- Spread Time or Peak time (ts or tp)
- It is time taken by the anode current to rise from (0.9IA to maximum value of IA) 90% to 100% of its full value. (or)
- It is the time taken by VA to fall from 0.1VA to its ON state voltage drop (near by zero).
- During this time the conduction spreads over the entire cross-section of cathode and so electrons spread over all the junctions.

**TURN OFF MECHANISM:**

- Turning OFF an SCR means bringing the SCR from conducting state to blocking state.
- To turn off an SCR two things are to be done
- Reduce the anode current below its holding current level.
- Application of reverse voltage.
- When the anode current is zero, if we apply forward voltage to the SCR, the device will not be able to block this forward voltage due to the fact that excess charge carriers are still at the junctions, so the device will start conducting even when the gate signal is not applied



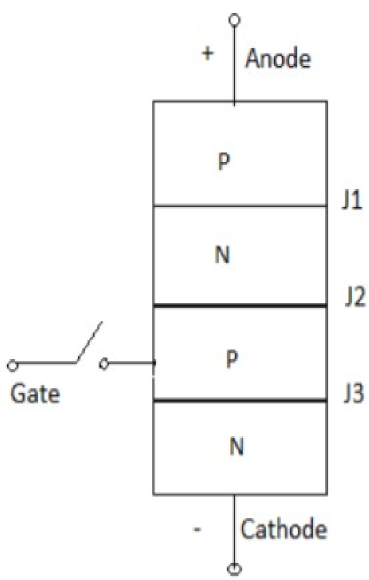

- In order to avoid this, reverse biasing of SCR is done to remove the excess charge carriers from all four layers.
- The turn OFF time is defined as the time from the instant the anode current becomes zero to the instant SCR reaches its forward blocking ability.
- Turn off time tOFF = trr + tgr
- trr = Reverse recovery time
- tgr =Gate recovery time
- Reverse recovery process is the removal of excessive charge carries from the top and bottom layers of SCR.
- At t1; current IA = 0

- After t1; IA build up in the reverse direction, due to the charge carriers stored in the four layers.
- Reverse recovery current removes the excessive carriers from junctions J1 and J3 during the time t1 to t3. (Reverse recovery current flows due sweeping out of holes from top p-layer and electrons from bottom n layer)
- Reverse Recovery Time (trr):-
- It is the time taken for the removal of excessive carriers from top and bottom layer of SCR.
- At t2: When nearly 60% of charges are removed from the outer two layers, the reverse recovery current decreases.
- This decaying causes a reverse voltage to be applied across the SCR.
- At t3 all excessive carriers from J1 and J3 is removed.
- The reverse voltage across SCR removes the excessive carriers from junction J2.
- Gate recovery process is the removal of excessive carriers from J2 junction by application of reverse voltage.
- Time taken for removal of trapped charges from J2 is called gate recovery time(tgr).
- At t4 all the carriers are removed and the device moves to the forward blocking mode.

**DIFFERENT TURN ON METHODS FOR SCR**

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

**1. FORWARD VOLTAGE TRIGGERING**




A forward voltage is applied between anode and cathode with gate circuit open.

- Junction $J1$ and $J3$ is forward biased
- Juntion $J2$ is reverse biased.

- As the anode to cathode voltage is increased breakdown of the reverse biased junction $J2$ occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward breakover voltage.
- The conduction of current continues even if the anode cathode voltage reduces below $VBO$ till $Ia$ will not go below$Ih$. Where $Ih$ is the holding current for the thyristor.

**2. GATE TRIGGERING**

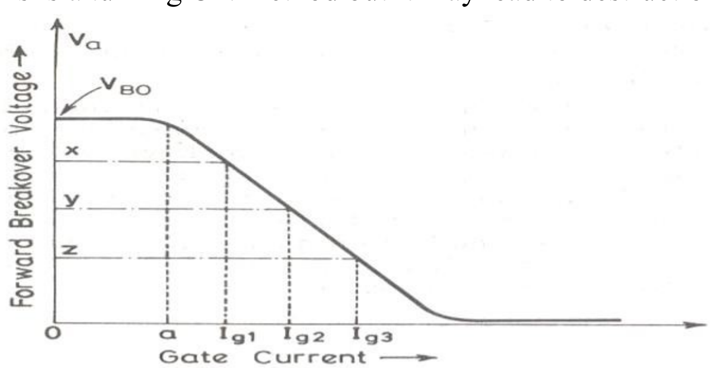
This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding $VBO$ is never employed as it may destroy the device. The magnitude of $VBO$, so forward breakover voltage is taken as final voltage rating of the device during the design of SCR application.

First step is to choose a thyristor with forward breakover voltage (say 800V) higher than the normal working voltage. The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with gate open. When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied. The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n-layer. Now the thyristor is forward biased, so some of these electron reach junction $J2$ .As a result width of $J2$ breaks down or conduction at $J2$ occur at a voltage less than $VBO$.As $Ig$ increases $VBO$ reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can't turn ON.

In this process power loss is less and also low applied voltage is required for triggering.

**3. DV/DT TRIGGERING**

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided




When SCR is forward biased, junction $J1$ and $J3$ are forward biased and junction $J2$ is reversed biased so it behaves as if an insulator is place between two conducting plate. Here $J1$ and $J3$ acts as a conducting plate and $J2$ acts as an insulator. $J2$ is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage.

Junction $J2$ breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from high $dv$/ dt.

$q = cv$

$Ia = c\ dv/dt$

$Ia\ \alpha\ dv/dt$

**4. TEMPERATURE TRIGGERING**

During forward biased, $J2$ is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat dissipitation of junction $J2$occurs. When this heat reaches a sufficient value $J2$ will break and conduction starts.

Disadvantages

This type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily. It is very costly as protection is costly.

**5.** Light triggering

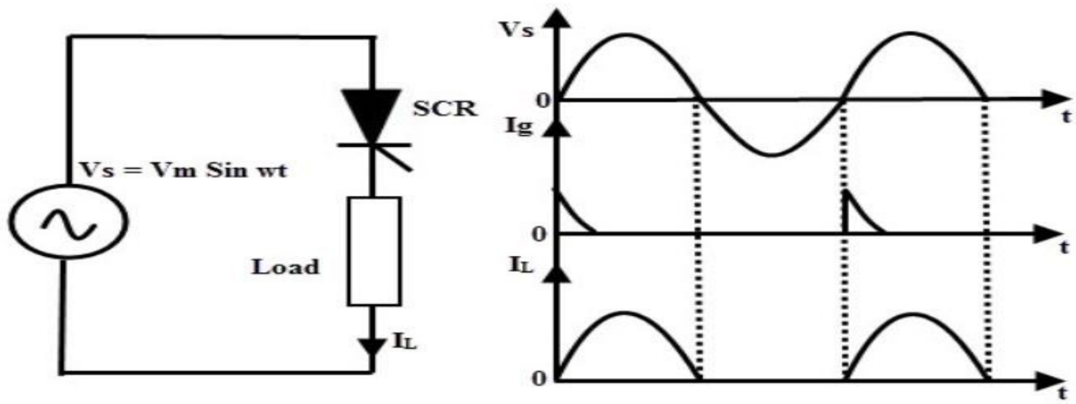
First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn ON of SCR. Such SCR are known as Light activated SCR (LASCR). Some definitions: Latching current The latching current may be defined as the minimum value of anode current which at must attain during turn ON process to maintain conduction even if gate signal is removed. Holding current It is the minimum value of anode current below which if it falls, the SCR will turn OFF.

## TURN OFF METHODS OF SCR (LINE COMMUTATION AND FORCED COMMUTATION)

### NATURAL COMMUTATION/ LINE COMMUTATION

In natural commutation, the source of commutation voltage is the supply source itself. If the SCR is connected to an AC supply, at every end of the positive half cycle the anode current goes through the natural current zero and also immediately a reverse voltage is applied across the SCR. These are the conditions to turn OFF the SCR.

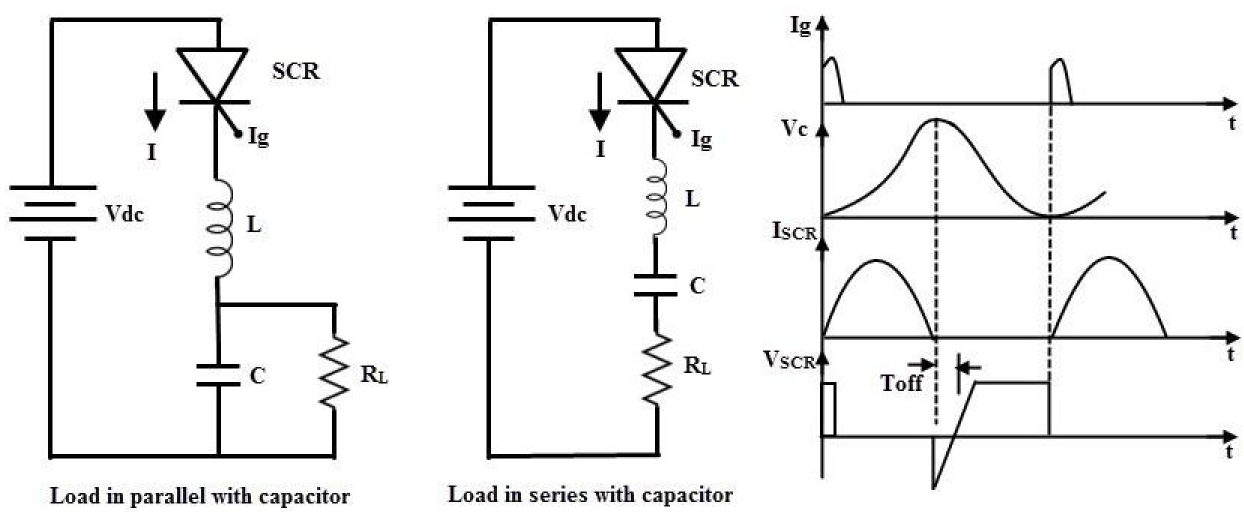
This method of commutation is also called as source commutation, or line commutation, or class F commutation. This commutation is possible with line commutated inverters, controlled rectifiers, cycloconverters and AC voltage regulators because the supply is the AC source in all these converters.




**LOAD COMMUTATION 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.




The value of load resistance and commutating components are so selected that they forms a under damped resonant circuit to produce natural zero. When the thyristor or SCR is triggered, the forward currents starts flowing through it and during this the capacitor is charged up to the value of E.

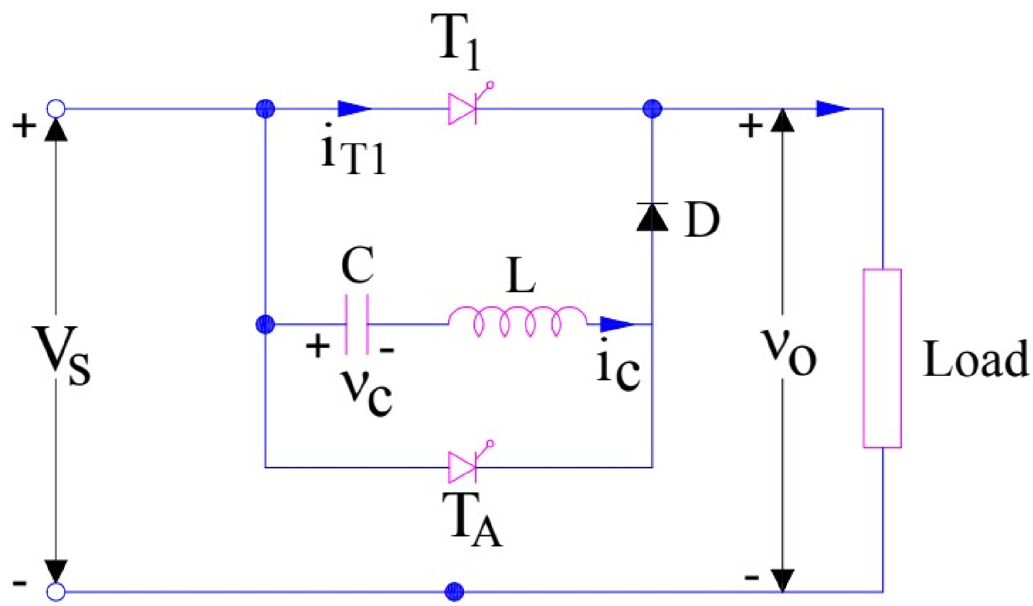
Once the capacitor is fully charged (more than the supply source voltage) the SCR becomes reverse biased and hence the commutation of the device. The capacitor discharges through the load resistance to make ready the circuit for the next cycle of operation. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.

This method is simple and reliable. For high frequency operation which is in the range above 1000 Hz, this type of commutation circuits is preferred due to the high values of L and C components.

**RESONANT PULSE COMMUTATION**

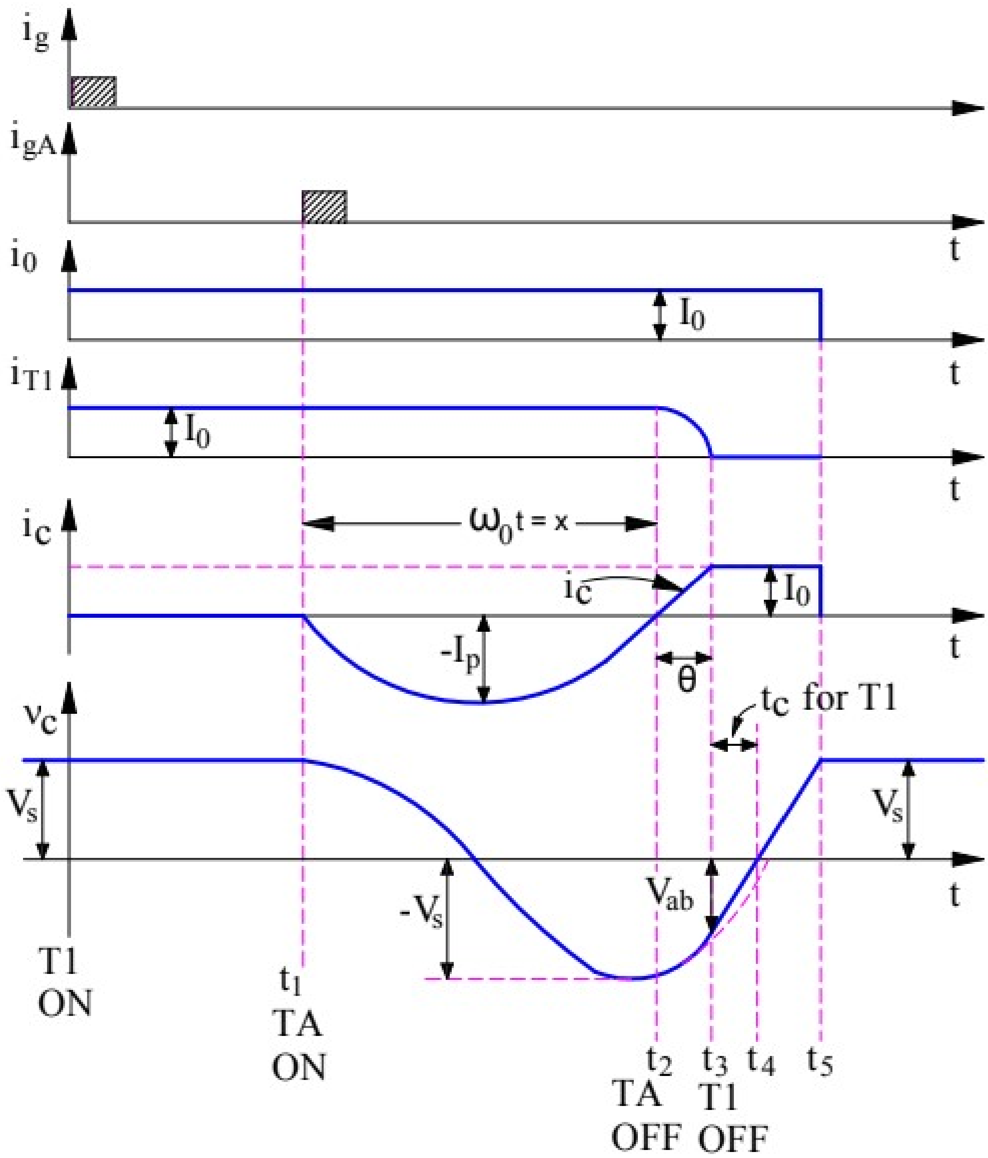
CLASS-B OR RESONANT PULSE COMMUTATION is a forced commutation technique to turn off an SCR. In this technique, thyristor or SCR is turned off by gradual build-up of resonant current in the reverse direction i.e. from cathode to anode of SCR. This technique is also known as current commutation and occurs in DC circuit not in AC circuit.

Let us consider the circuit diagram for Class-B or Resonant Pulse Commutation for better understanding of the commutation process involved.




The commutation circuit comprises of Capacitor C, Inductor L and an auxiliary thyristor TA. Initially thyristor $T_1$ and TA are in off state and capacitor C is charged to voltage $V_s$ with left hand plate positive
as shown in figure. Positive direction of capacitor voltage and capacitor current $i_c$ are shown in figure and taken as reference.

Now, at t=0, the main thyristor / SCR is gated and turned on. Load current equal to $I_0$ starts flowing through the main thyristor $T_1$ and Load. Now, we want to turn this thyristor off. To do this, we fire the auxiliary thyristor TA at $t=t_1$. Till time $t=t_1$, the capacitor is charged with source voltage $V_s$ i.e. $v_c = V_s$, capacitor current $i_c = 0$ and current through main thyristor $T_1$ i.e. $i_0 = I_0$. This is shown in figure below.




When auxiliary thyristor TA is fired, it starts conducting and provides a path for the discharge of capacitor C. L, C and TA forms a resonating circuit. The resonating current $i_c$ for this circuit is given as

$$ic = -Vs\sqrt{(\frac{C}{L})}Sin\omega t$$

$$ic = -ImSin\omega t$$

Negative sign in the above expression of resonating current is given as the actual current flows in a direction opposite to the direction of current $i_c$ shown in the first figure.

Carefully observe the waveform of $i_c$. It can be seen that, after half cycle, the value of $i_c$ reduces to zero at $t=t_2$. This means, the current through the auxiliary thuristor TA reduces to zero. Let's check if the auxiliary thyristor gets reversed biased after $t=t_2$. *Why are we checking this?* This is because, the current through TA is zero at $t=t_2$ and if it gets reversed biased after $t=t_2$ then TA will get turned off. The voltage across TA equals the voltage across capacitor. The expression for capacitor voltage can be calculated as

$$vc = (1/C)\int icdt$$

$$= VsCos\omega t$$

$$Where\ \omega = Resonant\ Frequency$$

$$= 1/\sqrt{LC}$$

From the above expression of voltage across capacitor, if we put $\omega t = \pi$ then value of $Cos\omega t$ will -1. This means, the capacitor voltage will get reversed after half a cycle of capacitor current i.e. at $t=t_2$. Thus, the auxiliary thyristor TA is reversed biased after $t=t_2$. Hence it will get turned off at $t=t_2$.

Now, TA is OFF and capacitor C is charged up to source voltage Vs with its right hand plate positive. This means, the diode D is now forward biased and hence resonating current $i_c$ will now flow through least resistive path i.e. through C, L, D and main thyristor $T_1$. But this resonating current ic will flow through the main SCR $T_1$ from cathode to anode i.e. in reverse direction. This simply means, the current I through the main thyristor $T_1$ will be given as

$I = I_0 - i_c$

When the magnitude of $i_c$ reaches $I_0$, the current through the SCR $T_1$ will become zero. This can be seen at $t=t_3$. Now, you might ask, when the resonating current will attain a value of $I_0$? This can easily be calculated from the equation of the resonating current. Let's find it.

$$Vs\sqrt{\left(\frac{C}{L}\right)}Sin\omega(t3 - t2) = I0$$

$$Sin\omega(t3 - t2) = \left(\frac{I0}{Im}\right)$$

$$\omega(t3 - t2) = Sin^{-1}\left(\frac{I0}{Im}\right)$$

$$Where\ \omega = \frac{1}{\sqrt{LC}}\ and\ Im = Vs\sqrt{\left(\frac{C}{L}\right)}$$

Now, at $t=t_3$, the current through the main thyrsistor $T_1$ is zero. Let's check, if it is reversed biased at this instant of time. Again, the voltage across the main SCR T1 at this instant of time ($t=t_3$) is equal to the capacitor voltage. The capacitor voltage after $\omega t = \pi$ is negative. This means, the right hand plate is positive whereas left hand plate is negative. Hence, the main thyristor $T_1$ is reversed biased. Thus, main thyristor $T_1$ will turn off at $t=t_3$ as the current through it is zero and it is reversed biased after this instant of time.

From the above discussion, it should have been clear that the peak value of resonating current $i_c$ i.e. $I_m$ in the expression of $i_c$, must be more than load current ($I_0$) for reliable commutation of thyristor / SCR. As SCR is commutated by the gradual build-up of the resonating current ic in the reverse direction of SCR, this method of commutation is called the *current commutation, resonant pulse commutation or Class-B commutation*.

Let's now check what happens after the commutation of main SCR $T_1$. Once the main SCR $T_1$ is turned off, load current I0 begins to flow from source $V_s$ to load though C, L and D. This causes capacitor C to charge linearly from $V_{ab}$ to zero at $t = t_4$ and then to source voltage $V_s$ at $t=t_5$. At $t=t_5$, the capacitor is charged up to source voltage $V_s$ with its left hand plate positive. Therefore, capacitor will not allow the flow of load current after $t = t_5$.

The circuit turn off time is equal to the time period for which the main thyristor / SCR is reversed biased. Here, this time period is $(t_4 – t_3)$. Therefore,

*Circuit Turn Off time $t_c$ for Class-A commutation* $= (t_4 – t_3) = (V_{ab}C) / I_0$.

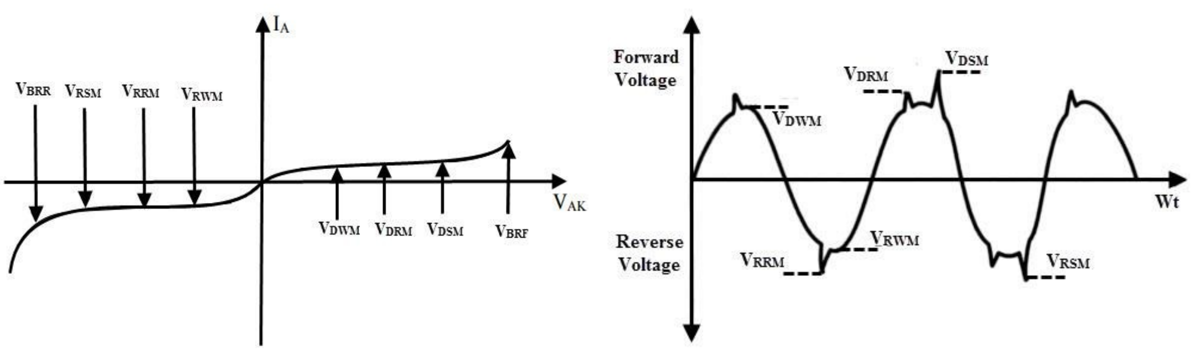
## VOLTAGE AND CURRENT RATINGS OF SCR.

### VOLTAGE RATINGS OF SCR

The voltage capability of the SCR should not be exceeded during the operation even for short periods. So the SCR is assigned with different voltage ratings, which are the maximum voltages at which the SCR can function normally without breakdown of junctions. These are assigned in both blocking states of an SCR and can withstand against voltage transients. The various voltage ratings of an SCR are given below.

### PEAK WORKING FORWARD-BLOCKING VOLTAGE $V_{DWM}$

It specifies the maximum instantaneous value of forward blocking voltage across the SCR excluding all surge and repetitive transient voltages. Beyond this value of the voltage the SCR cannot withstand during its operation. This VDWM is equal to the maximum or peak value of the supply voltage wave shown in figure.




### PEAK REPETITIVE FORWARD-BLOCKING VOLTAGE $V_{DRM}$

It is the maximum transient voltage that the SCR can block during it's the forward blocking state repeatedly or periodically. This is specified with a specific biasing resistance between cathode and gate or at a maximum permissible junction temperature with gate circuit open.

This voltage $V_{DRM}$ is encountered or appeared across the SCR , when the SCR is turned OFF or commutated or due to diodes in the converter circuit. During the turn OFF process, an abrupt change in reverse recovery current causes to create a voltage spike , which is responsible of $V_{DRM}$ to appear across the SCR.

### PEAK NON-REPETITIVE OR SURGE FORWARD-BLOCKING VOLTAGE $V_{DSM}$

This is the maximum instantaneous value of forward surge voltage across the SCR that is of non-repetitive. This $V_{DSM}$ is less than the forward break over voltage $V_{BO}$ and this value is in the range about 130 percent of $V_{DRM}$.

### PEAK WORKING REVERSE VOLTAGE $V_{RWM}$

This is the maximum instantaneous value of reverse voltage across the SCR excluding all surge and repetitive transient voltages. This $V_{RWM}$ is equal to the maximum negative value of the supply voltage wave shown in figure.

### PEAK REPETITIVE REVERSE VOLTAGE $V_{RRM}$

It is occurrence of the maximum reverse transient voltage repeatedly or periodically across the SCR in the reverse direction at permissible maximum junction temperature. Beyond this rating the SCR may get damaged due to excessive junction temperature. This voltage is also appeared due to the same reason as of $V_{DRM}$.

### PEAK NON-REPETITIVE OR SURGE REVERSE VOLTAGE $V_{RSM}$

It refers to the maximum value of reverse transient voltage across the SCR that is of non-repetitive. This $V_{RSM}$ is less than the reverse break over voltage $V_{BR}$ and this value is in the range about 130 percent of $V_{RRM}$. The surge voltage ratings $V_{DSM}$ and $V_{RSM}$ can be increased by connecting a diode of equal current rating in series with the SCR.

The above discussed voltage ratings are belonging to the forward and reverse blocking states with which the SCR is able to withstand with gate open.

### ON-STATE VOLTAGE $V_T$

This is the voltage drop between the anode and cathode with specified junction temperature and ON-state forward current. Generally, this value is in the order of 1 to 1.5 Volts.

### GATE TRIGGERING VOLTAGE $V_{GT}$

This is the minimum voltage required by the gate to produce the gate trigger current.

### FORWARD DV/DT RATING

This is the maximum rate of rise of anode voltage that will not trigger the SCR without any gate pulse or signal. If this value is more than the specified value, the SCR may be switched ON. The SCR in forward blocking mode is analogous to the capacitor with a dielectric.

So , the charging current flows through it when the applied voltage is increased. If the rate of rise of voltage is more, sufficient charges will flow through the junctions $J_2$ of the SCR and hence the SCR will be turned ON without any gate signal.

This type of triggering is called as false triggering and in practice it is not employed. Also, this rating depends on the junction temperature. If the junction temperature is high, the dv/dt rating of the SCR is lower and vice-versa. With the use of snubber networks across the SCRs, it is possible to limit the maximum dv/dt applied to the SCR.

### VOLTAGE SAFETY FACTOR $V_F$

Generally, the operating voltage of the SCR is kept below the $V_{RSM}$ to avoid the damage to the SCR due to uncertain conditions. Therefore, the voltage safety factor relates the operating voltage and $V_{RSM}$ and is given as

$V_f = V_{RSM}$ / (RMS value of the input voltage * $\sqrt{2}$)

### CURRENT RATINGS OF SCR

Basically an SCR is a unilateral device and hence average current rating is assigned to it (while RMS current rating is assigned to bilateral devices). An SCR has low thermal capacity and short time constant. This means the junction temperature exceeds its rated value even for short over current.

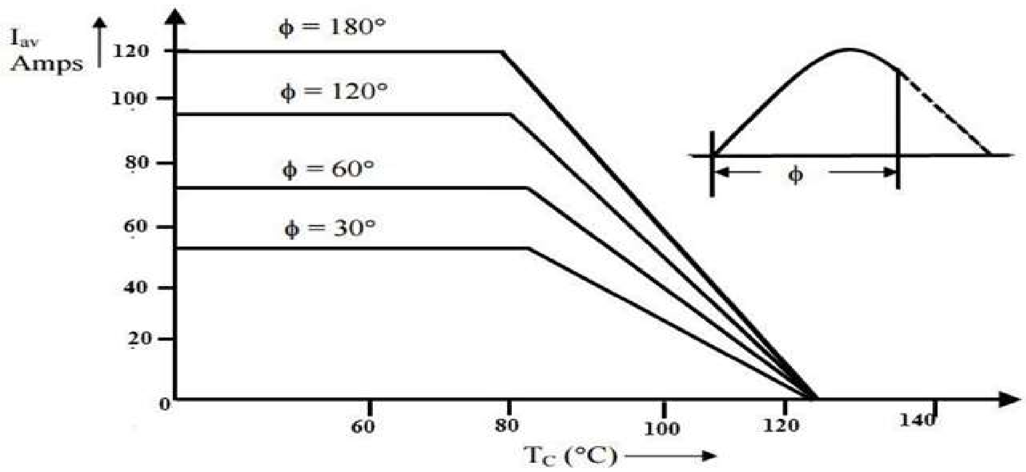
This may lead to damage the SCR. Therefore, current ratings must be properly selected for long life of SCR, as the junction temperature depends on the current handled by it. Let us look at various current ratings of an SCR.

### AVERAGE ON-STATE CURRENT RATING $I_{TAV}$

This is the maximum repetitive average value of forward current that can flow through the SCR such that the maximum temperature and RMS current limits are not exceeded. The forward voltage drop across the SCR is very low when it is in conduction mode. So the power loss in the thyristor is entirely depends on the forward current $I_{TAV}$.

In case of phase controlled SCRs, average forward current depends on the firing angle. For the given average forward current, the RMS value of the current is increased with decrease in conduction angle. This leads to increase the voltage drop across the SCR which in turn increases the average power dissipation. Hence the junction temperature rises beyond the safe limit.

In order to limit the maximum junction temperature, the permissible average forward current has to be lowered with decrease in conduction angle. The manufacturers usually provide the data sheet that shows the forward average current variation with respect to the case temperature. As an example the current waveform formed from the positive half cycle for different conduction angles is shown in below.




### RMS ON-STATE CURRENT $I_{TRMS}$

This is the maximum repetitive RMS current specified at a maximum junction temperature that can flow through the SCR. For a direct current, both RMS and average currents are same. However, this rating is important for SCRs subject to low duty waveforms with peak currents. And also this rating is required to prevent excessive heating in leads, metallic joints and interfaces of SCR.

### SURGE CURRENT RATING $I_{TSM}$

It specifies the maximum non-repetitive or surge current that the SCR can withstand for a limited number of times during its life span. The manufacturers specify the surge rating to accommodate the abnormal conditions of SCR due to short circuits and faults. If the peak amplitude and the number of cycles of the surge current are exceeded, the SCR may get damaged.

### $I^2_T$ RATING

This rating is used to determine the thermal energy absorption of the device. This rating is required in the choice of a fuse or other protective equipment employed for the SCR. This is the measure of the thermal energy that the SCR can absorb for a short period of time before clearing the fault by the fuse.

It is the time integral of the square of the maximum instantaneous current. For a reliable protection of SCR by the fuse or other protective equipment, the $I^2_t$ rating of the fuse (or any other protective equipment) must be less than the $I^2_t$ rating of the SCR.

**DI/DT RATING**

It is the maximum allowable rate of rise of anode to cathode current without any damage or harm to an SCR. If the rate of rise of anode current is very rapid compared to the spreading velocity of the charge carriers, local hot spots are created due to concentration of carriers (on account of high current density) in the restricted area of the junctions.

This raises the junction temperature above the safe limit and hence the SCR may be damaged. Therefore, for all SCRs the maximum allowable di/dt rating specified in order to protect the SCR. It is specified in amperes/microseconds and typically it lies in the range 50 to 800 ampere/microseconds.

**LATCHING CURRENT $I_L$**

It is the minimum ON state current required to maintain the SCR in ON state after gate drive has been removed. After turning ON of the SCR, the anode current must be allowed to build up such that the latching current is attained before the gate pulse is removed. Otherwise the SCR will be turned OFF if the gate signal is removed.

**HOLDING CURRENT $I_H$**

This is the minimum value of the anode current below which SCR stops conducting and turns OFF. The holding current is associated with turn OFF process and usually it is a very small value in the range of mill amperes.

**GATE CURRENT $I_G$**

As the gate current is more, earlier will be the turn ON of the SCR and vice-versa. However, safety limits must be provided for gate by specifying maximum and minimum gate currents. For controlling the SCR, gate current is applied to the gate terminal. This gate current is divided into two types; minimum gate current $I_{Gmin}$ and maximum gate current $I_{Gmax}$.

The minimum gate current $I_{Gmin}$ is the current required by the gate terminal to turn ON the SCR where as $I_{Gmax}$ is the maximum current that can be applied safely to the gate. Between these two limits the conduction angle of the SCR is controlled.

**TEMPERATURE RATING OF SCR**

The forward and reverse blocking capability of the SCR is determined by junction temperature $T_j$. If the maximum junction temperature is exceeded, the SCR will be driven to conduction state even without any gate signal. This upper limit of $T_j$ is imposed by considering the temperature dependence on break over voltage, thermal stability and turn OFF time.

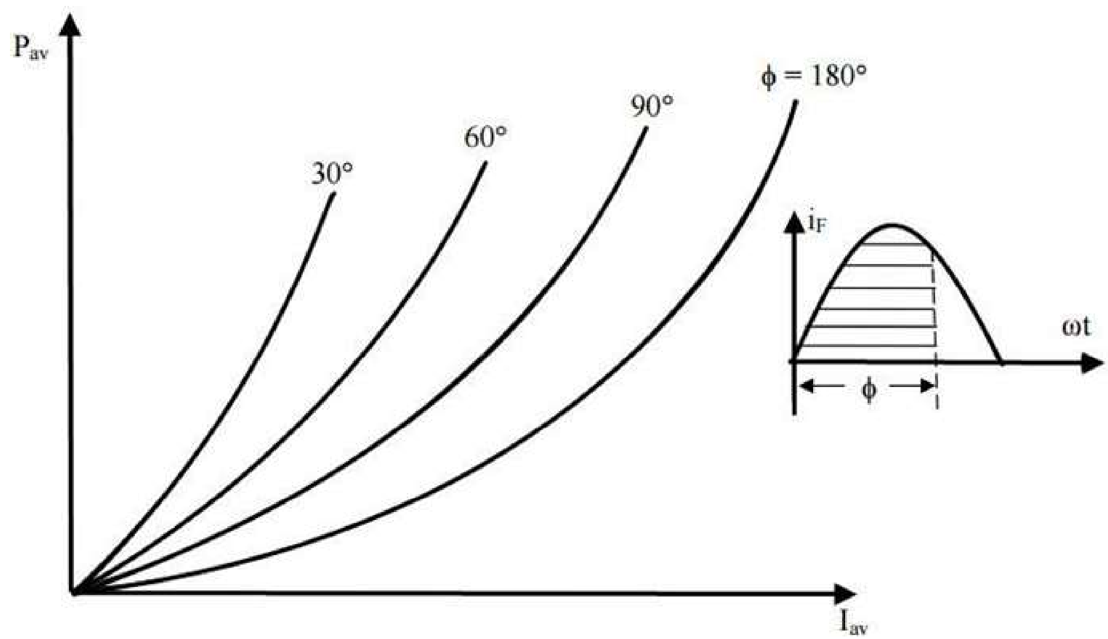
And also an upper storage temperature limit $T_s$ is also required to limit thermal stresses on silicon crystal, lead attachments and encapsulating epoxy. Excess of these two temperature limits may cause unreliable operation of an SCR. In some cases, upper storage temperature limit is higher than the operating temperature limit of an SCR.

## POWER RATINGS OF SCR

The power dissipation in the SCR produces a temperature rise in the junction regions. The dissipation of power in the SCR includes forward power dissipation; turn ON and OFF losses and gate power dissipation.

## AVERAGE POWER DISSIPATION $P_{AV}$

It is the multiplication of the average anode current and forward voltage drop across the SCR. This is the major source of junction heating in an SCR for normal duty cycle operations. The peak power from a given source must not exceed the average power dissipation rating to maintain the safety of the device. This rating is specified for different conduction angles as a function of average forward current as shown in figure.




## GATE POWER DISSIPATION $P_G$

This rating defines both forward or reverse peak power and the average power applied to the gate. If these ratings are exceeded, considerable damage occurs to the gate. Therefore, while calculating the voltage and currents applied, the width of gate pulses has to be considered (because the peak power is the function of time). For pulse type triggering, gate losses are negligible whereas gate signals with a high duty cycle, the gate losses becomes more significant.

Other power losses include ON state losses, OFF state losses, forward blocking losses and reverse blocking losses. Turn ON and OFF losses have to be taken into consideration while selecting the SCR rating since these constitute a significant portion of the total losses. And also forward and reverse blocking losses are very small compared to the conduction losses since a small leakage current and negligible voltage drop in blocking states.

## TURN ON AND TURN OFF TIME RATINGS

The turn ON time is the time interval between the instant at which the gate signal is applied and the instant at which the ON-state current reaches 90 percent of its final value. Shorter will be the turn ON time if the gate drive is increased. This turn ON time is valid only for resistive load because the rate of rise of anode current is slow in inductive load.

Therefore, the turn ON time does not indicate the time in which the device stays ON if the gate signal is removed. And if the load is resistive, turn ON time surely, indicates the time interval in which the SCR stays ON even the gate is removed.

Turn OFF time is the time interval between the instant at which the anode current goes zero or negative and the instant positive voltage is reapplied to the SCR. For fast switching SCRs both turn ON and OFF time values are very low.

## PROTECTION OF SCR

Thyristors are very sensitive to Overvoltages just as other Semiconductor devices are. Overvoltage transients are perhaps the main cause of thyristor failure. Transient Overvoltages cause either maloperation of the circuit by unwanted turn on of a thyristor or permanent damage to the device due to reverse breakdown. A thyristor may be subjected to internal or external Overvoltages; the former is caused by the thyristor operation where as the letter comes from the supply lines or the load circuit.

## OVERVOLTAGE PROTECTION

### Internal Overvoltages

Internal over voltages arise while the SCR is in operation. During the turn OFF of an SCR, a reverse current continues to flow through the SCR after the anode current decreased to zero to sweep away the earlier stored charge. This reverse current decay at a faster rate at the end of reverse recover interval.

Due to the inductance of the circuit, this high di/dt produces a high voltage. This voltage value may be much higher than the rated value of the SCR and hence the SCR may be damaged.

### External Over Voltage

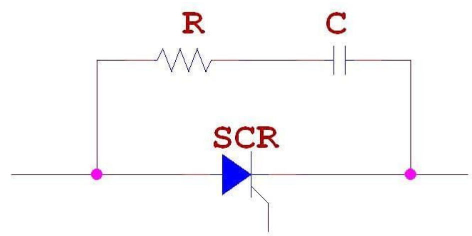
This is due to external supply and load condition. This is because of the interruption of current flow in an inductive circuit and also due to lightening strokes on the lines feeding the thyristor systems. When a SCR converter is fed from a transformer, voltage transient occur when transformer primary will energize or de-energised.

Search Overvoltages may cause random turn on of a thyristor as a result the Overvoltages may appear across the load causing the flow of large fault currents Overvoltages may also damage the thyristor by an inverse breakdown. For reliable operation the Overvoltages must be suppressed by adopting suitable techniques.

In order to keep the protective components to a minimum, thyristors are chosen with their peak voltage ratings of 2.5 to 3 times their normal peak working voltage. The effect of Overvoltages is usually minimized by using RC circuits and non-linear registers called voltage clamping devices.

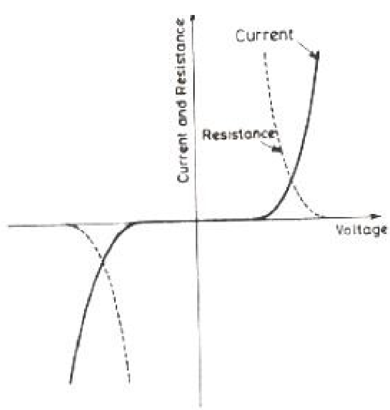
**Snubber circuit**

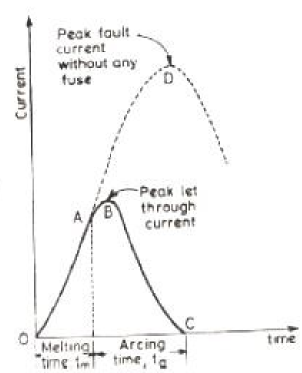
The RC circuit called snubber circuit is connected across the device to be protected as shown in fig. It provides a local path for internal overvoltage caused by reverse recovery current .Snubber circuit is also helpful in damping overvoltage transient spikes and for limiting dv/dt across the thyristor. The capacitor charges at a slow rate and thus the rate of rise of Forward voltage dv/dt across SCR is also reduced. The resistance $R_S$ damps out the ringing oscillations between the Snubber circuit and the stray circuit inductance.




**Voltage clamping device**

It is a non-linear resistor called as VARISTOR (VARIable resiSTOR) connected across the SCR. The resistance of varistor will decrease with increase in voltage. During normal operation, varistor has high Resistance and draws only small leakage current. When high voltage appears, it operates in low resistance region and the surge energy is dissipated across the resistance by producing a virtual short-circuit across the SCR.



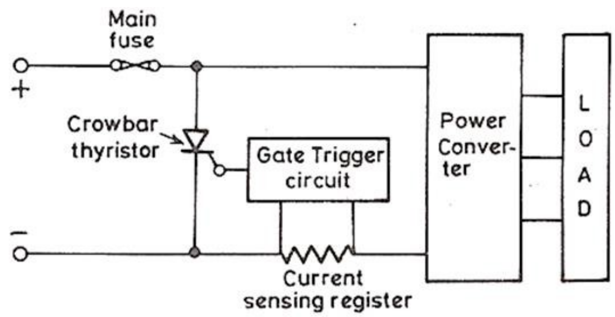

**OVER CURRENT PROTECTION**

**OVER CURRENT PROTECTION:**

In an SCR due to over-current, the junction temperature exceeds the rated value and the device gets damaged. Over-current is interrupted by conventional fuses and circuit breakers. The fault current must be interrupted before the SCR gets damaged and only the faulty branches of the network should be isolated. Circuit breaker has long tripping time. So it is used for protecting SCR against continuous over loads (or) against surge currents of long duration. Fast acting current limiting fuse is used to protect SCR against large surge currents of very short duration.

**Electronic Crowbar Protection:**

SCR has high surge current ability.SCR is used in electronic crowbar circuit for overcurrent protection of power converter. In this protection, an additional SCR is connected across the supply which is known as 'Crowbar SCR'. Current sensing resistor detects the value of converter current. If it exceeds preset value, then gate trigger circuits turn ON the crowbar SCR. So the input terminals are short-circuit by SCR and thus it bypass the converter over current. After some time the main fuse interrupts the fault current.

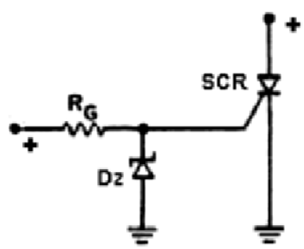



**GATE PROTECTION**

The first circuit adds resistor Rg to limit the current into the gate of the SCR and a Zener diode to protect against voltage transients.

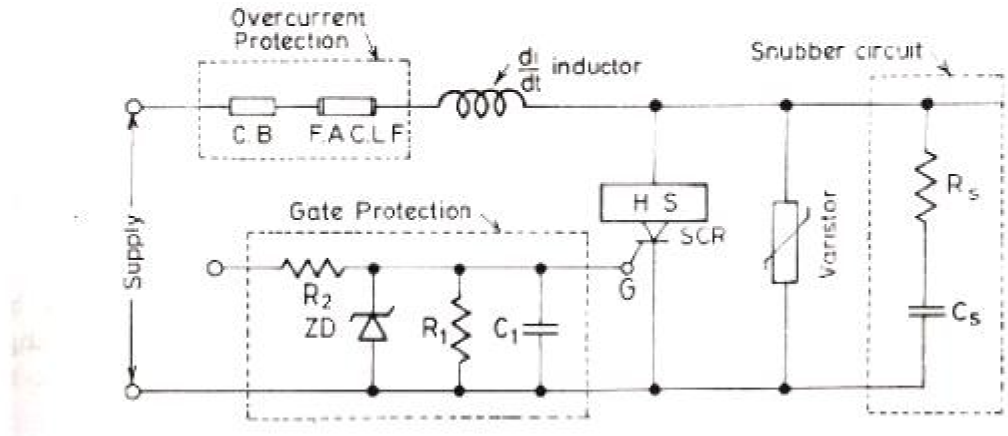
When the gate of the SCR is turned on the Zener diode [Dz] protects against any voltage transients.

A capacitor and resister is connected across gate to cathode to bypass noise signal.




SCR Protection Circuit

The diagram below shows the various components used to provide overall protection to scr.

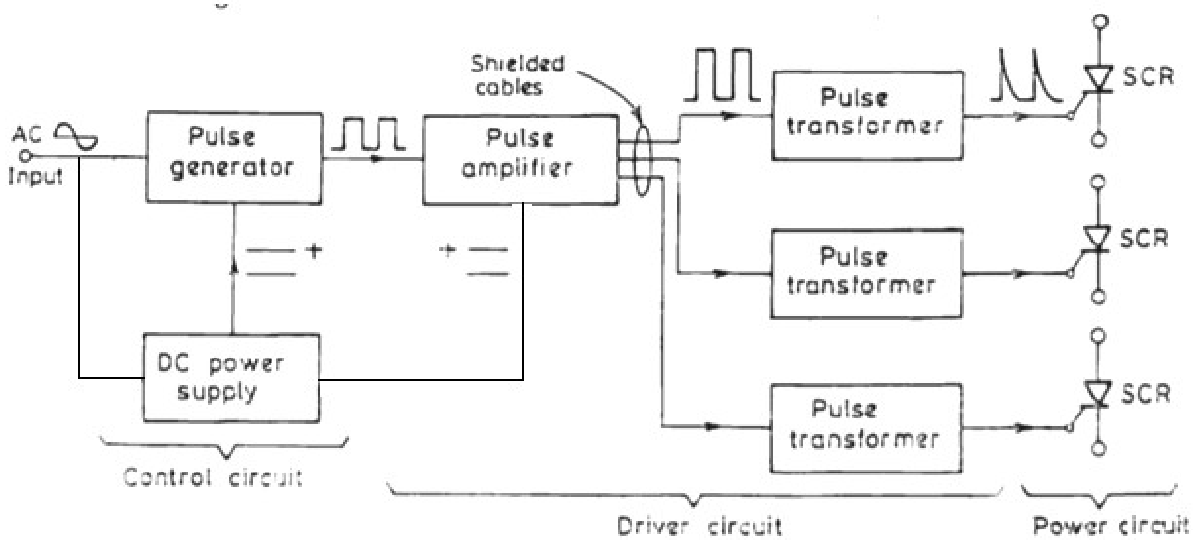



Thyrister protection circuit

**FIRING CIRCUITS**

**GENERAL LAYOUT DIAGRAM OF FIRING CIRCUIT**

The most common method for controlling the onset of conduction in an SCR is by means of gate voltage control. The gate control circuit is also called firing, or triggering, circuit. These gating circuits are usually low-power electronic circuits. A firing circuit should fulfill the following two functions.




A geneal layout of firing circuit scheme for scr

(i) If power circuit has more than one SCR, the firing circuit should produce gating pulses for each SCR at the desired instant for proper operation of the power circuit. These pulses must be periodic in nature and the sequence of firing must correspond with the type of thyristorised power controller. For example, in a single-phase semiconverter using two SCRs, the triggering circuit must produce one firing pulse in each half cycle; in a 3-phase full converter using SCRs, gating circuit must produce one trigger pulse after every 60° interval.

(ii) The control signal generated by a firing circuit may not be able to turn-on an SCR It is therefore common to feed the voltage pulses to a driver circuit and then to gate-cathode circuit. A driver circuit consists of a pulse amplifier and a pulse transformer. A firing circuit scheme, in general, consists of the components shown in Fig. A regulated dc power supply is obtained from an alternating voltage source. Pulse generator, supplied from both ac and dc sources, gives out voltage pulses which are then fed to pulse amplifier for their amplification. Shielded cables transmit the amplified pulses to pulse transformers. The function of pulse transformer is to isolate the low-voltage gate-cathode circuit from the' high-voltage anode-cathode circuit. Some firing circuit schemes are described in this section.

## DRAW R FIRING CIRCUITS AND EXPLAIN

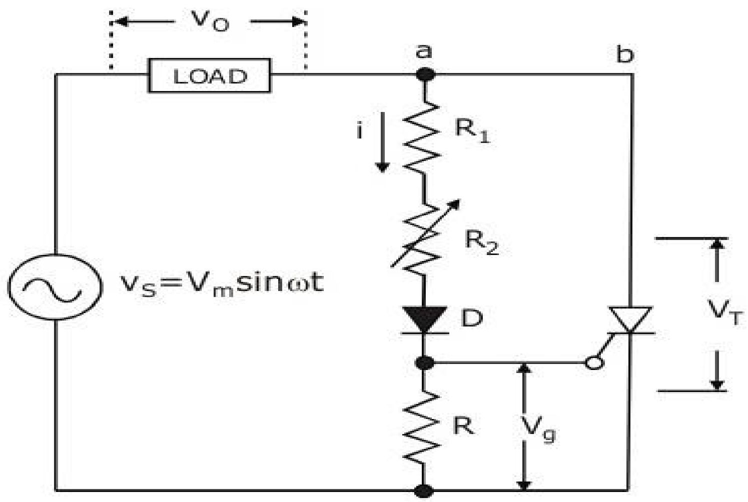
The circuit below shows the resistance triggering of SCR where it is employed to drive the load from the input AC supply. Resistance and diode combination circuit acts as a gate control circuitry to switch the SCR in the desired condition.
As the positive voltage applied, the SCR is forward biased and doesn't conduct until its gate current is more than minimum gate current of the SCR.
When the gate current is applied by varying the resistance R2 such that the gate current should be more than the minimum value of gate current, the SCR is turned ON. And hence the load current starts flowing through the SCR.
The SCR remains ON until the anode current is equal to the holding current of the SCR. And it will switch OFF when the voltage applied is zero. So the load current is zero as the SCR acts as open switch.
The diode protects the gate drive circuit from reverse gate voltage during the negative half cycle of the input. And Resistance R1 limits the current flowing through the gate terminal and its value is such that the gate current should not exceed the maximum gate current.

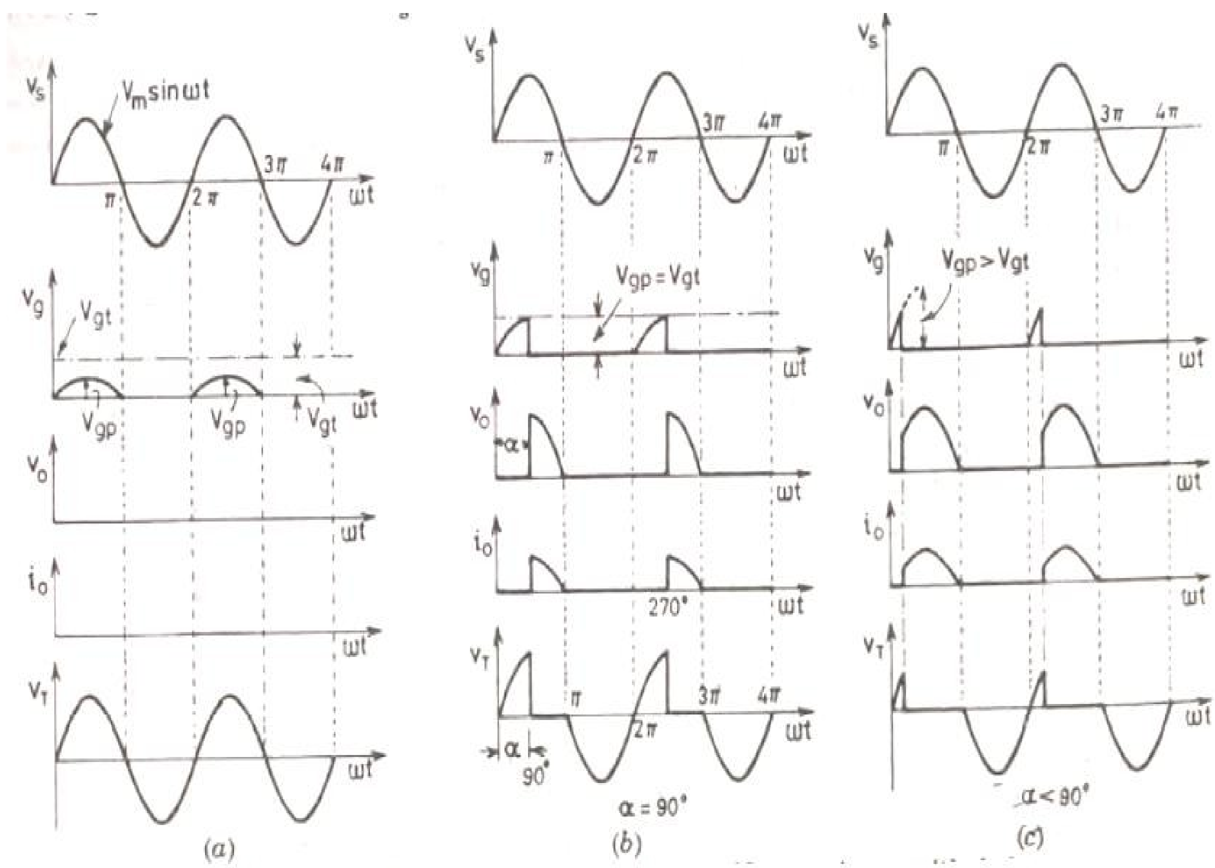
$$\frac{v_m}{R_1 + R} \times R \leq V_{gm}$$

$$R \leq \frac{V_{gm} \cdot R_1}{v_m - V_{gm}}$$

It is the simplest and economical type of triggering but limited for few applications due to its disadvantages.

In this, the triggering angle is limited to 90 degrees only. Because the applied voltage is maximum at 90 degrees so the gate current has to reach minimum gate current value somewhere between zero to 90 degrees.
R triggering circuit with its waveform




Resistance firing of an scr in a half wave circuit with dc load

(a)No triggering of scr (b)α=90° (c) α<90°

## RESISTANCE – CAPACITANCE (RC) FIRING CIRCUIT

The limitation of resistance firing circuit can be overcome by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude of the gate current, a large variation of firing angle is obtained using this circuit.

Below figure shows the RC triggering circuit consisting of two diodes with an RC network connected to turn the SCR.

By varying the variable resistance, triggering or firing angle is controlled in a full positive half cycle of the input signal.

During the negative half cycle of the input signal, capacitor charges with lower plate positive through diode D2 up to the maximum supply voltage Vmax at $\omega t=90^\circ$.

After $\omega t=90^\circ$ source voltage $v_s$ decreases from $-v_m$ at $\omega t=90^\circ$ to 0 at $\omega t=0^\circ$.During this period capacitor voltage $v_c$ may fall from $-v_m$ at $\omega t=90^\circ$ to some lower value –oa at $\omega t=0^\circ$.

During the positive half cycle of the input, the SCR becomes forward biased and the capacitor starts charging through variable resistance R to the triggering voltage value of the SCR.

When the capacitor charging voltage is equal to the gate trigger voltage, SCR is turned ON and the capacitor holds a small voltage. Therefore the capacitor voltage is helpful for triggering the SCR even after 90 degrees of the input waveform.

In this, diode D1 prevents the negative voltage between the gate and cathode during the negative half cycle of the input through diode D2.

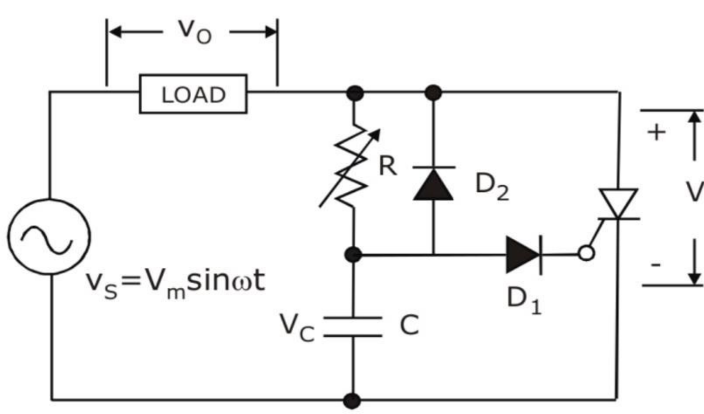
The value of rc is given by $RC \geq \frac{1.3T}{2} \cong \frac{4}{\omega}$ where T=1/f

The SCR will trigger when $v_c=v_{gt}+v_d$.At the instant of triggering, if $v_c$ is assumed constant,the current $i_{gt}$ must be supplied by voltage source through R,$D_1$ and gate to cathode circuit hence maximum value of R is given by

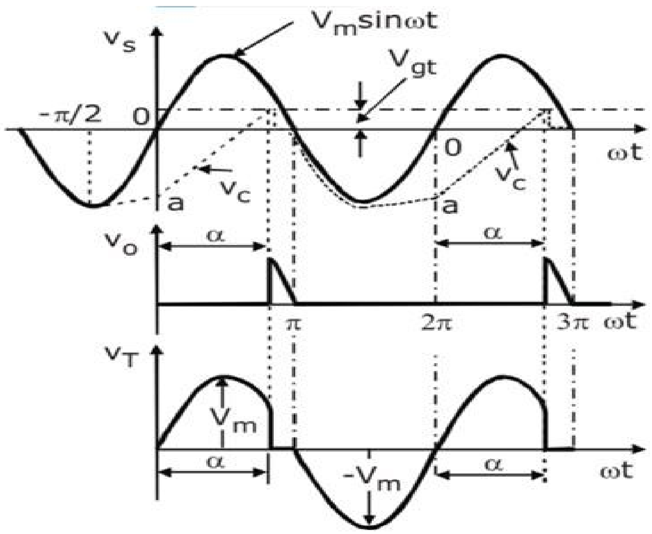
$v_s \geq RI_{gt} + V_c$

$v_s \geq RI_{gt} + v_{gt} + v_d$

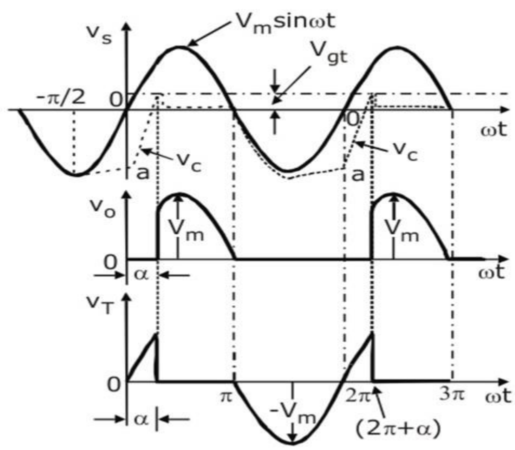
$$R \leq \frac{vs - vgt - vd}{Igt}$$




RESISTANCE – CAPACITANCE (RC) FIRING CIRCUIT




**High Value of R**




**Low Value of R**

## RC FULL WAVE TRIGGER CIRCUIT

Power can be delivered to the load in Half wave during the positive half-cycle of $v_s$ because the SCR conducts only when it is forward biased. This limitation can be overcome in several ways, one of which is shown in Fig. below Here; the ac line voltage is converted to pulsating dc. by the full-wave diode bridge. This allows the SCR to be triggered "on" for both half-cycle of the line voltage, which doubles the available power to the load.

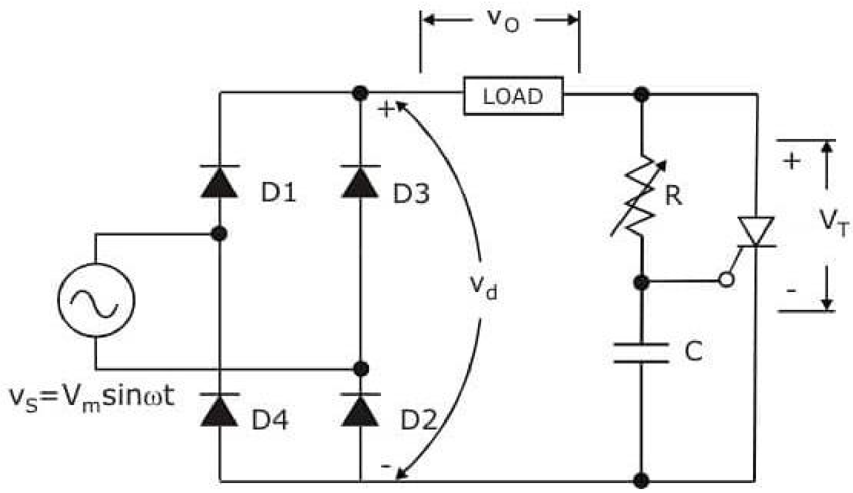
In this circuit, the initial voltage from which capacitor *C* charges is almost zero. Capacitor *C* is set to this low positive voltage (upper plate positive) by the clamping action of SCR gate. When the capacitor charges to a voltage equal to Vgt SCR triggers and rectified voltage Vdc appears across load as Vo. The value of RC is obtained from the following relation:

$$RC \geq 50\frac{T}{2} \cong \frac{157}{\omega}$$

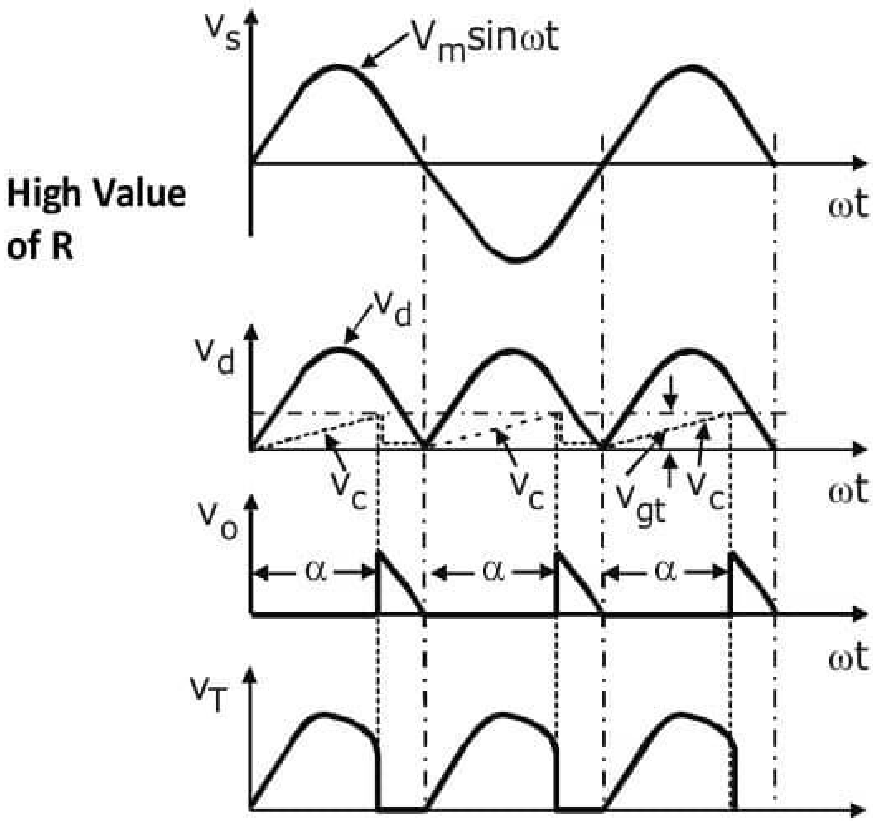
The value of R is given by

$$R \ll \frac{Vs - Vgt}{Igt}$$

Where Vs is the source voltage at which thyrister turns on.in this fig firing angle α is more than 90°.

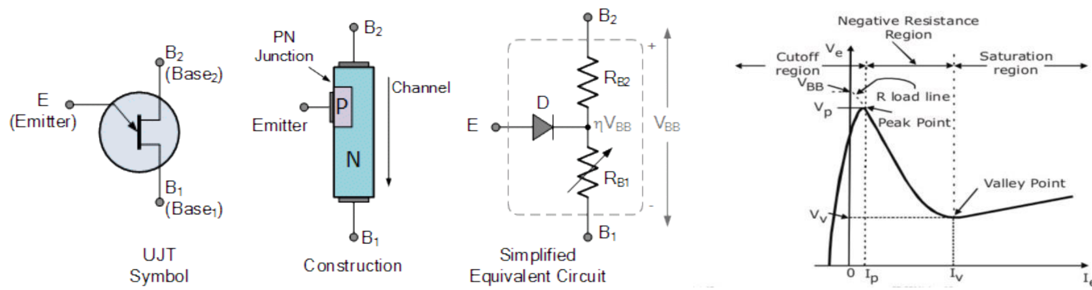



RC full wave trigger circuit diagram




RC full wave trigger waveform

## UJT PULSE TRIGGER CIRCUIT



VI characterstics of ujt

The unijunction transistor is a highly efficient switch; its switching time is in the range of nanoseconds. Since UJT exhibits negative resistance characteristics, it can be used as a relaxation oscillator.

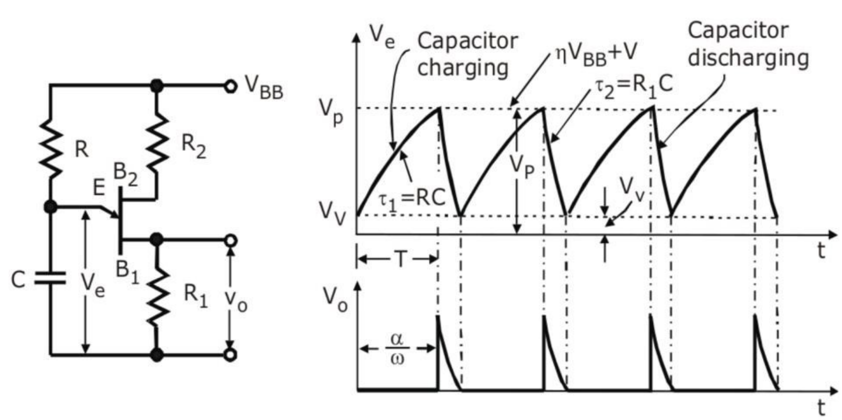
The Fig. below shows a circuit diagram with UJT working in the oscillator mode. The external resistances R 1.R2 are small in comparison with the internal resistances RB1, RB2 of UJT bases. The charging resistance R should be such that its load line intersects the device characteristics only in the negative resistance region.

In this Fig. when source voltage VBB is applied. capacitor C begins to charge through R exponentially towards VBB' During this charging, emitter circuit of UJT is an open circuit. The capacitor voltage Vc equal to emitter voltage Ve is given by

$Vc=Ve=V_{BB}(1-e^{-t/rc})$

The time constant of the charge circuit is $\tau_1$=RC

The time constant of the charge circuit is $\tau_1$=RC. When this emitter voltage Vc (or Ve) reaches the peak-point voltage Vp (= $\eta V_{BB}$ + VD)' the unijunction between E - BI breaks down. As a result, UJT turns on and capacitor C rapidly discharges through low resistance R1 with a time constant $\tau_2 = R_tC$. Here $\tau_2$ is much smaller than $\tau_1$. When the emitter voltage decays to the valley-point voltage Vv, emitter current (Vv/(R B1 + R1) falls below Iv and UJT turns off. The time T required for capacitor C to charge from initial voltage Vv to peak-point voltage Vp through large resistance R, can be obtained as under:



$$V_p = \eta V_{BB} + V_D = V_v + V_{BB}(1 - e^{-T/RC})$$

Assuming $V_D = V_v, \quad \eta = (1 - e^{-T/RC})$

or $T = \frac{1}{f} = RC \ln\left(\frac{1}{1-\eta}\right)$

In case T is taken as the time period of output pulse duration (neglecting small discharge time), then the value of firing angle α1 is given by $\alpha_1 = \omega T = \omega RC \ln(1/1-\eta)$

**EXPLAIN SYNCHRONOUS TRIGGERING (RAMP TRIGGERING)**

A synchronized UJT trigger circuit using an UJT is shown in Fig. Diodes Dl - D4 rectify ac to dc. Resistor Rl lowers Vdc to a suitable value for the zener diode and UJT. Zener diode Z functions to clip the rectified voltage to a standard level $V_s$ which remains constant except near the Vdc zero as in Fig. This voltage $V_s$ is applied to the charging circuit RC. Current $i_1$ charges a C at a rate determined by R. Voltage across capacitor is marked by C in Figs. when voltage $V_s$ reaches the unijunction threshold voltage ηVs, the E – $B_1$ junction of UJT breaks down and the capacitor C discharges through primary of pulse transformer sending a current $i_2$ as shown in Fig. As the current i2 is in the form of pulse, 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. As soon as the capacitor discharges, it starts to recharge as shown. Rate of rise of capacitor voltage can be controlled by varying R. The firing angle can be controlled up to about 150°C.

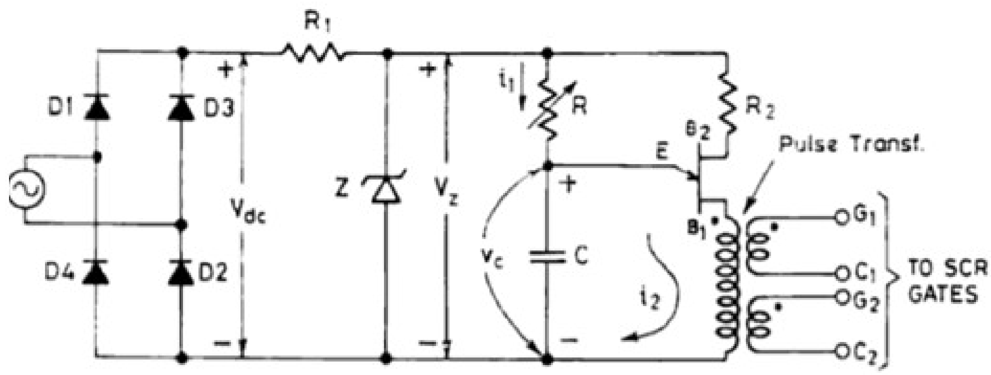



Fig. Synchronised UJT trigger circuit.

This method of controlling the output power by varying charging resistor R is called ramp control, open loop control or manual control. As the zener diode voltage Vz 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. Small variations in the supply voltage and frequency are not going to effect the circuit operation.

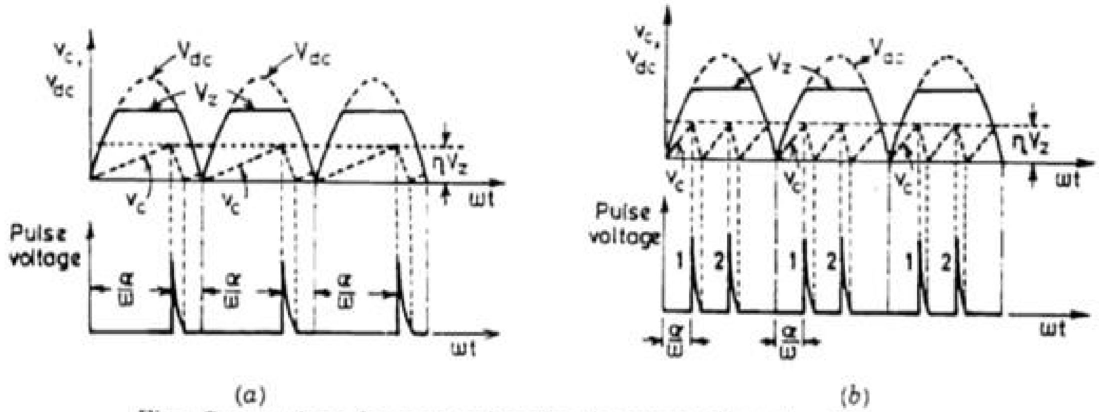



Fig. Generation of output pulses for the circuit Here, $t = \alpha/\omega$.

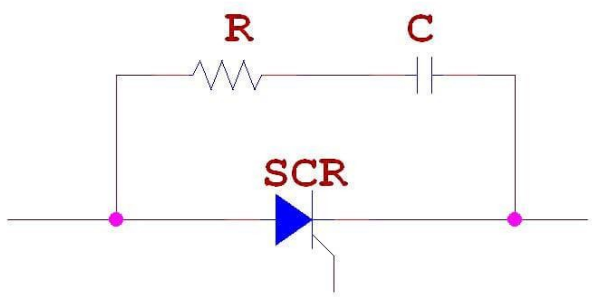
In case R is reduced so that Vc reaches UJT threshold voltage twice in each half cycle as shown in Fig. then there will be two pulses in each half cycle. As the first pulse will be able to turn-on the SCR, second pulse in each cycle is redundant.

**DESIGN OF SNUBBER CIRCUITS**

Power semiconductors are the heart of power electronics equipment. Snubbers are circuits which are placed across semiconductor devices for protection and to improve performance. Snubbers can do many things: ·

Reduce or eliminate voltage or current spikes · Limit dI/dt or dV/dt · Shape the load line to keep it within the safe operating area (SOA) · Transfer power dissipation from the switch to a resistor or a useful load · Reduce total losses due to switching · Reduce EMI by damping voltage and current ringing

With the help of snubber circuit, the false turn-on of a thyristor due to large dv/dt can be prevented.




**RC Snubber Circuit for SCR dv/dt Protection:**

This type of snubber circuit consists of a series combination of resistance R and Capacitance C in parallel with a SCR.

- When a reverse voltage is applied, commutation process is initiated and the forward current flow through SCR approaches zero.
- Due to the inductance, current continuous to flow due to sweeping of charge carries at the external junctions.
- When it reaches a peak value it cannot be further supported by the charge carriers and falls very quickly to zero. This causes a voltage spike with the value of L(di/dt).

- Also when the supply is closed to the circuit ( in the above figure say the switch S is closed), sudden voltage appears across SCR.
- Now, as the thyristor current is zero it can be considered as an open switch.
- At this moment, the capacitor C behaves like a short-circuit and therefore voltage across the SCR is zero.
- With the passage of time capacitor C gets charged at a slow rate such that dv/dt across the capacitor and therefore across SCR is less than the specified maximum dv/dt rating of the device.
- Thus the capacitor protects the SCR against high voltages and high dv/dt.

Based on the above discussion we can say that simply a Capacitor C is sufficient to protect the SCR against dv/dt false triggering.

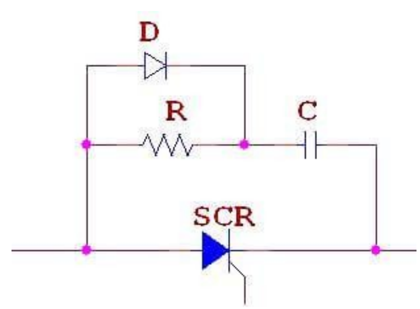
Then what is the purpose of resistance R?

- In the RC snubber circuit, the resistance R limits the discharge current of capacitor at the instant of firing of SCR.
- Before SCR is fired, capacitor C charges to full voltage V.
- If SCR is fired, when the capacitor voltage is maximum, it discharges through the local path formed by capacitor C, Resistance R and SCR.
- During this time, if the resistance R is not included in the circuit, the discharge current will be high and consequently may damage the SCR due to large di/dt.
- Thus the Resistance R in the snubber circuit reduces the discharge current of the capacitor C and thus protect the SCR against large di/dt.

In actual practice, R, C and the load current parameters should be such that

1. dv/dt across C during its charging is less than the specified dv/dt rating of the SCR
2. Discharge current at the turn ON of the SCR is within reasonable limits.

Normally R,S and load circuit parameters form an under damped circuit so that dv/dt is limited to acceptable values.




In some RC snubber circuits, a diode D used to connect in parallel with the resistor R. It is used for the purpose of bypass and thus giving improved dv/vt protection.

## 2. UNDERSTAND THE WORKING OF CONVERTERS, AC REGULATORS AND CHOPPERS.

### EXPLAIN CONTROLLED RECTIFIERS TECHNIQUES (PHASE ANGLE, EXTINCTION ANGLE CONTROL & PWM)

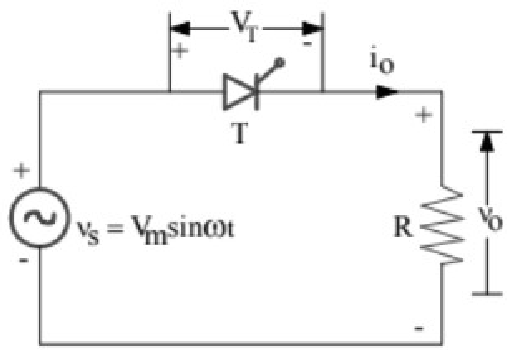
Definition:

Phase Control of SCR means having control on the phase relationship between the start of current through the SCR and source voltage.

Phase Control of SCR Explanation:

Whenever we talk of phase angle, we generally mean the angle of a sinusoidal quantity at any instant of time. Phase control of SCR means the phase angle (with reference to source voltage) where it is getting turned ON by the application of gate signal.

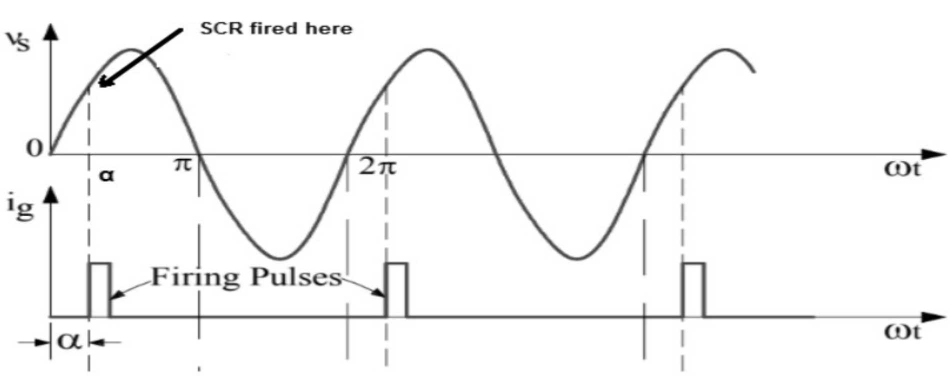
Let us understand the concept with the help of a simple circuit diagram as shown below.



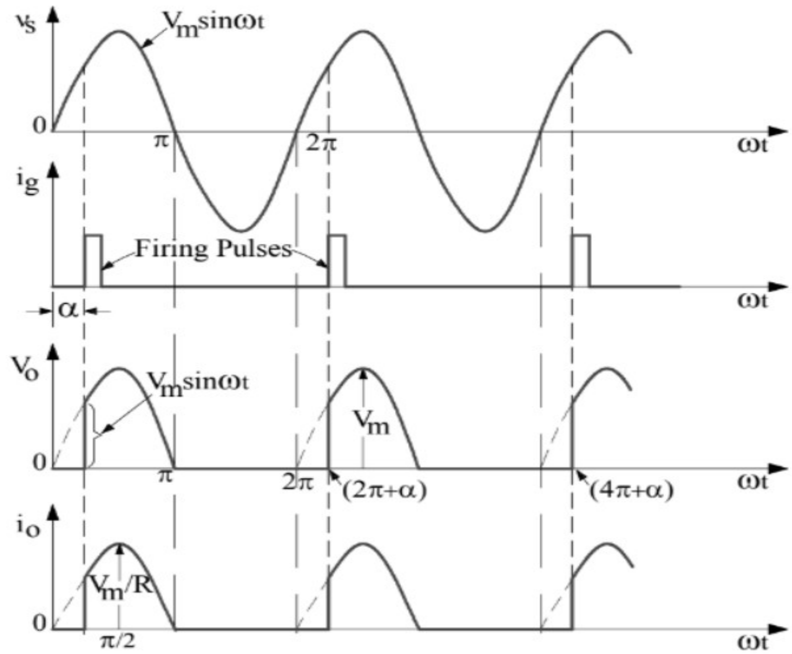

**PHASE CONTROL OF SCR**

In the above circuit, a thyristor (or SCR) T is connected to load R and voltage source vs. This SCR will not conduct until and unless it is forward biased and gate signal is applied. Application of gate signal is called firing.

During positive half cycle of supply voltage vs, the SCR is forward biased. If the thyristor T is fired (say at some phase angle α on the source voltage), it will become ON.



As SCR is now ON, it will start conducting. It will conduct from $\omega t = \alpha$ to $\pi$. Since load is resistive in nature, the load voltage $v_0$ and load current $i_0$ will follow the waveform of supply voltage. The load voltage, load current and supply voltage waveforms are shown in figure below. Compare the waveform of source voltage vs and load current $i_0$. You will observe that, the SCR is getting turned ON at a phase angle of α. Thus phase angle where thyristor T starts conducting is dependent on firing angle. If firing angle α is 0 degree, then load current and source voltage will be in phase whereas if α is 90 degree then load current will start when the source voltage is maximum. Thus the starting phase angle of load is controlled by firing angle.




At $\omega t = \pi$, thyristor T will get commutated as the load current becomes zero and SCR is reversed biased from $\omega t = \pi$ to $2\pi$. This is known as Natural Commutation. We again need to fire SCR at $(2\pi+\alpha)$, $(4\pi+\alpha)$, $(6\pi+\alpha)$ and so on.

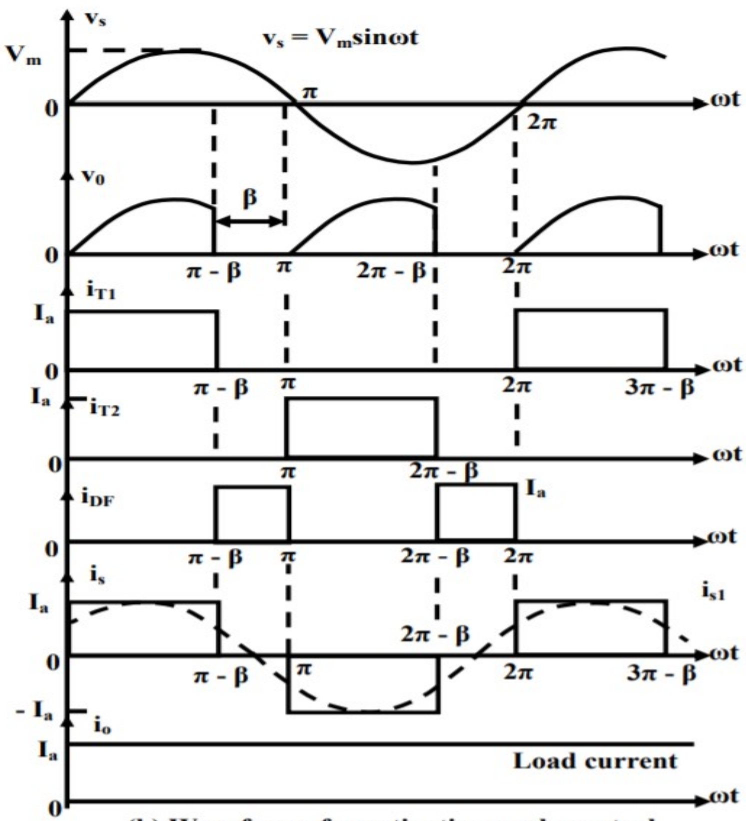
**Extinction angle control**

In power electronics extinction angle is one where thyristor gets switched off at desied angle. The output voltage is controlled by varying the extinction angle, β.

A gate turn-off thyristor (GTO) also may be used, in which case, it may be turned off by applying a short negative pulse to its gate, but is turned on by a short positive pulse, like a thyristor. In case of power transistor, the power transistor is turned on by applying a signal at the base, and turned off by withdrawing the signal at the base.

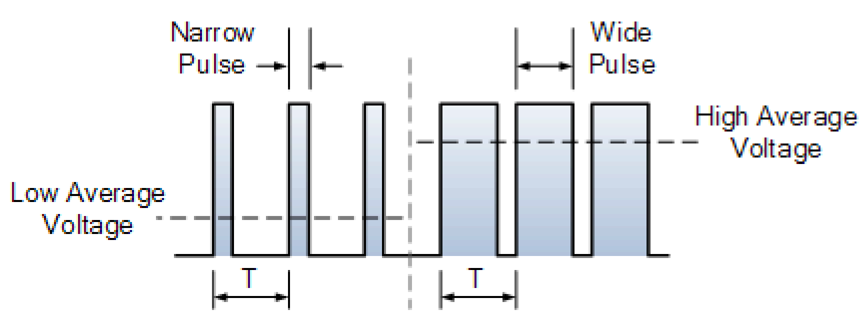
In extinction angle control, switch, S1 is turned on at $\omega t=0$, and then turned off by forced commutation at $\omega t = (\pi-\beta)$. The switch, S2 is turned on at $\omega t = \pi$, and then turned off at $(\omega t = 2\pi-\beta)$. The output voltage is controlled by varying the extinction angle, β.

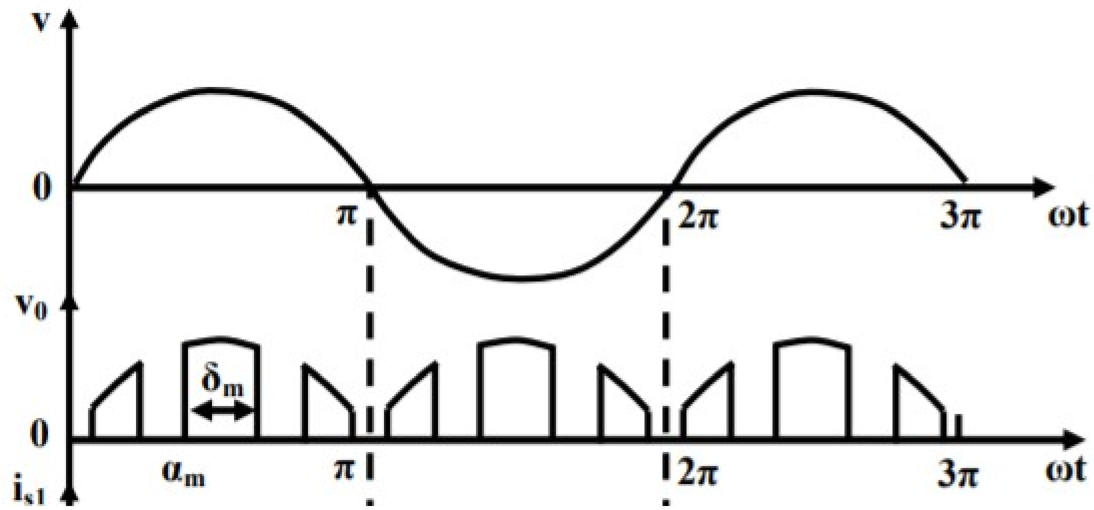
Fig. shows the waveforms for input voltage, output voltage, input current, and the current through thyristor switches



(b) Waveforms for extinction angle control

**Pwm control**






In Pulse Width Modulation (PWM) control, the converter switches are turned on and off several times during a half cycle, and the output voltage is controlled by varying the width of pulses. Fig. shows the input voltage, output voltage.

The average output voltage waveform and control pulses using PWM control is shown.

**EXPLAIN SINGLE QUADRANT SEMI CONVERTER, TWO QUADRANT FULL CONVERTER AND DUAL CONVERTER**

The phase controlled converters may be classified as semi-converter, full converter, dual converter. Depending on the input ac supply used they are classified as single phase and three phase converters.

Semi-converter: -A semi-converter is a one quadrant converter and it has one polarity of output voltage and current. It contains a mixture of diodes and thyristors allowing more limited control over the dc output voltage level than the full controlled rectifier. It is cheaper. It permits power flow from AC system to DC load. It is also known as half-wave controlled converter.

Full-converter: -A full-converter is a two-quadrant converter and the polarity of its output voltage can be either positive or negative. However, the output current of full-converter has one polarity only. Here power can be transmitted from AC side to DC side (conversion) and from DC side to AC side (inversion). It uses only thyristor as rectifying elements.

Dual-converter: -If two full converters are connected back to back they form a dual converter. It can operate in four quadrants and both the output voltage and current can be either positive or negative. Normally these are used in high power applications.

**WORKING OF SINGLE-PHASE HALF WAVE CONTROLLED CONVERTER WITH RESISTIVE AND R-L LOADS.**

In this article, we will see the analysis of Single Phase Half Wave Controlled Rectifier with Resistive (R) Load as shown in Figure 1. $V_s$ is supply and '$i_s$'is the source current. $V_T$ and '$i_T$' is the SCR voltage and current respectively. $V_o$ and '$i_o$'is the load voltage and current respectively.

$V_s = V_m\sin(\omega t)$

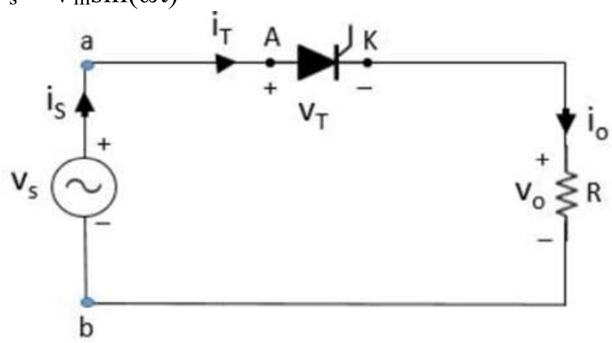



Fig. 1

**Step-1: Write KVL in the given circuit**

$v_s - v_T - v_o = 0$

$v_{ab} = v_s = v_T + v_o$

$v_{ab} = v_s = V_m\sin(\omega t)$

$v_{ba} = - v_{ab} = - V_m\sin(\omega t)$

**Step-2: Device working status**

In the positive half cycle, SCR is forward biased and is turned ON at $\omega t = \alpha$ by giving a firing pulse (triggering pulse). The angle **α** is called delay angle or firing angle**.** It is measured from the instant the SCR has become forward biased.

At $\omega t = \pi$, the current through the SCR falls to zero i.e. below zero and simultaneously a reverse voltage appears across SCR and it turns OFF. Since the line voltage is used for commutation, it is also known as line commutation converter**.**

**1). $0 < \omega t < \alpha$**

SCR is in forward blocking mode and SCR is OFF.

$i_o = i_s = i_T = 0$ Amp

$v_o = 0$ V

$v_T = v_{ab} = V_m\sin(\omega t)$

**2). $\alpha < \omega t < \pi$**

SCR is in forward conduction mode and SCR is ON.

$v_T = 0$ V

$i_o = i_s = i_T = (V_m\sin(\omega t))/R$

$v_o = v_{ab} = V_m\sin(\omega t)$

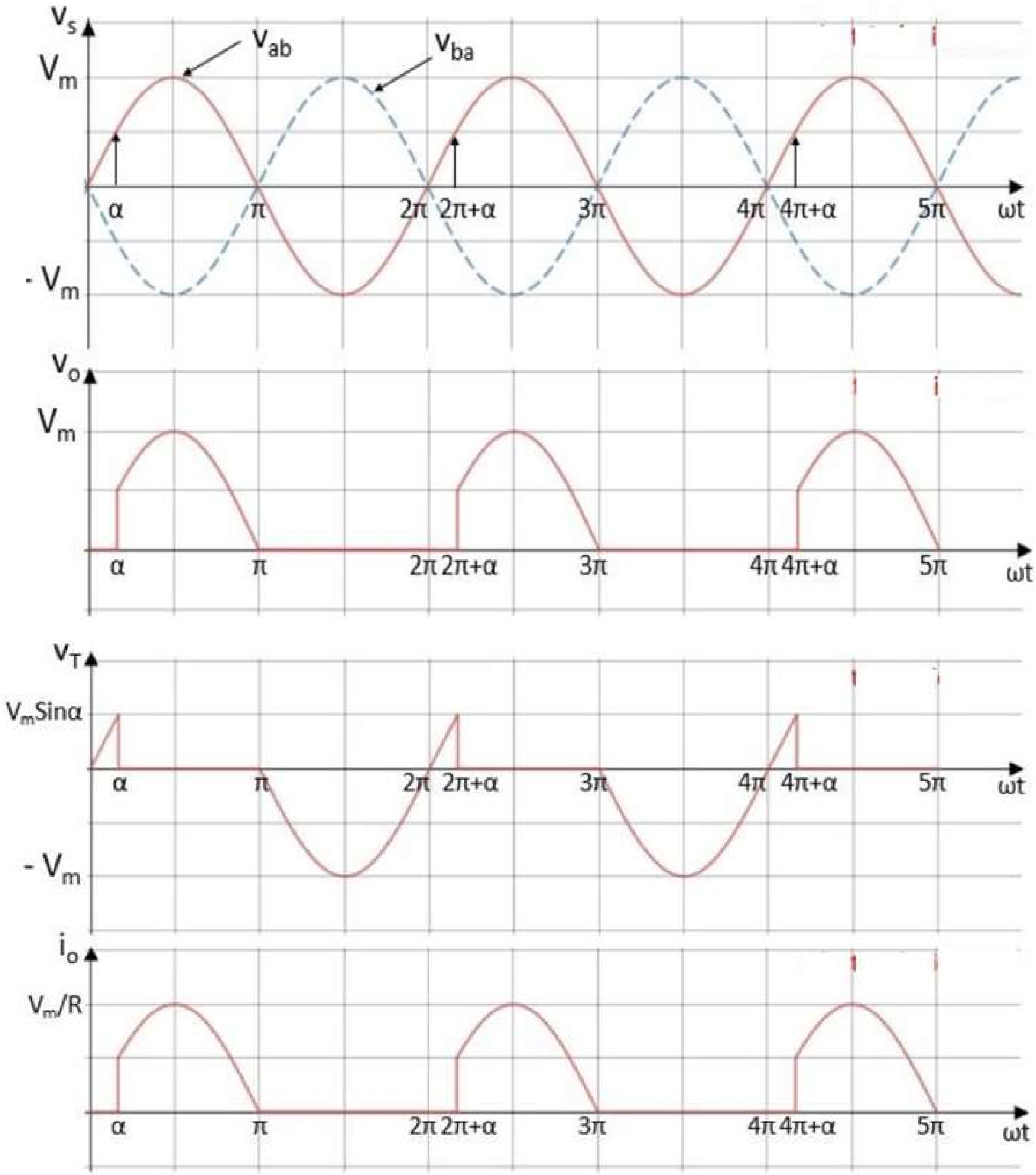



Fig. 2

**3). $\pi < \omega t < 2\pi$**

SCR is in forward blocking mode and SCR is OFF.

$i_o = i_s = i_T = 0$ Amp

$v_o = 0$ V

$v_T = v_{ab} = V_m \sin(\omega t)$

**4). $2\pi + \alpha < \omega t < 3\pi$**

SCR is in forward conduction mode and SCR is ON.

$v_T = 0$ V
$i_o = i_s = i_T = (V_m \sin(\omega t))/R$
$v_o = v_{ab} = V_m \sin(\omega t)$

The waveforms for load voltage ($v_o$), and current ($i_o$), SCR voltage ($v_T$) is shown in figure 2. The waveforms of supply current and SCR current is same as load current.
**Note:** For a resistive load, $v_o$ and Io waveform will be same in nature except in magnitude.

**Step-3:**
1). Firing angle (α) = α

2). Extinction angle (β) = π

3). Conduction angle (γ) = β − α = π − α

4). Conduction time ($t_c$) = γ/ω = (π − α)/ω
5). Circuit turn off time ($t_{ckt\text{-}off}$) = (2π − π)/ω = π/ω
6). Peak Inverse voltage (PIV) = $V_m$

**Step-4:**
**Average Values**
The average output voltage $V_{o(avg)}$ across load R is given by

$$V_{o(avg)} = \frac{1}{2\pi}\int_{\alpha}^{2\pi+\alpha} v_o(t)\ d\omega t$$
$$= \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m \sin(\omega t)\ d\omega t + \int_{\pi}^{2\pi+\alpha} 0\ d\omega t\right]$$
$$= \frac{1}{2\pi}\left[-V_m[Cos(\omega t)]_{\alpha}^{\pi}\right]$$
$$V_{o(avg)} = \frac{V_m}{2\pi}(1 + Cos\alpha)$$

The average output current $I_{o(avg)}$ through the load R is given by

$$I_{o(avg)} = \frac{V_{o(avg)}}{R}$$
$$I_{o(avg)} = \frac{V_m}{2\pi R}(1 + Cos\alpha)$$

**RMS values**

$$V_{o(rms)} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{2\pi+\alpha}[V_m \sin(\omega t)]^2\ d\omega t}$$

$$I_{o(rms)} = \frac{V_{o(rms)}}{R}$$

**Single Phase Half Wave Controlled Rectifier with RL LOAD**

The single phase half-wave controlled rectifier with inductive-load is shown in Fig.1.a The wave shapes for voltage and current in case of an inductive load are given in Fig.1.b. The load is assumed to be highly inductive.

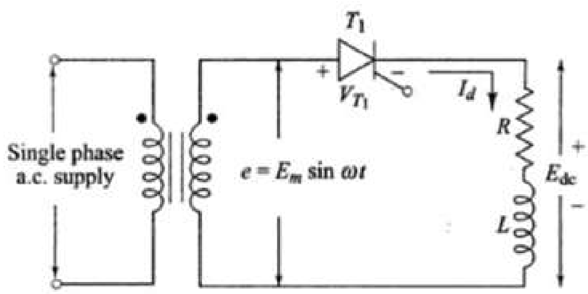



**Fig.1(a)** *Half-wave controlled rectifier with R-L load*

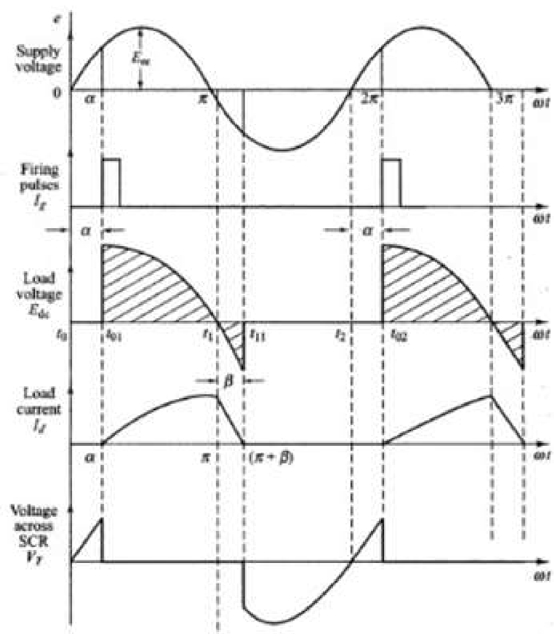



**Fig.1(b)** *Waveforms for a half-wave controlled rectifier with RL load*

The operation of the circuit on inductive loads changes slightly. Now at instant t01 , when the thyristor is triggered, the load-current will increase in a finite-time through the inductive load. The supply voltage from this instant appears across the load. Due to inductive load, the increase in current is gradual. Energy is stored in inductor during time t01 to t1. At t1, the supply voltage reverses, but the thyristor is kept conducting. This is due to the fact that current through the inductance cannot be reduced to zero.

During negative-voltage half-cycle, current continues to flow till the energy stored in the inductance is dissipated in the load-resistor and a part of the energy is fed-back to the source. Hence, due to energy stored in inductor, current , current continuous to flow up to instant t1 at instant, t11, the load-current is zero and due to negative supply voltage, thyristor turns-off.

At instant t02, when again pulse is applied, the above cycle repeats. Hence the effect of the inductive load is increased in the conduction period of the SCR.

The half-wave circuit is not normally used since it produces a large output voltage ripple and is incapable of providing continuous load-current.

The average value of the load-voltage can be derived as:

Here, it has been assumed that in negative half-cycles, the SCR conducts for a period of α

$$E_{dc} = \frac{E_m}{2\pi}[-\cos\omega t]_{\alpha}^{\pi+\alpha}$$

$$E_{dc} = \frac{E_m}{\pi}\cos\alpha$$

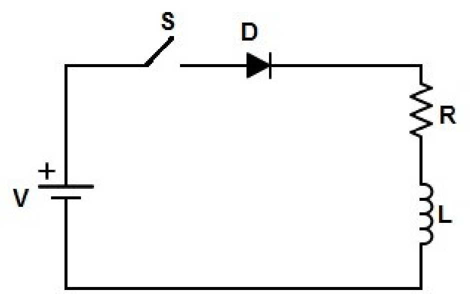
From the above equation, it is clear that the average load-voltage is in case of inductive load.

This is due to the conduction of SCR in negative cycle.

**UNDERSTAND NEED OF FREEWHEELING DIODE.**

A freewheeling diode is basically a diode connected across the inductive load terminals to prevent the development of high voltage across the switch. When the inductive circuit is switched off, this diode gives a short circuit path for the flow of inductor decay current and hence dissipation of stored energy in the inductor. This diode is also called Flywheel or Flyback diode

**Working Principle of Freewheeling Diode:**




When switch S is closed, the steady state current I through the circuit is (V/R) and hence the stored energy in inductor is $(LI^2)/2$. When this switch S is opened, the current will suddenly decay to zero from steady value I = (V/R). Due to this sudden decay of current, a high reverse voltage (as per lenz's law) equal to L(di/dt) will appear across the inductor terminals and hence across the diode and switch. This will lead to sparking across the switch contacts. If this reverse voltage exceeds the Peak Inverse Voltage of diode, then it may get damage. To avoid such occurrences, a diode, called freewheeling or flyback diode is connected across the inductive load RL as shown in figure below.

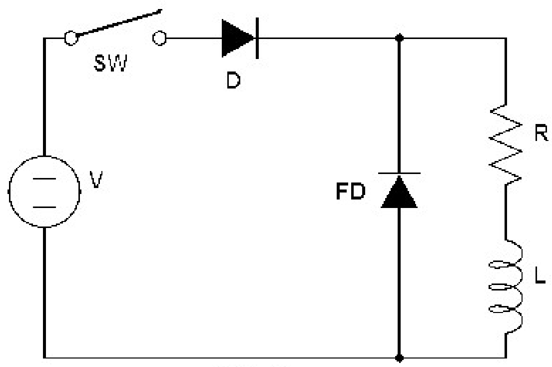
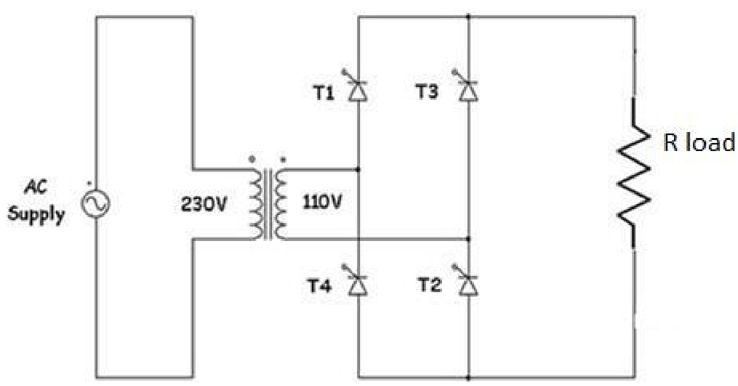



Fig - 1

Thus, the main circuit current is transferred to the circuit consisting of freewheeling diode FD, R and L as shown in above figure. In this new circuit, the current will exponentially decay to zero Thus we see that, freewheeling diode dissipates the stored energy in inductor by providing a short circuit path. It also provides a shorted path for exponentially decay of circuit current. Thus high voltage is not induced. Therefore, the switches and diode is protected from the high voltage.

**WORKING OF SINGLE PHASE FULLY CONTROLLED CONVERTER WITH RESISTIVE AND R- L LOADS.**

**WORKING OF SINGLE PHASE FULLY CONTROLLED CONVERTER WITH RESISTIVE LOAD**




Full wave bridge rectifier circuit with resistive load.

Figure above shows a full-wave controlled bridge rectifier circuit with a resistive load. In this circuit, diagonally opposite pairs of SCRs turn on and off together.

During the positive half-cycle of the input .voltage, SCRl, SCR2 is forward-biased. If we apply the gate signal at a SCRl and SCR2 turns on. The output Voltage (Vo) follows the input voltage. The load current (io = vo/R|) has the same waveform as the load voltage. At π, when the current through SCR1and SCR4 becomes zero, it turns off naturally.

During the negative half-cycle; SCR3 and SCR4 is forward biased. SCR3 and SCR4 is fired at $(\pi + \alpha)$. The output voltage again follows the input voltage."The current through SCR4 and SCR3 becomes zero at 2 π; and it turns off.

SCRl, SCR2 is fired again at (2π+α), SCR3 and SCR4 at (3π+α), and the cycle repeats.

Figure shows the resulting voltage and current waveforms.. The average DC output voltage can be controlled from zero to its maximum value by varying the firing angle.

The SCRs are controlled and fire in pairs with a delay angle of α. The current and voltage waveform become full-wave, as shown in figure below

**(a) Average output voltage ($V_{dc}$)**

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t.d\omega t$$

$$V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)$$

**(b) RMS output voltage ($V_{0rms}$)**

$$V_{0rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2\omega t.d\omega t\right]^{1/2} = V_m\left[\frac{\pi-\alpha}{2\pi}+\frac{\sin 2\alpha}{4\pi}\right]^{1/2}$$

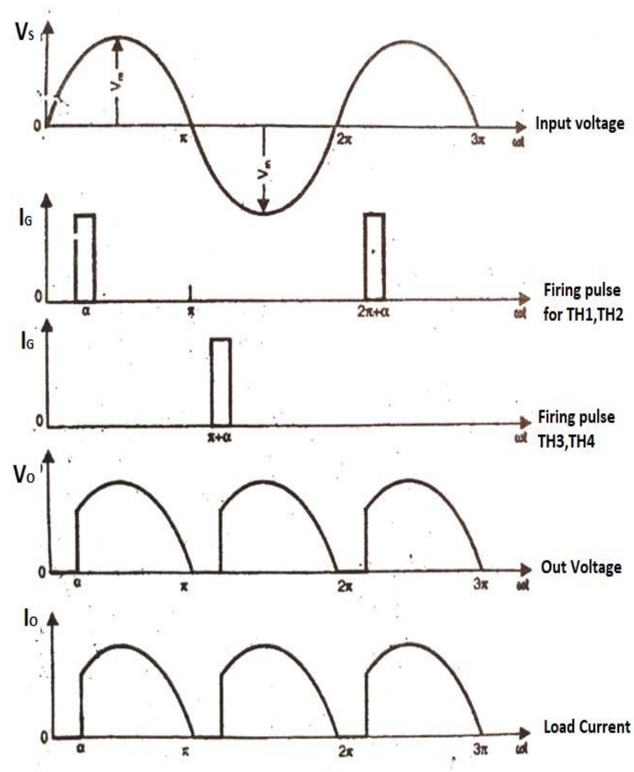
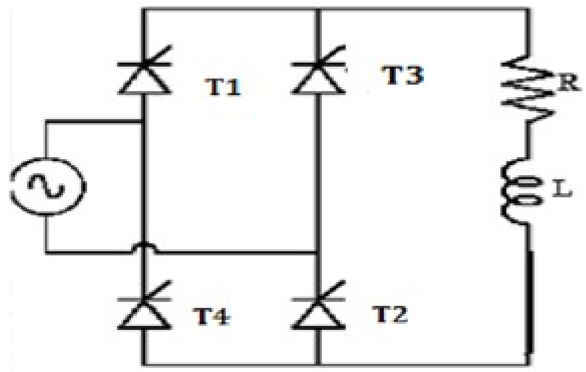



Fig. Voltage and current waveforms

## SINGLE PHASE FULL WAVE CONVERTER WITH RL LOAD




**Operation of this mode can be divided between four modes**

**Mode 1 (α to π)**

• In positive half cycle of applied ac signal, SCR's T1 & T2 are forward bias & can be turned on at an angle α.

• Load voltage is equal to positive instantaneous ac supply voltage. The load current is positive, ripple free, constant and equal to Io.

Due to positive polarity of load voltage & load current, load inductance will store energy.

**Mode 2 (π to π+α)**

• At wt=π, input supply is equal to zero & after π it becomes negative. But inductance opposes any change through it.

• In order to maintain a constant load current & also in same direction. A self induced emf appears across 'L' as shown.

• Due to this induced voltage, SCR's T1 & T2 are forward bias in spite the negative supply voltage.

The load voltage is negative & equal to instantaneous ac supply voltage whereas load current is positive.

• Thus, load acts as source & stored energy in inductance is returned back to the ac supply.

**Mode 3 (π+α to 2π)**

• At wt=π+α SCR's T3 & T4 are turned on & T1, T2 are reversed bias.

• Thus, process of conduction is transferred from T1, T2 to T3, T4.

• Load voltage again becomes positive & energy is stored in inductor

• T3, T4 conduct in negative half cycle from (π+α) to 2π with positive load voltage & load current energy gets stored

**Mode 4 (2π to 2π+α)**

• At wt=2π, input voltage passes through zero.
• Inductive load will try to oppose any change in current if in order to maintain load current constant & in the same direction.
• Induced emf is positive & maintains conducting SCR's T3 & T4 with reverse polarity also.
• Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to be positive.
• Thus load acts as source & stored energy in inductance is returned back to ac supply
• At wt=α or 2π+α, T3 & T4 are commutated and T1, T2 are turned on.

**(a) Average output voltage ($V_{dc}$)**

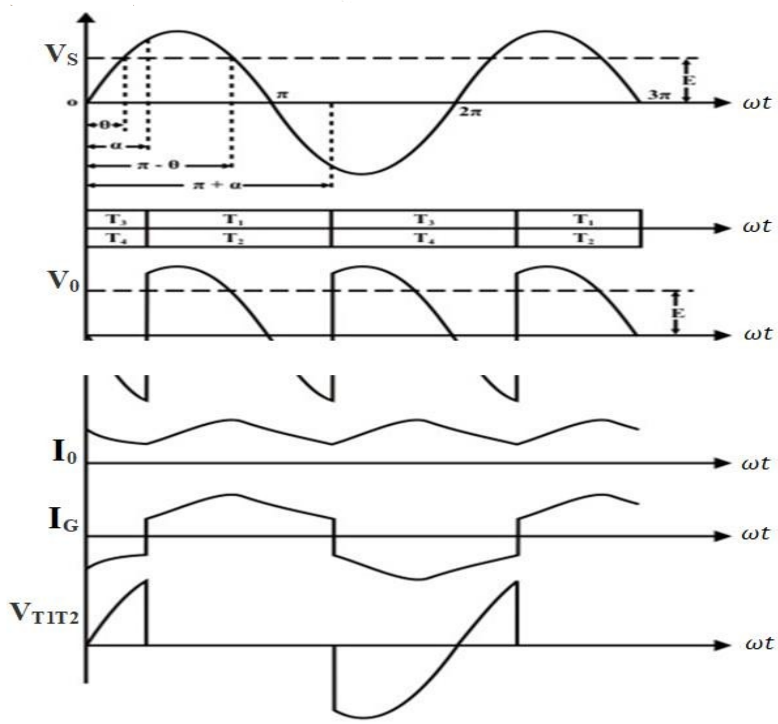
$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t.d(\omega t) = \frac{V_m}{\pi}\left|-\cos\omega t\right|_{\alpha}^{\pi+\alpha}$$

$$= \frac{V_m}{\pi}\left|\cos\omega t\right|_{\pi+\alpha}^{\alpha} = \frac{V_m}{\pi}\left[\cos\alpha - (-\cos\alpha)\right]$$

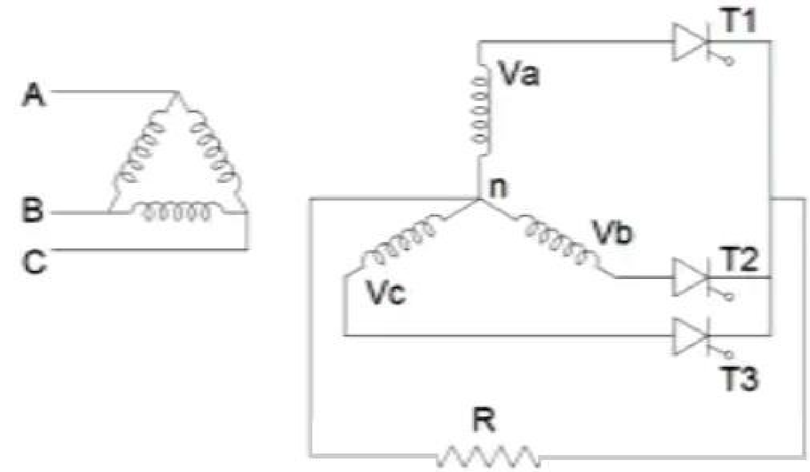
$$\boxed{V_{dc} = \frac{2V_m}{\pi}\cos\alpha}$$

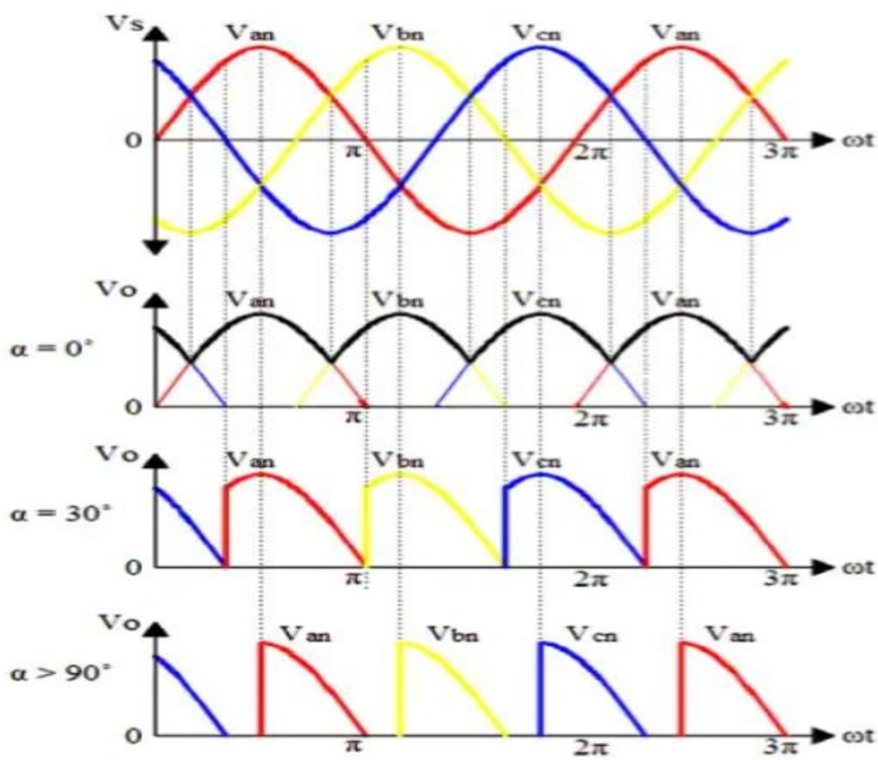
**(b) RMS output voltage ($V_{orms}$)**

$$V_{orms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2 \omega t d(\omega t)\right]^{1/2} = V_m\left[\frac{1}{2} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2}$$



WORKING OF THREE-PHASE HALF WAVE CONTROLLED CONVERTER WITHRESISTIVE LOAD



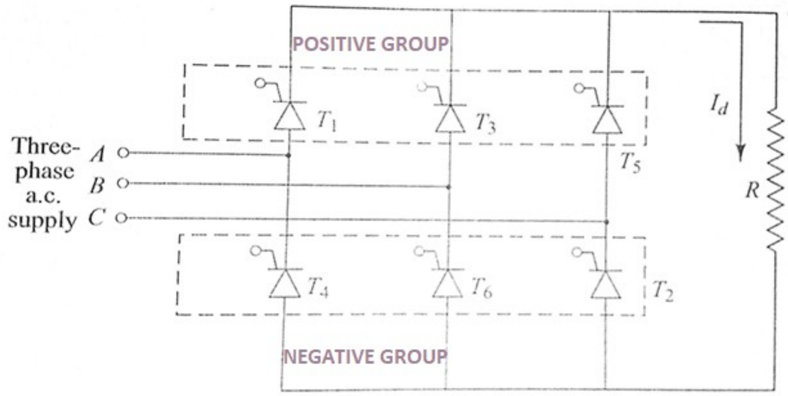




**WORKING PRINCIPLE**

- The circuit consists of a delta star transformer and 3 thyristors T1, T2, T3 which are connected on the secondary star connected winding and a resistive load.
- When Va is positive, T1 becomes forward biased and conducts when triggered. During the negative cycle of Va, T1 turns OFF.

- When VB is positive, T2 becomes forward biased and conducts when triggered. During the negative cycle of Vb, T2 turns OFF.
- Similarly T3 conducts only during the positive cycles of Vc when triggered and turns OFF during negative cycle of Vc
- The above figure shows waveforms for different triggering angles.
- The average output voltage can be varied by varying the firing angles of the thyristors.
- The waveform shows the output voltage for various firing angles. In the waveform, Va is denoted as Van, Vb as Vbn, Vc as Vcn.

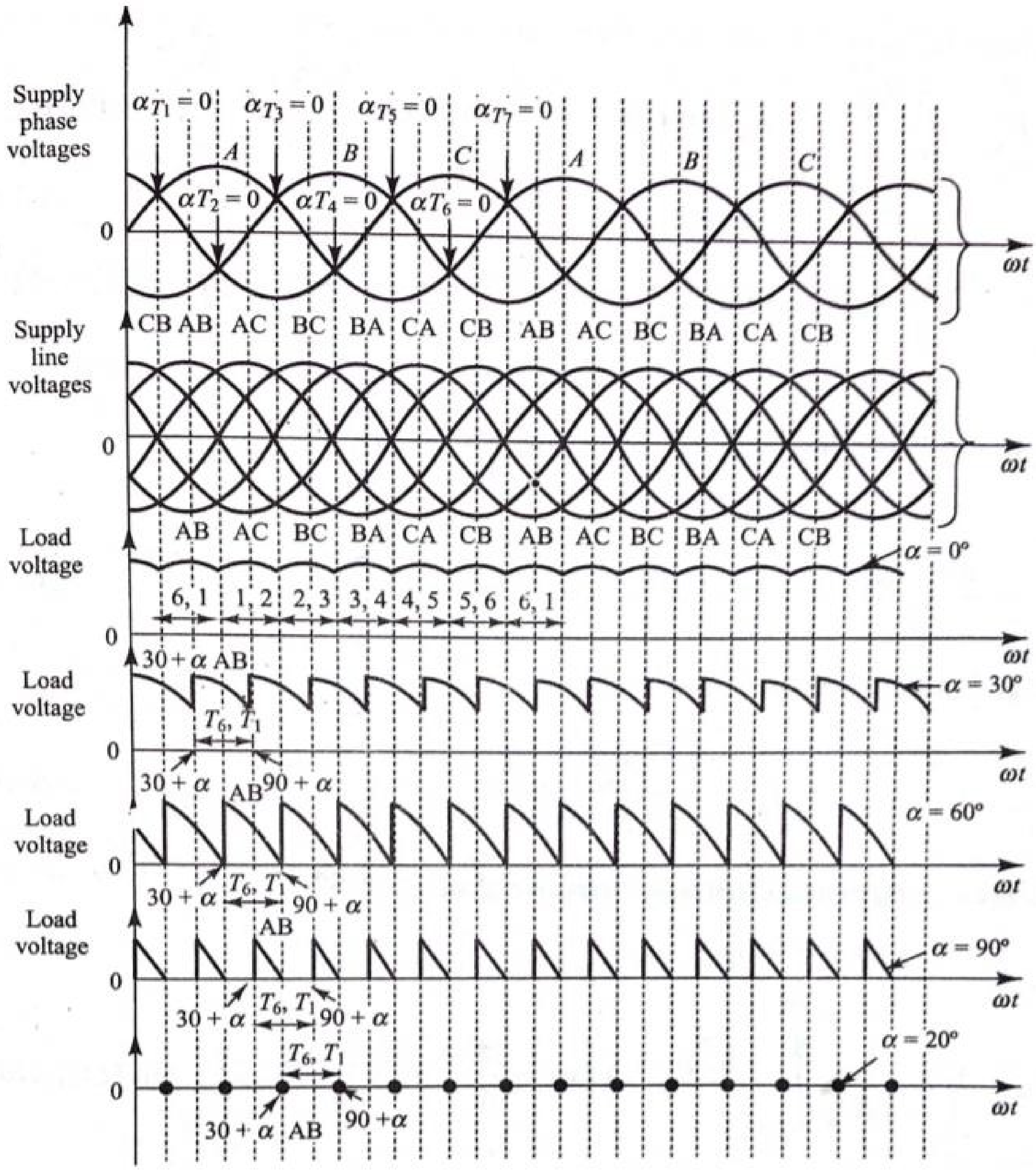
## WORKING OF THREE PHASE FULLY CONTROLLED CONVERTER WITHRESISTIVE LOAD.




3 φ FULL CONVERTER

Three phase full wave controlled rectifier with resistive load is shown above
The circuit diagram consists of 6 SCRS, SCR T1, T3, T5 forms positive group and SCR T4 T6 T2 forms negative group.
The positive groups of SCRs are turned on when the supply voltage is positive and the negative groups of SCRs are turned on when the supply voltage is negative.
Operation
Each device is triggered at a desired firing angle Alpha (α)
Each SCR conducts for 120 degree
SCRs are triggered in the sequence T1 T2 T3 T4 T5 T6
Each SCRs conducts in two pair and each pair conducts for 60 degree
When two SCRs are conducting one from positive group and one from negative group the corresponding line voltage is applied across the load
The six pairs of thyristors which conducts are (T6 T1) (T1 T2) (T2 T3) (T3 T4) (T5 T6)
FIRING SEQUENCE OF SCR

| S.No. | $\omega t$ | Incoming SCR | Conducting pair | Outgoing SCR | Line voltage across the load |
|---|---|---|---|---|---|
| 1. | $30° + \alpha$ | $T_1$ | $(T_6, T_1)$ | $T_5$ | $E_{AB}$ |
| 2. | $90° + \alpha$ | $T_2$ | $(T_1, T_2)$ | $T_6$ | $E_{AC}$ |
| 3. | $150° + \alpha$ | $T_3$ | $(T_2, T_3)$ | $T_1$ | $E_{BC}$ |
| 4. | $210° + \alpha$ | $T_4$ | $(T_3, T_4)$ | $T_2$ | $E_{BA}$ |
| 5. | $270° + \alpha$ | $T_5$ | $(T_4, T_5)$ | $T_3$ | $E_{CA}$ |
| 6. | $330° + \alpha$ | $T_6$ | $(T_5, T_6)$ | $T_4$ | $E_{CB}$ |



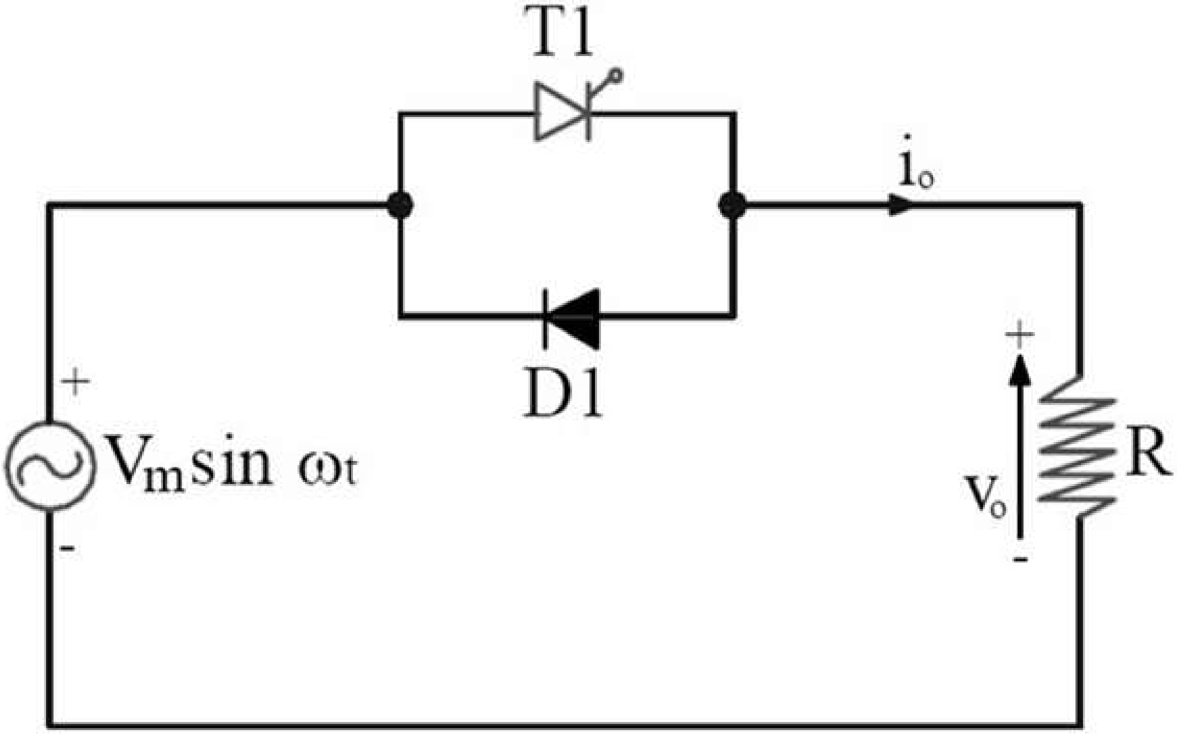

**VOLTAGE WAVEFORM AND CONDUCTION OF THYRISTORS FOR 3-PHASE FULL CONVERTER**

## WORKING OF SINGLE PHASE AC REGULATOR

Single Phase AC Voltage regulator is a device which converts fixed single phase alternating voltage directly to a variable alternating voltage without a change in frequency. The input and output of the device is single phase. There are two types of single phase AC Voltage Controller i.e. **Single phase Half Wave and Single phase Full Wave regulator.**

**Single Phase Half Wave AC Voltage Controller:**

A single phase half wave AC voltage controller comprises of a thyristor connected in anti-parallel with a power diode. The circuit diagram is shown in figure below.




The load is assumed resistive for the sake of simplicity. The input source is $V_m Sin\omega t$.

For the positive half cycle of input source, thyristor T1 is forward biased and hence it is able to conduct provided gate signal is applied. This means that T1 will remain OFF until gate signal is applied.

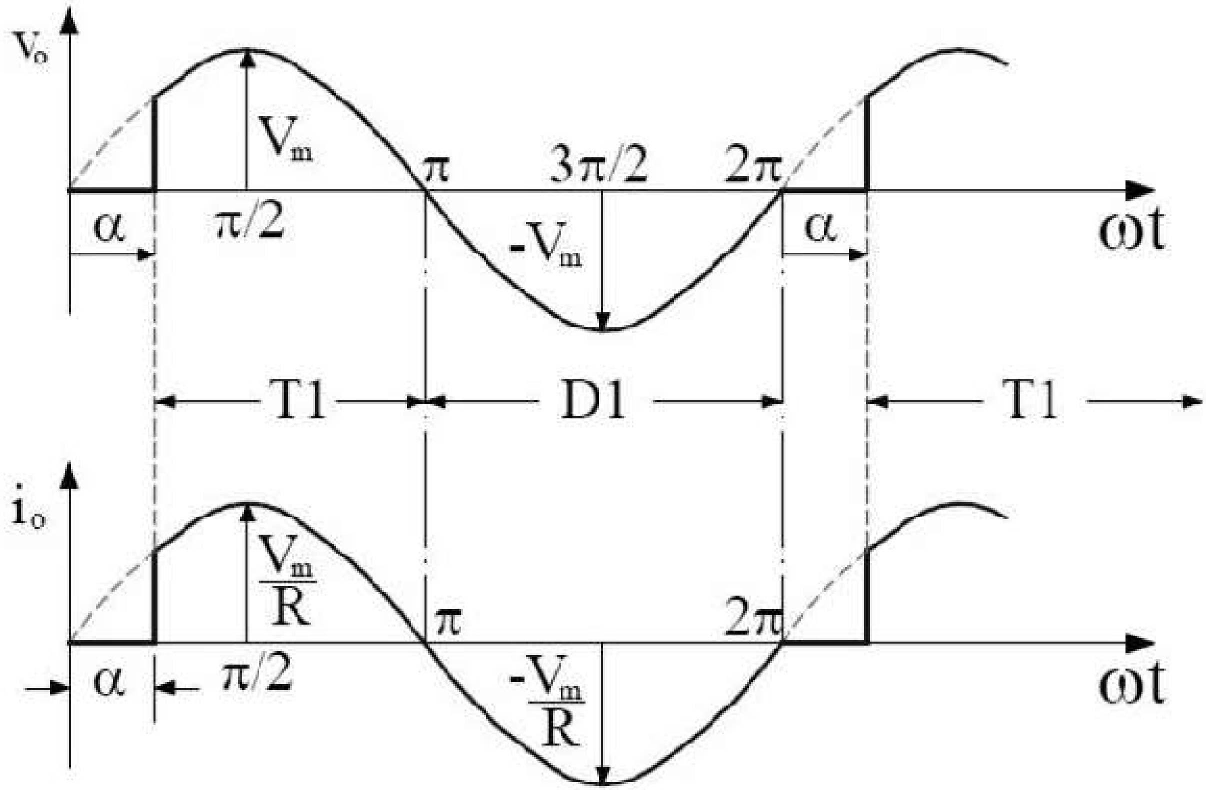
Now suppose, at some angle α (called the firing angle), thyristor T1 is gated. As soon as T1 is fired / gated, it starts conducting and hence, load gets directly connected to the source. This makes load voltage $V_o = V_m Sin\alpha$ and load current $I_o = (V_m Sin\alpha / R)$ at the instant T1 is fired.

From $\omega t = \alpha$ to $\pi$, the load voltage and current follows the input voltage waveform $V_m Sin\omega t$ and $(V_m Sin\omega t / R)$ respectively.

After $\omega t = \pi$, thyristor T1 becomes reversed biased and the load current becomes zero (note that load voltage and current are in phase, hence as soon as load voltage becomes zero, load current also becomes zero) and hence thyristor T1 is commutated naturally.

After $\omega t = \pi$, diode D1 becomes forward biased and hence starts conducting. This makes load voltage & current to follow the supply voltage $V_m Sin\omega t$ and ($V_m Sin\omega t$ / R) respectively for the negative half cycle.

The output waveform for load voltage & current is shown below.




Following points may be noted from the above waveforms:

- By having a control on the firing angle α, the load voltage may be controlled. It may be seen from the output waveform that, there is no control on the negative half cycle of the input voltage. This is the reason, a single phase half wave AC voltage controller is also known as single phase unidirectional voltage controller.
- The positive and negative half cycle of the load voltage & current are not identical. As a result, DC component is introduced in the supply and load circuit which is undesirable.

Let us now calculate the rms value of load voltage and current. This will give us an idea of the magnitude of output voltage and current.

$RMS\ Load\ Voltage\ Vo =$

$$\sqrt{\frac{1}{2\pi}\int_{\alpha}^{2\pi}\{V_m\ Sin\omega t\}^2\,d(\omega t)}$$

$$= \frac{V_m}{2}\sqrt{\frac{1}{\pi}\{(2\pi-\alpha)+\frac{Sin2\alpha}{2}\}}$$

RMS Load Current = Vo / R

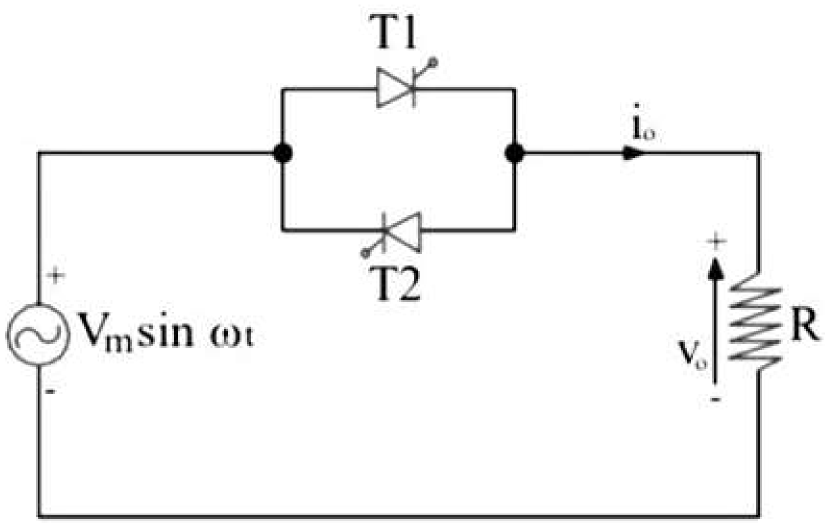
$Average\ Load\ Voltage =$

$$\frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m\ Sin\omega t\, d(\omega t)$$

$$= \frac{V_m}{2\pi}(Cos\alpha - 1)$$

**Single Phase Full Wave AC Voltage Controller:**

A single phase full wave AC voltage controller comprises of two thyristor connected in anti-parallel. The circuit diagram is shown in figure below.




The load is assumed resistive for the sake of simplicity. The input source is $V_m$Sinωt.

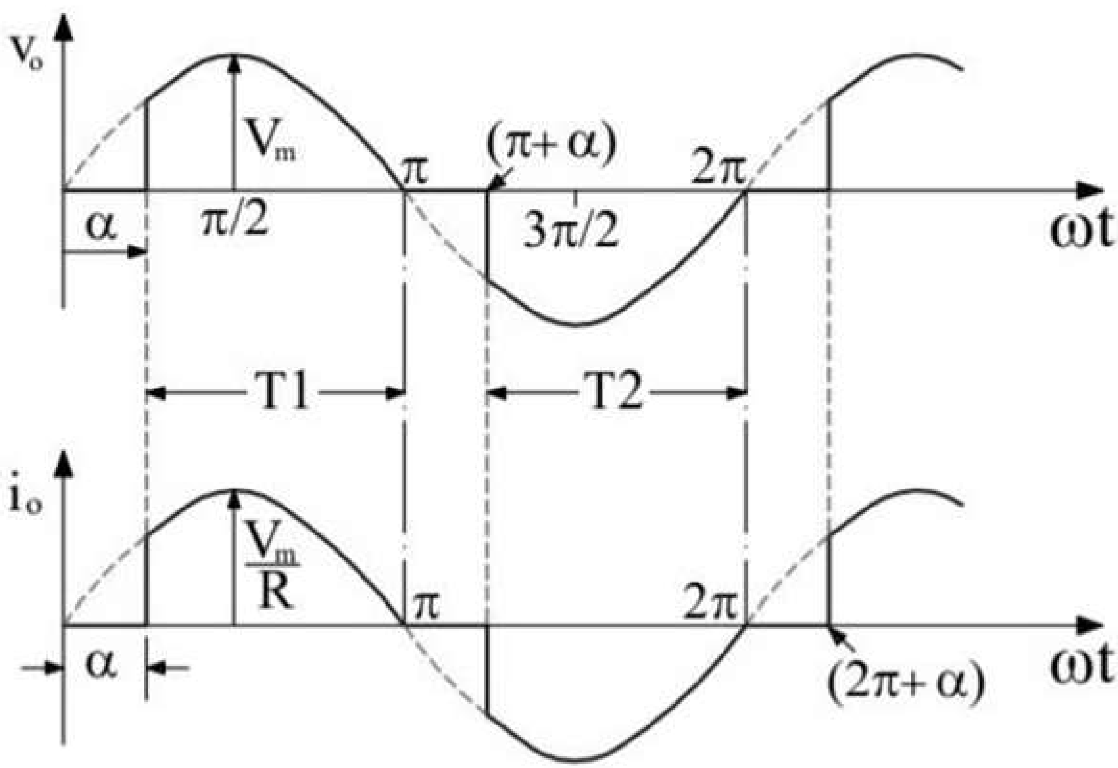
For the positive half cycle of input source, thyristor T1 is forward biased and hence it is able to conduct provided gate signal is applied. This means that T1 will remain OFF until gate signal is applied.
Now suppose, at some angle α (called the firing angle), thyristor T1 is gated. As soon as T1 is fired / gated, it starts conducting and hence, load gets directly connected to the source. This makes load voltage $V_o = V_m$Sinα and load current $I_o = (V_m$Sinα / R) at the instant T1 is fired.

From wt = α to π, the load voltage and current follows the input voltage waveform $V_m$Sinωt and ($V_m$Sinωt / R) respectively.

At wt = $\pi$, the load voltage becomes zero and current, also, becomes zero. Since, thyristor T1 is reversed biased after $\omega t = \pi$ and current through it is zero, it gets naturally commutated.

At $\omega t = (\pi+\alpha)$, forward biased thyristor T2 is gated. Hence, it conducts and connected load to the source. The load voltage now follows the negative envelop of the AC input supply and the load current does the same. Thus, the root mean square voltage may be controlled by having a control of firing angle. In this way, voltage control is achieved in AC voltage Controller.

The output waveform for load voltage & current is shown below.




It may be noted from the above waveform that the positive and negative half cycle of the load voltage & current are identical. As a result, DC component is not introduced in the supply and load circuit. This is the main advantage of single phase full wave AC voltage controller.
Single phase full wave AC voltage controller is also known as single phase bidirectional voltage controller. Let us now calculate the rms value of load voltage and current.

$RMS\ Load\ Voltage\ Vo =$

$$\sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\{V_m\,Sin\omega t\}^2\,d(\omega t)}$$

$$= V_m\sqrt{\frac{1}{2\pi}\{(\pi-\alpha)\ +\frac{Sin2\alpha}{2}\}}$$

*RMS Load Current = Vo / R*

$Average\ Load\ Voltage = 0$

Single phase full wave voltage controllers are more suitable to practical circuits. It also overcomes the problem of dc component which is present in supply and load circuit of half wave voltage controller.

WORKING PRINCIPLE OF STEP UP & STEP DOWN CHOPPER.

A chopper uses high speed to connect and disconnect from a source load. A fixed DC voltage is applied intermittently to the source load by continuously triggering the power switch ON/OFF. The period of time for which the power switch stays ON or OFF is referred to as the chopper's ON and OFF state times, respectively.

Choppers are mostly applied in electric cars, conversion of wind and solar energy, and DC motor regulators.

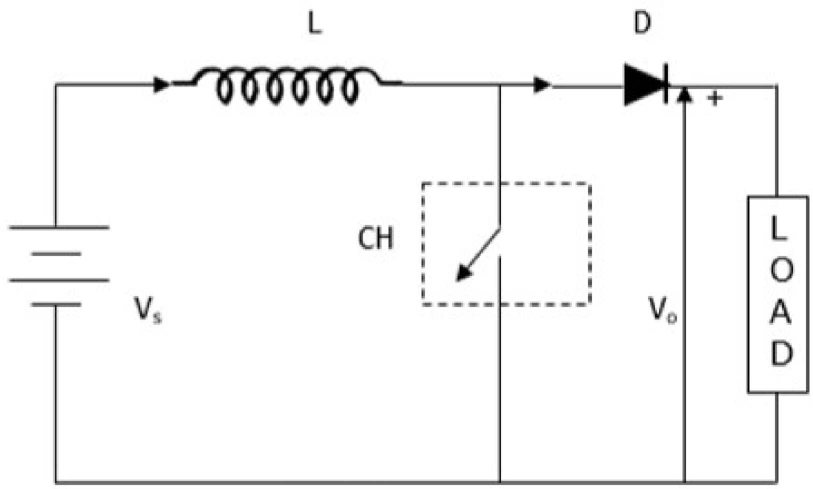
Classification of Choppers

Depending on the voltage output, choppers are classified as −

- Step Up chopper boost converter
- Step Down Chopper Buck converter
- Step Up/Down Chopper Buck−boost converter

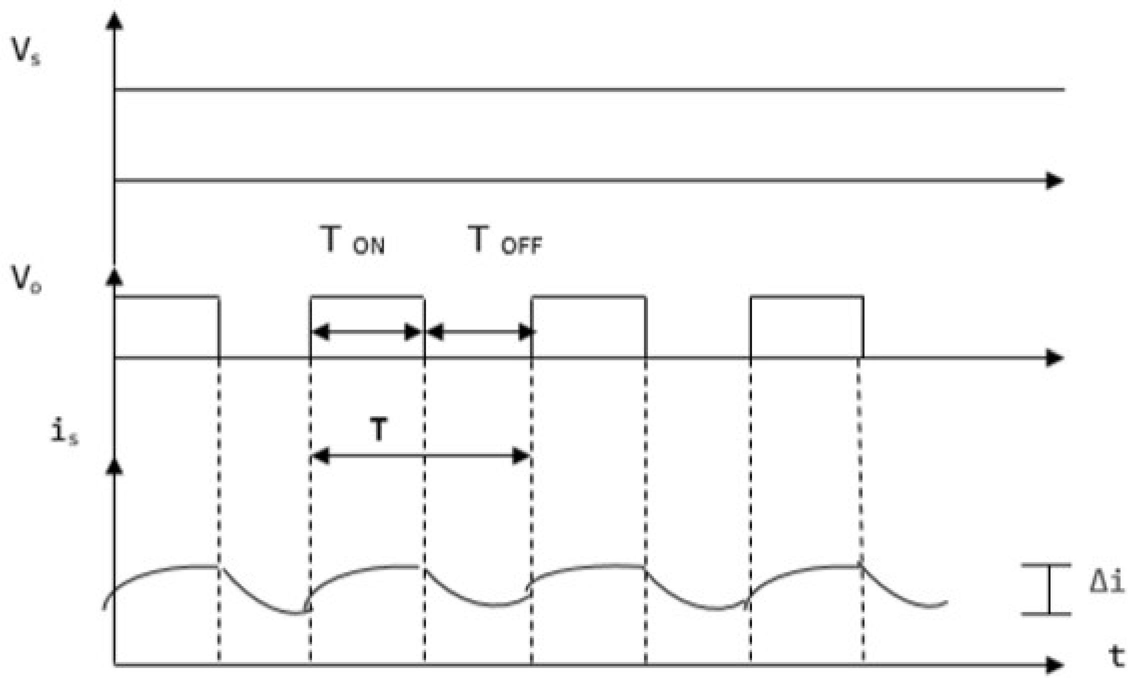
STEP UP CHOPPER.

The average voltage output ($V_o$) in a step up chopper is greater than the voltage input ($V_s$). The figure below shows a configuration of a step up chopper.




Current and Voltage Waveforms

$V_0$ average voltage output is positive when chopper is switched ON and negative when the chopper is OFF as shown in the waveform below.




Where

$T_{ON}$ – time interval when chopper is ON

$T_{OFF}$ – time interval when chopper is OFF

$V_L$ – Load voltage

$V_s$ – Source voltage

T – Chopping time period = $T_{ON} + T_{OFF}$

$V_o$ is given by – $V_0 = \frac{1}{T}\int_0^{T_{ON}} V_S dt$

When the chopper CHCH is switched ON, the load is short circuited and, therefore, the voltage output for the period $T_{ON}$ is zero. In addition, the inductor is charged during this time. This gives $V_S = V_L$

$$L\frac{di}{dt} = V_S, \qquad \frac{\Delta i}{T_{ON}} = \frac{V_S}{L}$$

Hence, $\Delta i = \frac{V_S}{L}T_{ON}$

$\Delta i$ = is the inductor peak to peak current. When the chopper CHCH is OFF, discharge occurs through the inductor L. Therefore, the summation of the $V_s$ and $V_L$ is given as follows −

V0=VS+VL, VL=V0−VS

But $$L\frac{di}{dt} = V_0 - V_S$$

Thus, $$L\frac{\Delta i}{T_{OFF}} = V_0 - V_S$$

This gives, $$\Delta i = \frac{V_0 - V_S}{L}T_{OFF}$$

Equating $\Delta i$ from ON state to $\Delta i$ from OFF state gives –

$$\frac{V_S}{L}T_{ON} = \frac{V_0 - V_S}{L}T_{OFF}\ , \qquad V_S\left(T_{ON} + T_{OFF}\right) = V_0 T_{OFF}$$

$$V_0 = \frac{TV_S}{T_{OFF}} = \frac{V_S}{\frac{(T + T_{ON})}{T}}$$

This give the average voltage output as,

$$V_0 = \frac{V_S}{1 - D}$$

The above equation shows that $V_o$ can be varied from $V_S$ to infinity. It proves that the output voltage will always be more than the voltage input and hence, it boosts up or increases the voltage level.

STEP DOWN CHOPPER

This is also known as a buck converter. In this chopper, the average voltage output $V_O$ is less than the input voltage $V_S$. When the chopper is ON, $V_O = V_S$ and when the chopper is off, $V_O = 0$

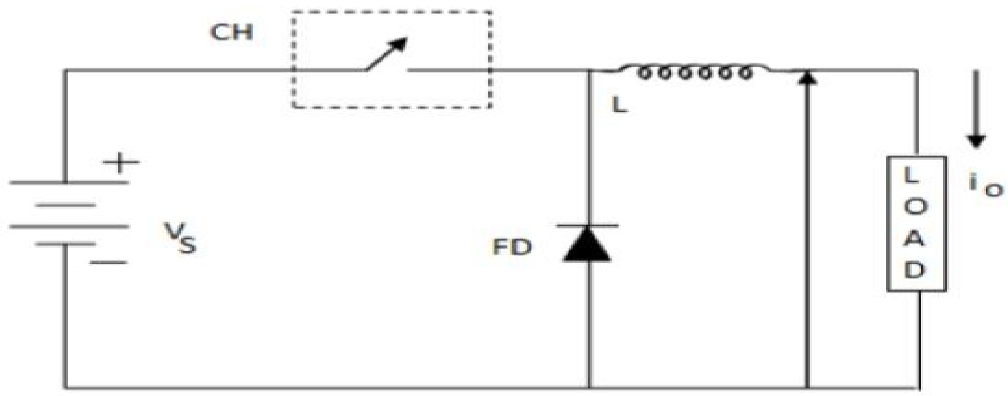
When the chopper is ON –

$$V_S = (V_L + V_0), \quad V_L = V_S - V_0, \quad L\frac{di}{dt} = V_S - V_0, \quad L\frac{\Delta i}{T_{ON}} = V_s + V_0$$

Thus, peak-to-peak current load is given by,

$$\Delta i = \frac{V_s - V_0}{L} T_{ON}$$

Circuit Diagram




Where **FD** is free-wheel diode.

When the chopper is OFF, polarity reversal and discharging occurs at the inductor. The current passes through the free-wheel diode and the inductor to the load. This gives,

$$L\frac{di}{dt} = V_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

Rewritten as − $L\frac{\Delta i}{T_{OFF}} = V_0$

$$\Delta i = V_0 \frac{T_{OFF}}{L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (ii)$$

Equating equations $i$ and $ii$ gives;

$$\frac{V_S - V_0}{L} T_{ON} = \frac{V_0}{L} T_{OFF}$$

$$\frac{V_S - V_0}{V_0} = \frac{T_{OFF}}{T_{ON}}$$

$$\frac{V_S}{V_0} = \frac{T_{ON} - T_{OFF}}{T_{ON}}$$

The above equation gives;

$$V_0 = \frac{T_{ON}}{T} V_S = DV_S$$

Equation i give –

$$\Delta i = \frac{V_S - DV_S}{L} DT \text{ , from } D = \frac{T_{ON}}{T}$$

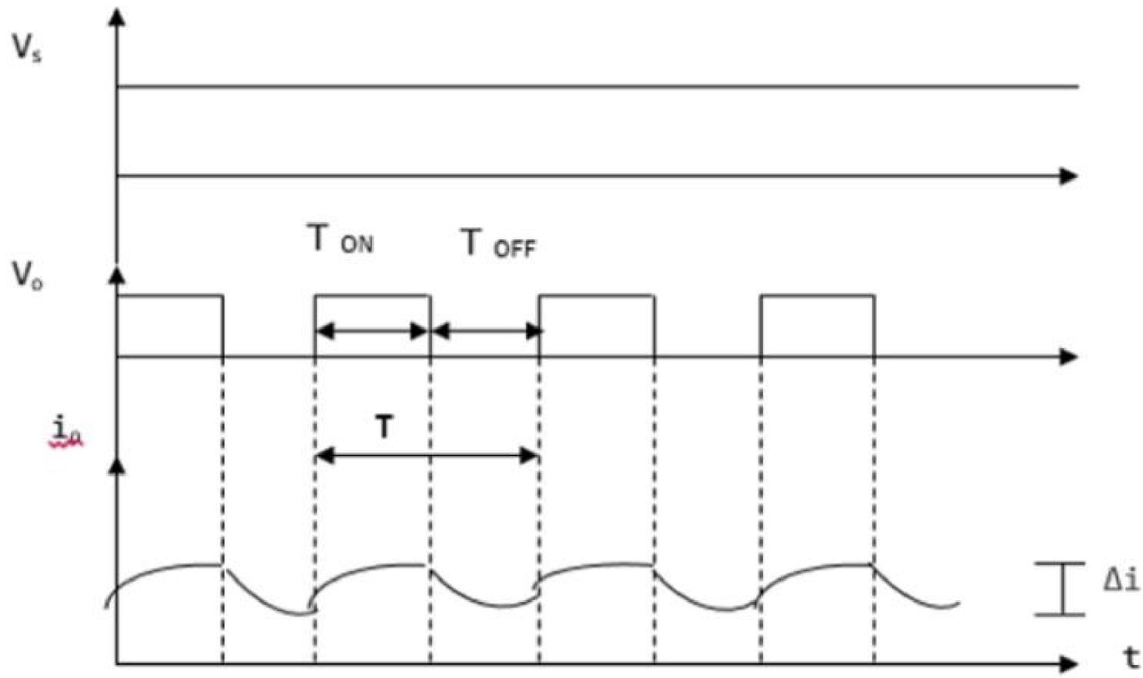
$$= \frac{V_S - (1-D)D}{Lf}$$

$$f = \frac{1}{T} = \text{ chopping frequency}$$

## Current and Voltage Waveforms

The current and voltage waveforms are given below −

For a step down chopper the voltage output is always less than the voltage input. This is shown by the waveform below.




CONTROL MODES OF CHOPPER

In DC-DC converters, the average output voltage is controlled by varying the alpha (α) value.
This is achieved by varying the Duty Cycle of the switching pulses.
Duty cycle can be varied usually
in 2 ways:
1. Time Ratio Control
2. Current Limit Control

In this post we shall look upon both the ways of varying the duty cycle.
Duty Cycle is the ratio of ‘On Time’ to ‘Time Period of a pulse’.

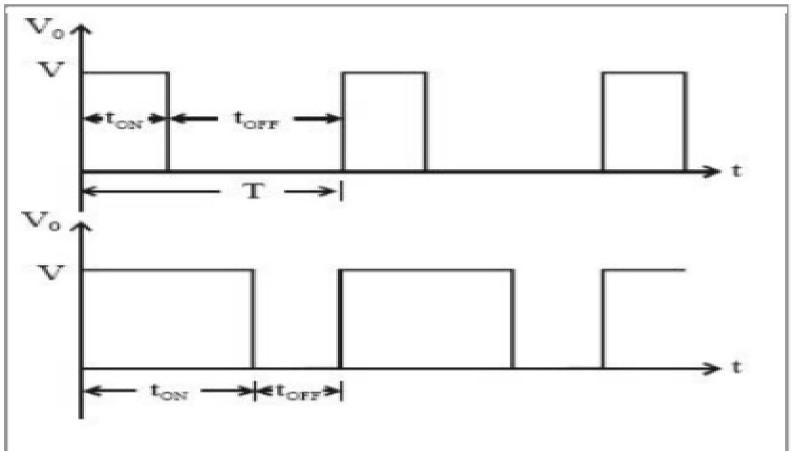
**Time Ratio Control:**

As the name suggest, here the time ratio (i.e. the duty cycle ratio Ton/T) is varied.
This kind of control can be achieved using 2 ways:

- Pulse Width Modulation (PWM)
- Frequency Modulation Control (FMC)

Pulse Width Modulation (PWM):

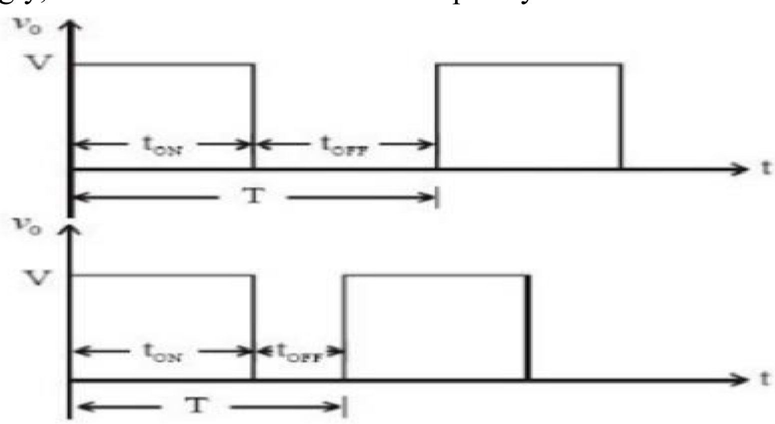
In this technique, the time period is kept constant, but the ‘On Time’ or the ‘OFF Time’ is varied. Using this, the duty cycle ratio can be varied. Since the ON time or the ‘pulse width’ is getting changed in this method, so it is popularly known as Pulse width modulation.



Pulse Width Modulation

## Frequency Modulation Control (FMC)

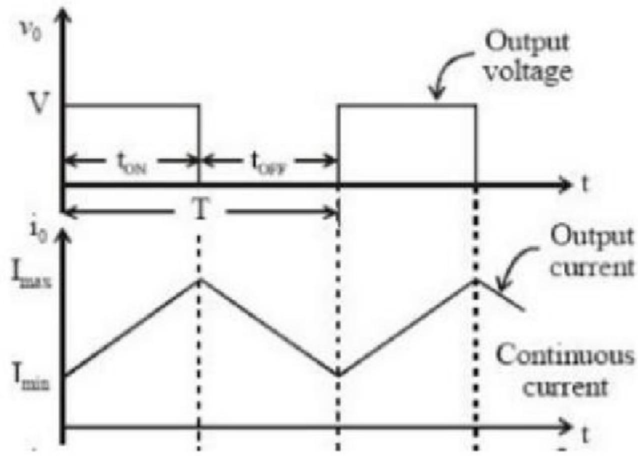
In this control method, the 'Time Period' is varied while keeping either of 'On Time' or 'OFF time' as constant. In this method, since the time period gets changed, so the frequency also changes accordingly, so this method is known as frequency modulation control.



Frequency Modulation Control

## Current Limit Control:

As is obvious from its name, in this control strategy, a specific limit is applied on the current variation. In this method, current is allowed to fluctuate or change only between 2 values i.e. maximum current (I max) and minimum current (I min). When the current is at minimum value, the chopper is switched ON. After this instance, the current starts increasing, and when it reaches up to maximum value, the chopper is switched off allowing the current to fall back to minimum value. This cycle continues again and again.




Current Limit Control

## OPERATION OF CHOPPER IN ALL FOUR QUADRANTS

CHOPPERCONFIGURATION AND QUADRANT OF OPERATION
The configuration of chopper is done according to direction of output voltage and output current.

**Type A Chopper**

The output voltage and current both are positive in the Type A chopper.
It works in the first quadrant.
The Type A chopper works as forward drive.

**Type B Chopper**

The output voltage is positive but output current negative in the Type B chopper.
The power flow from load to supply side. It works in second quadrant.
This Type of chopper is used in the regenerative braking of DC Motor.

**Type C Chopper**

The load current is either positive or negative but load voltage remains positive in the Type C chopper.
This type of chopper works in first and second quadrant.
The Type C chopper is combination of both Type A and Type B chopper.

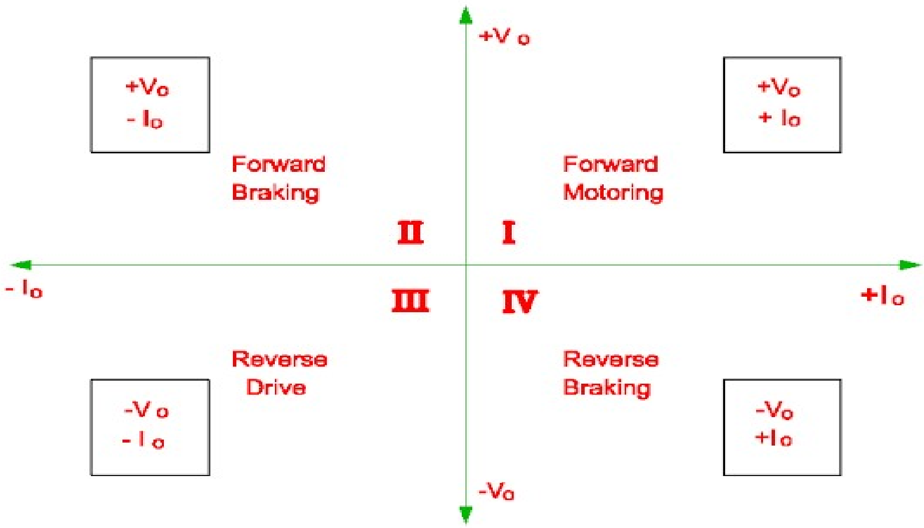
**Type D Chopper**

The load voltage is either positive or negative but load current always positive in the Type D chopper.
This chopper works in first as well as fourth quadrant.

**Type E Chopper**

The load voltage and load current are either positive or negative in the Type E chopper.
This type of chopper works in all quadrants. It is a combination of two Type C quadrants.
Forward Drive
If the chopper works in first quadrant, it is called as forward drive because the output voltage and current both are positive in this quadrant.
Reverse Drive

If the chopper works in third quadrant, it is called as reverse drive because the output voltage and current both are negative in this quadrant.
The DC motor works as DC generator in the second and fourth quadrant because the power flows from load to supply side in this quadrant.

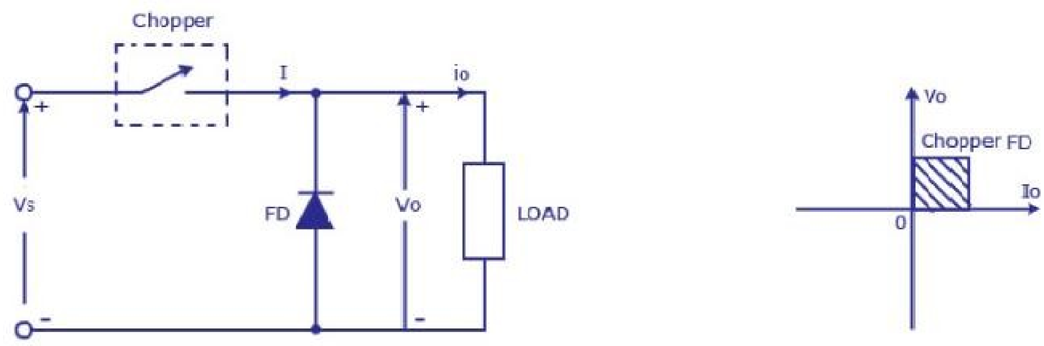



CHOPPER CONFIGURATION

**TYPE A, B, C, D AND E CHOPPER**

**Type A Chopper or First–Quadrant Chopper**

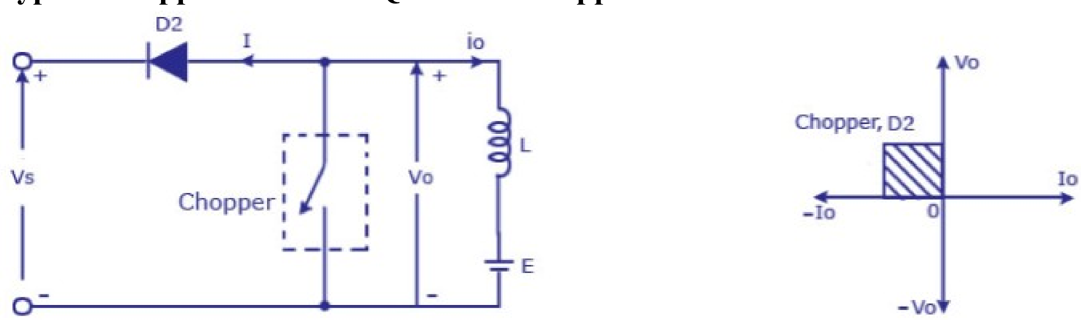
This type of chopper is shown in the figure. It is known as first-quadrant chopper or type A chopper. When the chopper is on, v0 = VS as a result and the current flows in the direction of the load. But when the chopper is off v0 is zero but I0 continues to flow in the same direction through the freewheeling diode FD, thus average value of voltage and current say V0 and I0 will be always positive as shown in the graph.




Chopper First Quadrant

In type A chopper the power flow will be always from source to the load. As the average voltage $V_0$ is less than the dc input voltage $V_s$

**Type B Chopper or Second-Quadrant Chopper**

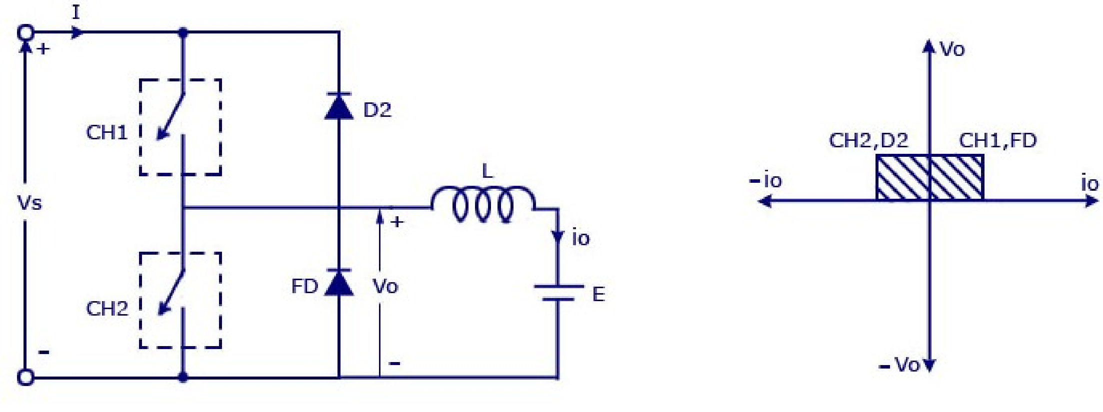



Chopper Second Quadrant

In type B or second quadrant chopper the load must always contain a dc source E. When the chopper is on, $v_0$ is zero but the load voltage E drives the current through the inductor L and the chopper, L stores the energy during the time $T_{on}$ of the chopper. When the chopper is off, $v_0$ =( E+ L . *di/dt)* will be more than the source voltage Vs. Because of this the diode D2 will be forward biased and begins conducting and hence the power starts flowing to the source. No matter the chopper is on or off the current $I_0$ will be flowing out of the load and is treated negative. Since $V_O$ is positive and the current $I_0$ is negative, the direction of power flow will be from load to source. The load voltage $V_0$ = (E+L *.di/dt )* will be more than the voltage $V_s$ so the type B chopper is also known as a step up chopper .

**Type -C chopper or Two-quadrant type-A Chopper**

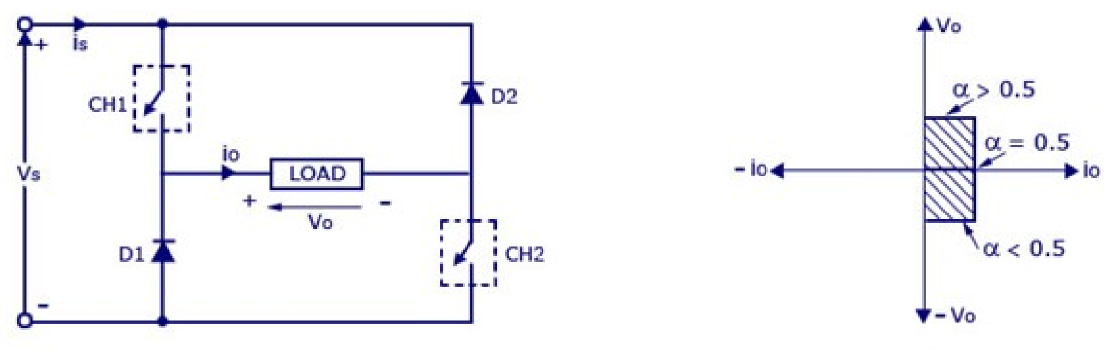
Type C chopper is obtained by connecting type –A and type –B choppers in parallel. We will always get a positive output voltage $V_0$ as the freewheeling diode FD is present across the load. When the chopper is on the freewheeling diode starts conducting and the output voltage $v_0$ will be equal to $V_s$ . The direction of the load current $i_0$ will be reversed. The current $i_0$ will be flowing towards the source and it will be positive regardless the chopper is on or the FD conducts. The load current will be negative if the chopper is or the diode D2 conducts. We can say the chopper and FD operate together as type-A chopper in first quadrant. In the second quadrant, the chopper and D2 will operate together as type –B chopper.




Chopper Two Quadrant

The average voltage will be always positive but the average load current might be positive or negative. The power flow may be life the first quadrant operation ie from source to load or from load to source like the second quadrant operation. The two choppers should not be turned on simultaneously as the combined action my cause a short circuit in supply lines. For regenerative braking and motoring these type of chopper configuration is used.

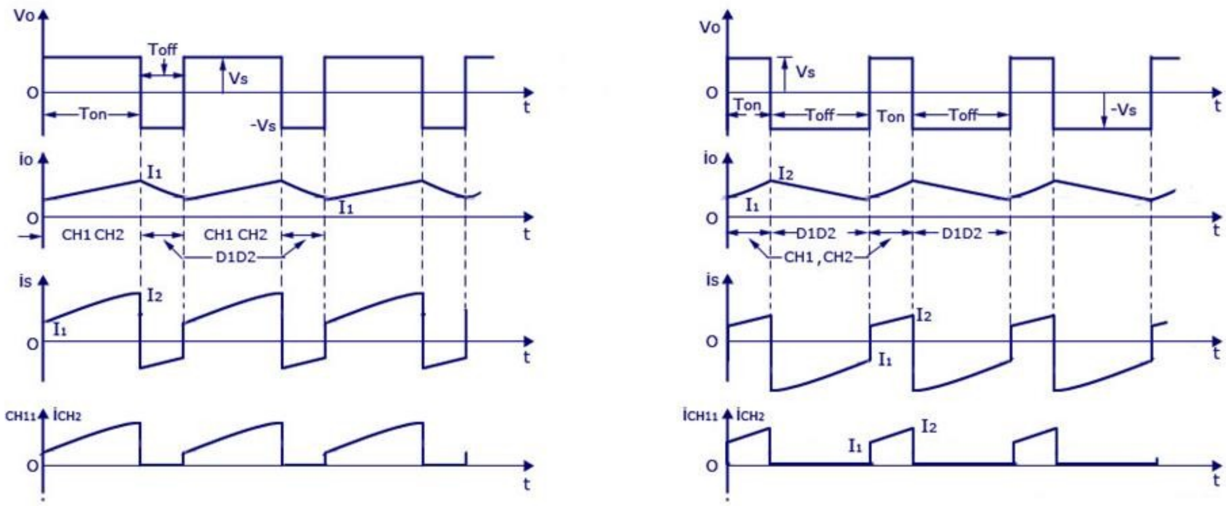
Type D Chopper or Two-Quadrant Type –B Chopper




Two Quadrant Type B-chopper or D-chopper Circuit

**Two Quadrant Type B chopper or D Chopper Circuit**

The circuit diagram of the type D chopper is shown in the above figure. When the two choppers are on the output voltage $v_0$ will be equal to $V_s$ . When $v_0 = -V_s$ the two choppers will be off but both the diodes D1 and D2 will start conducting. $V_0$ the average output voltage will be positive when the choppers turn-on the time $T_{on}$ will be more than the turn off time $T_{off}$ it's shown in the wave form below. As the diodes and choppers conduct current only in one direction the direction of load current will be always positive.



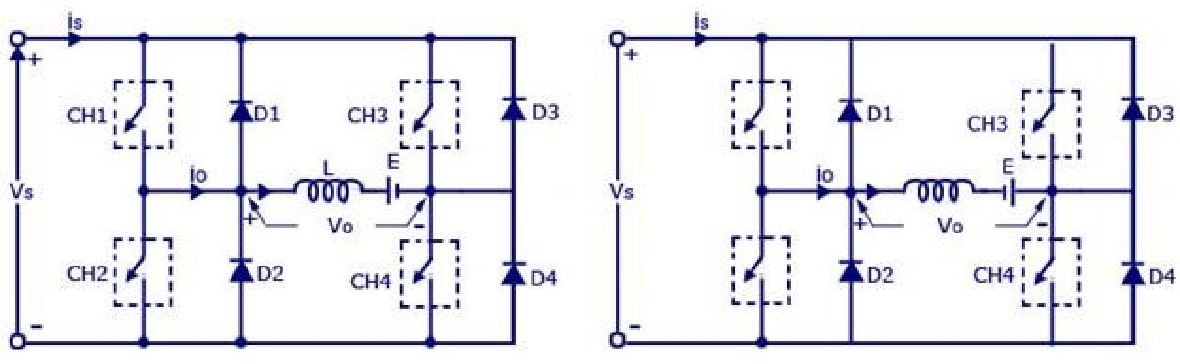

Positive First Quadrant Operation and Negative Fourth Quadrant Operation

The power flows from source to load as the average values of both $v_0$ and $i_0$ is positive. From the wave form it is seen that the average value of $V_0$ is positive thus the forth quadrant operation of type D chopper is obtained.

From the wave forms the Average value of output voltage is given by $V0= (V_s T_{on}-V_s T_{off})/ T = V_s.(T_{on}-T_{off})/T$

**Type –E chopper or the Fourth-Quadrant Chopper**

Type E or the fourth quadrant chopper consists of four semiconductor switches and four diodes arranged in antiparallel. The 4 choppers are numbered according to which quadrant they belong. Their operation will be in each quadrant and the corresponding chopper only be active in its quadrant.




E-type Chopper Circuit Diagram With Load emf E and E Reversed

- **First Quadrant**

During the first quadrant operation the chopper CH4 will be on. Chopper CH3 will be off and CH1 will be operated. AS the CH1 and CH4 is on the load voltage $v_0$ will be equal to the source voltage $V_s$ and the load current $i_0$ will begin to flow. $v_0$ and $i_0$ will be positive as the first quadrant operation is taking place. As soon as the chopper CH1 is turned off, the positive current freewheels through CH4 and the diode D2. The type E chopper acts as a step- down chopper in the first quadrant.

- **Second Quadrant**

In this case the chopper CH2 will be operational and the other three are kept off. As CH2 is on negative current will starts flowing through the inductor L . CH2, E and D4. Energy is stored in the inductor L as the chopper CH2 is on. When CH2 is off the current will be fed back to the source through the diodes D1 and D4. Here (E+L.di/dt) will be more than the source voltage $V_{s.}$ In second quadrant the chopper will act as a step-up chopper as the power is fed back from load to source

- **Third Quadrant**

In third quadrant operation CH1 will be kept off , CH2 will be on and CH3 is operated. For this quadrant working the polarity of the load should be reversed. As the chopper CH3 is on, the load gets connected to the source $V_s$ and $v_0$ and $i_0$ will be negative and the third quadrant operation will takes place. This chopper acts as a step-down chopper

- **Fourth Quadrant**

CH4 will be operated and CH1, CH2 and CH3 will be off. When the chopper CH4 is turned on positive current starts to flow through CH4, D2, E and the inductor L will store energy. As the CH4 is turned off the current is feedback to the source through the diodes D2 and D3, the operation will be in fourth quadrant as the load voltage is negative but the load current is positive. The chopper acts as a step up chopper as the power is fed back from load to source.

# 3. UNDERSTAND THE INVERTERS AND CYCLO-CONVERTERS

## INVERTERS

A device that converts de power into ac power at desired output voltage and frequency is called an inverter. Some industrial applications of inverters are for adjustable-speed ac drives, induction heating, stand by air-craft power supplies, UPS (uninterruptible power supplies) for computers, hvdc transmission lines etc

## CLASSIFY INVERTERS.

1. Inverters can be broadly classified into two types;

Voltage source inverters and current source inverters. A voltage-fed inverter (VFl), or voltage-source inverter (VSl), is one in which the dc source h small or negligible impedance. In other words, a voltage source inverter has stiff de voltage source at its input terminals.

A current-fed inverter (CFI) or current-source inverter (CSl) is fed with adjustable current from a dc source of high impedance, i.e. from a stiff dc current source. In: a CSI fed with stiff current source, output current waves are not affected by the load.

2. From the viewpoint of connections of semiconductor devices, inverters are classified as under:
   1. Bridge inverters 2. Series inverters 3. Parallel inverters
3. According to the Type of Load
   Single-phase Inverter
   Three-phase Inverter
4. According to the Number of Levels at the Output
   Regular Two-Level Inverter
   Multi-level Inverter

EXPLAIN THE WORKING OF SERIES INVERTER.

Series Inverter (Load Commutated Inverter or Self Commutated Inverter)

The commutating components L and C are connected in series with the load therefore this inverter is called as SERIES INVERTER.

The value of commutating components is selected such that the circuit becomes under damped.

The anode current itself becomes zero in this inverter resulting the SCR turns off automatically therefore this inverter is also called as SELF COMMUTATED OR LOAD COMMUTATED INVERTER.

Power Circuit Diagram

The power circuit diagram of the series inverter is shown in the figure A. The SCR T1 and SCR T2 are turned on at regular interval in order to achieve desirable output voltage and output frequency.

The SCR T2 is kept off at starting condition and polarity of voltage across capacitor is shown in the figure A.

The operation of the series inverter is explained as follows.

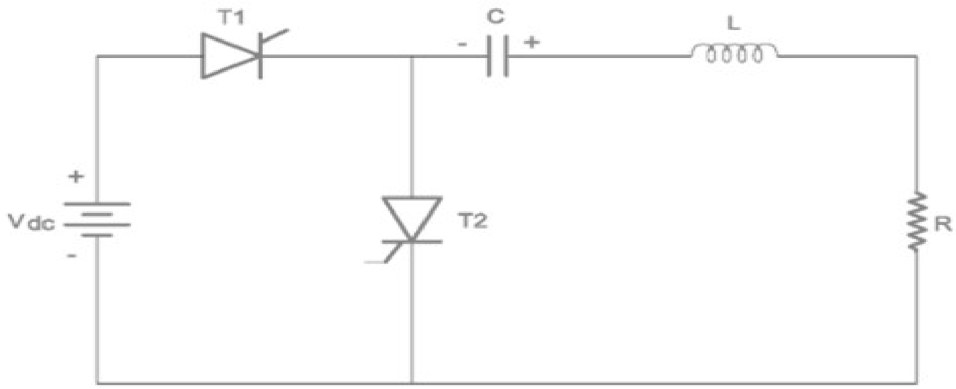



FIGURE A : BASIC SERIES INVERTER

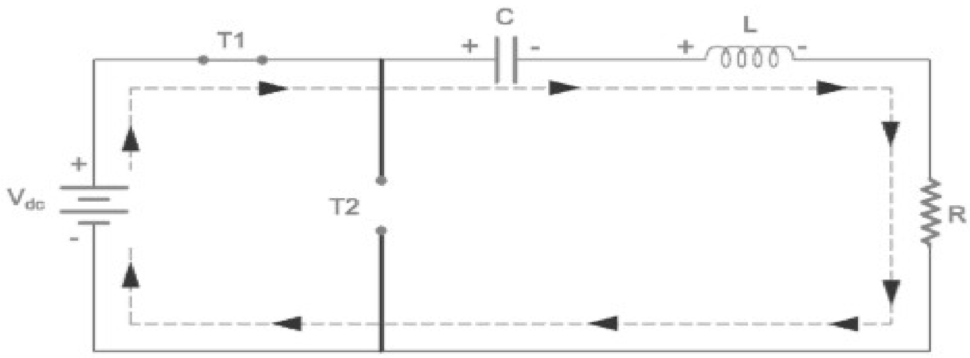



FIGURE B : EQUIVALENT CIRCUIT WHEN SCR T1 'ON'

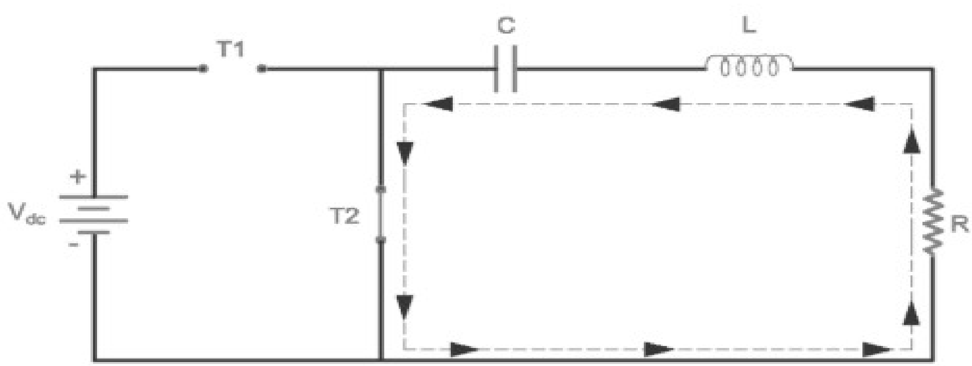



FIGURE C : EQUIVALENT CIRCUIT WHEN SCR T2 'ON'

Operation

Mode 1

The voltage $V_{dc}$ directly applies to RLC series circuit as soon as the SCR T1 is turned on.

The polarity of capacitor charging is shown in the figure B.

The nature of the load current is alternating as there is under damped circuit of the commutating components.

The voltage across capacitor becomes + $V_{dc}$ when the load current becomes maximum.

The voltage across capacitor becomes $+2V_{dc}$ when the load current becomes zero at point a ( figure D ).

The SCR T1 automatically turns off at point a because the load current becomes zero.

Mode 2

The load current becomes zero from point a to b as the SCR T1 turns off in this time period.
The SCR T1 and SCR T2 are turned off in this time duration and voltage across capacitor becomes equal to +2 $V_{dc}$.

Mode 3

The SCR T2 is turned on at point b due to it receives positive capacitor voltage.
The discharging of capacitor is done through SCR T2 and R – L circuit as shown in the figure C.
The load current becomes zero after it becomes maximum in the negative direction.
The capacitor discharges from +2 $V_{dc}$ to – $V_{dc}$ during this time and SCR T2 turns off automatically at point C due to load current becomes zero.
The SCR T2 turns off during point C to D and SCR T1 again turns on. This way cycle repeat after it complete one turns.
The positive AC output voltage half cycle generates due to DC voltage source whereas negative half cycle generates due to capacitor.
There is always some time delay kept between one SCR turned on time and other SCR turned on time.
The DC output gets short circuited due to continuous conduction of both SCRs if there is no time delay between SCRs.
The time duration ab and cd must be greater than the SCR specific turn off time and it is called as dead zone.

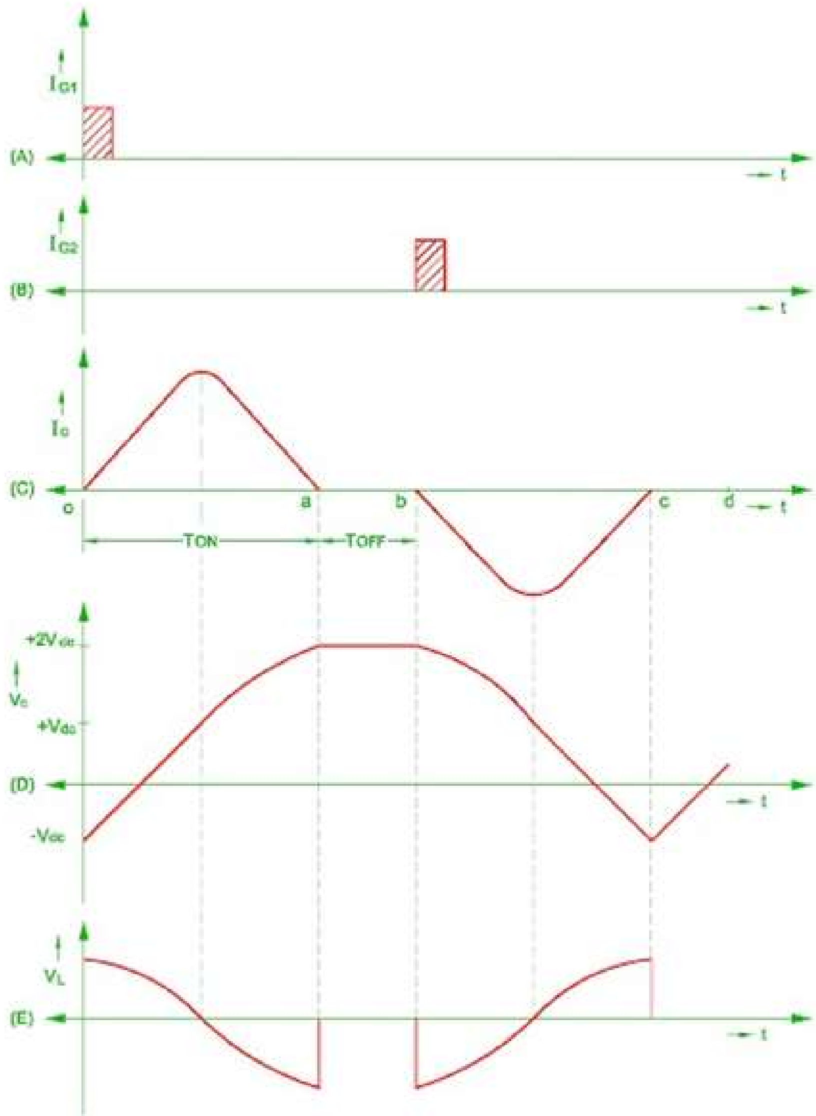



FIGURE D : VOLTAGE AND CURRENT WAVEFORMS OF SERIES INVERTER
(A) Gate pulse for SCR T1 (B) Gate pulse for SCR T2 (C) output current,
(D) Capacitor voltage (E) Load voltage

**Limitations of Series Inverter**

The limitation of series inverter is as given below.

The load current flows only during positive half cycle from supply source.

The DC supply source gets short circuited if SCR T1 and SCR T2 simultaneously turned on.

The rating of commutating components should high because the load current flows through it.

The load voltage waveform gets distorted if the dead zone time or SCR turns on time high.

The maximum output frequency of the inverter should be less than the ringing frequency.

The DC supply source is short circuited if the output frequency of the inverter is higher than the ringing frequency.

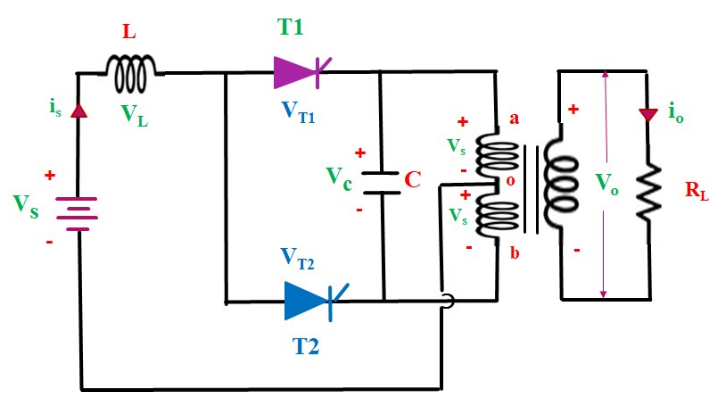
The maximum current during each high cycle and its time duration depends upon parameter of load this will result in poor regulation of the inverter output.

Applications

- This type of inverter generates sinusoidal waveform whose output frequency is in the range of 200 Hz to 100 kHz therefore it is applicable for
- Induction heating
- Sonar transmitter
- Fluorescent lighting and
- Ultrasonic generator

EXPLAIN THE WORKING OF PARALLEL INVERTER

Parallel inverter circuit consist of two thyristor T1 and T2, a transformer, inductor L and a commutating component C. Capacitor (C) is connected in parallel with the load via transformer therefore it is called a parallel inverter. And inductor (L) is connected in series with supply to make the source current constant. Here we also use a center -tapped transformer. Centre tapping is done in the primary winding of transformer so, primary winding is divided into two equal halves ao and ob.

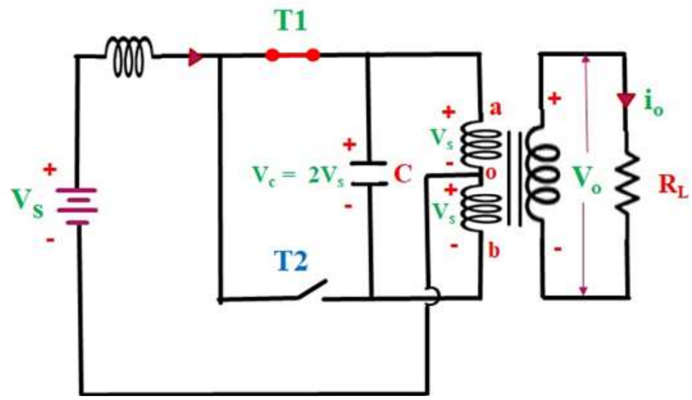



**Circuit Diagram of Parallel Inverter**

**Operation of Parallel Inverter:**

**The operation is divided into four modes:**

**Mode I (0< t < t1):** In this mode we give firing pulse to thyristor T1 and T1 get turned on and T2 is turned off. Current flow from Supply Vs …. T1…. ao (upper half of primary winding) …. back to Vs. As a result, Vs voltage is induced across upper as well as lower half of the primary winding of transformer. And Vs voltage is induced in secondary winding.

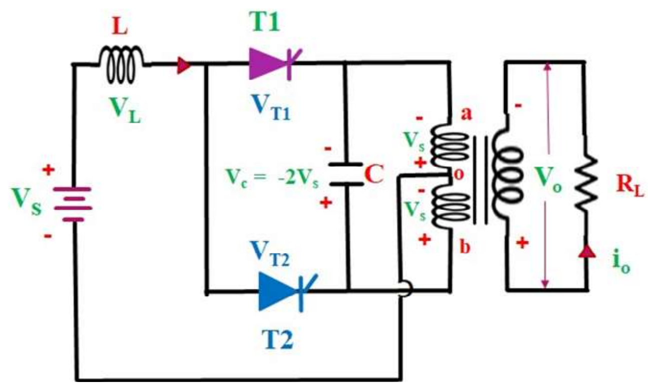



**Mode I – Operation where T1 ON and T2 OFF**

**So, output voltage across load is Vs.**

So, the total voltage across primary winding is 2Vs. Here capacitor is connected in parallel with primary winding therefore capacitor charge with 2Vs voltage with upper plate is positive and lower plate is negative.

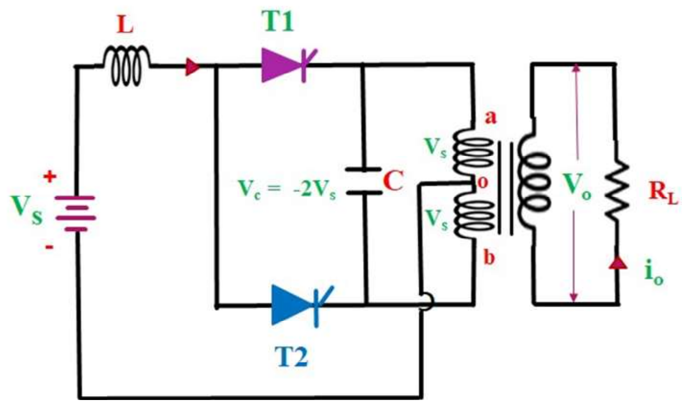
**Mode II (t1< t < t3):** In this duration we give firing pulse to thyristor T2 and T2 get turned on. At this time capacitor start discharging through T1 therefore T1 turned OFF. This time current flow from supply Vs …. T2…. bo (lower half of primary winding) …. back to Vs.




**Mode II – Operation**

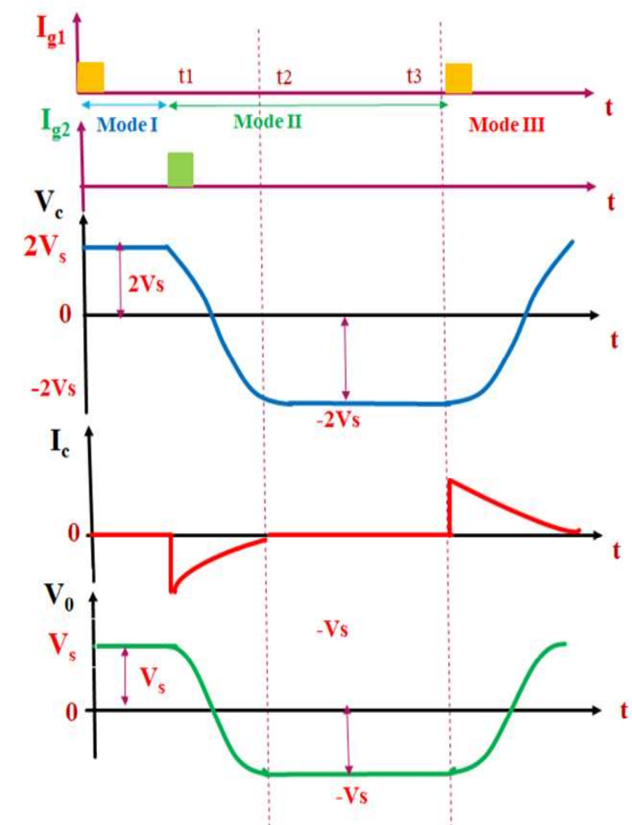
Now this time capacitor charged with upper plate is negative, from +2Vs at t=t1 to -2Vs at t=t2. Load voltage also changes from Vs at t=t1 to -Vs at t=t2. After t=t2 voltage across capacitor is maintain constant -2Vs between t= t2 to t3.So, load voltage is also constant -Vs.

**Mode III (t3< t < t4):** In this mode again, we give firing pulse to thyristor T1 and T1 get turned on. At this time capacitor start discharging through T2 therefore T2 turned OFF. This time current flow from supply Vs …. T1…. ao (upper half of primary winding) …. back to Vs. So, the total voltage across primary winding is 2Vs.




**Mode III – Operation**

Now this time capacitor charged with upper plate is positive, from -2Vs at t=t3 to +2Vs at t=t4. Load voltage also changes from Vs at t=t3 to -Vs at t=t4.So, output voltage across load is Vs.




Waveform of parallel Inverter 1) Ig1 is the gate current given to T1 2) Ig2 is the gate current given to T2. 3) Vc capacitor voltage 4) Ic current across capacitor 5) Vo output voltage waveform

**EXPLAIN THE WORKING OF SINGLE-PHASE BRIDGE INVERTER.**

Single phase half bridge inverter

Circuit Description:-

- Two Thyristor S1 and S2 are used along with two feedback diode D1 and D2 respectively.
- Resistive load is connect between point A and B, as shown in fig:-
- Supply voltage is divided into 2 parts, here two DC voltage source are used V/2 and V/2.
- Fig of the single phase half bridge inverter is given below:

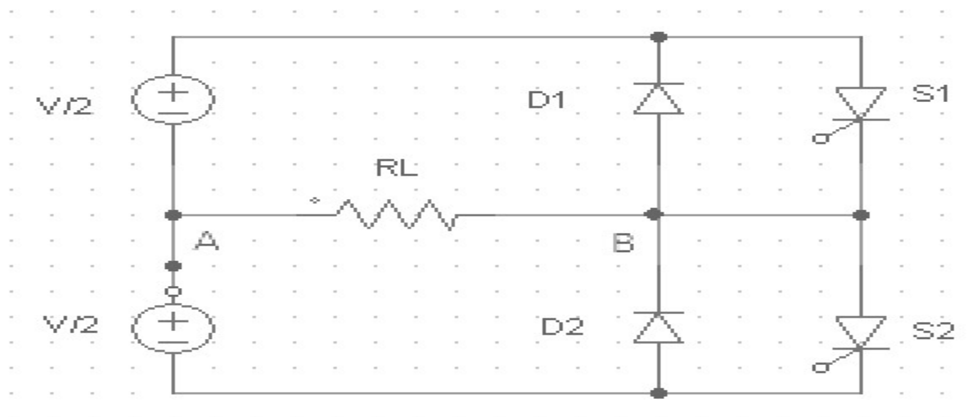



Fig : Single phase half bridge inverter

Working:

- Mode 1 (0 to T/2):-

- During this mode switch S1 is ON and switch S2 is OFF From period 0 to T/2.
- Current flowing path during this mode is V/2-S1-B-R(Load resistor)-A-V/2.
- Hence the voltage across the load is positive V/2

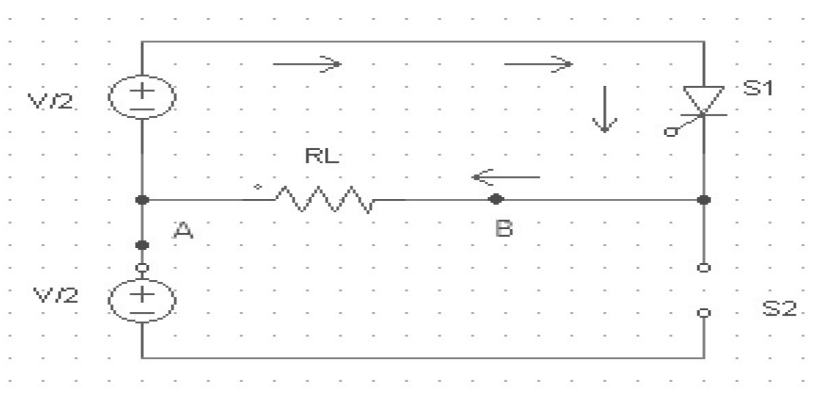



Fig: conducting mode 1

Mode 2 (T/2 to T):-

- During this mode switch S1 is OFF and switch S2 is ON From period T/2 to T.
- Current flowing path during this mode is V/2-A-R(Load resistor)-B-S2-V/2.
- Hence the voltage across the load is negative V/2.

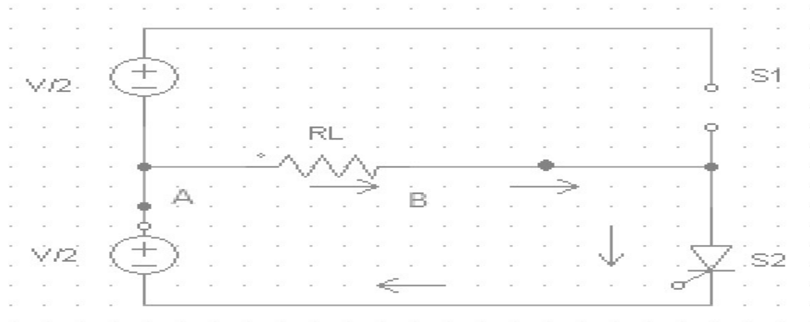



Fig: conducting mode 2

1. Load is resistive hence it does not store any charge therefore feedback diode D1 and D2 are not effective here.
2. The main drawback of half bridge inverter is that two DC voltage source are require. By using full bridge inverter we can overcome that drawback.

Waveform of output voltage thyristor current with resistive load are shown in fig

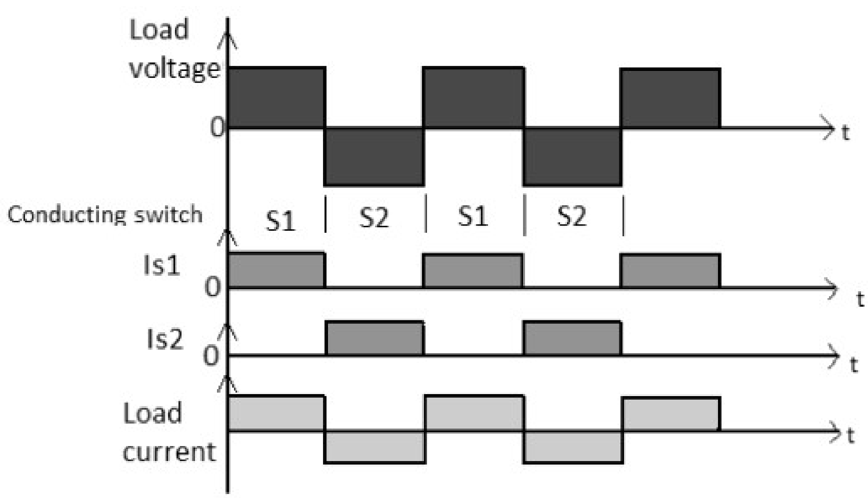



fig: waveform single phase half bridge inverter

Single phase Full bridge inverter

Circuit Description:-

- Four thyristor are used in full bridge inverter. Thyristor S1 and S2 are used along with two feedback diode D1 and D2 and thyristor S3 and S4 are used along with another two feedback diode D3 and D4 respectively.
- Resistive load is connect between point A and B,as shown in fig:-
- DC voltage source is applied to circuit.
- Fig of the single phase full bridge inverter is given below:

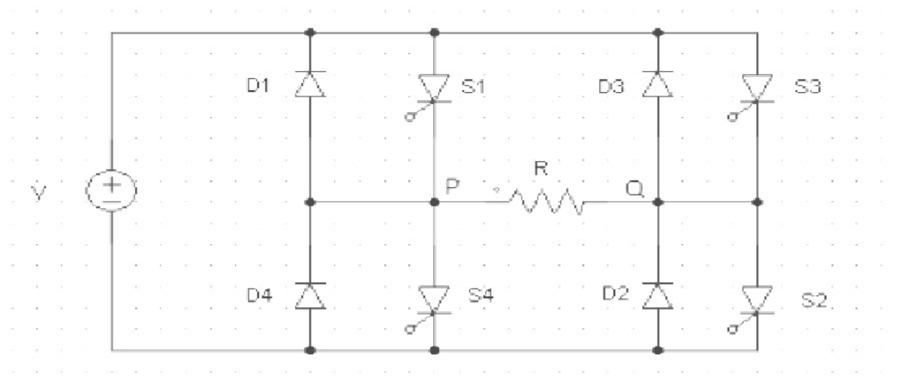
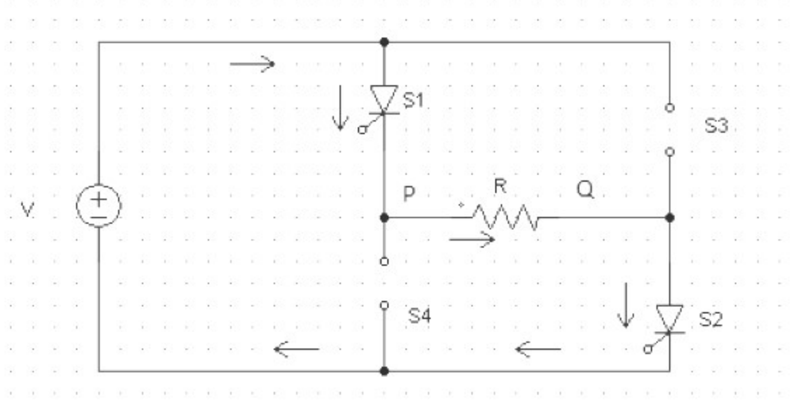



Fig: single phase full bridge inverter

**Mode 1 (0 to T/2):-**

- During this mode switch S1 and switch S2 are ON and switch S3 and switch S4 are OFF From period 0 to T/2.
- Current flowing path during this mode is Vdc – S1- P -R(load reistor) – Q – S2 – Vdc.
- Voltage across the load resistor is positive Vdc




fig; conducting mode 1

**Mode 2 (T/2 to T):-**

- During this mode switch S3 and switch S4 are ON and switch S1 and switch S2 are OFF From period T/2 to T.
- Current flowing path during this mode is Vdc – S3 – Q – R(load reistor) – P – S4 – Vdc.
- Voltage across the load resistor is negative Vdc.

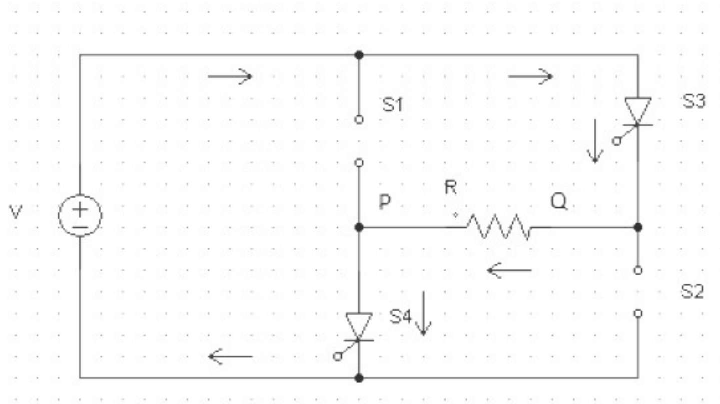



fig : conducting mode 2

1. Load is resistive hence it does not store any charge. therefore, feedback diode D1, D2, D3 and D4 are not effective here.

Waveform of output voltage thyristor current with resistive load are shown in fig:

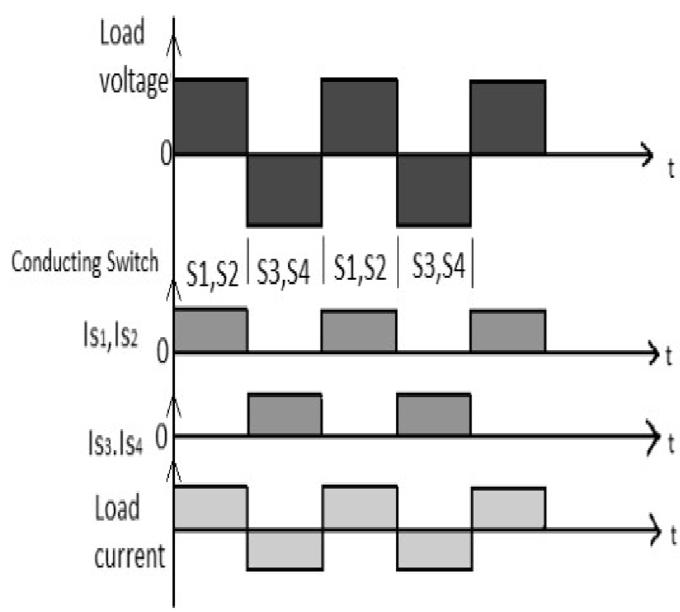



Fig: waveform single phase full bridge inverter

## EXPLAIN THE BASIC PRINCIPLE OF CYCLO-CONVERTER

Cyclo-converters are AC to AC converters and are used to vary the frequency of a supply to a desired load frequency. A cycloconverter achieves this through synthesizing the output waveform from segments of the AC supply (without an intermediate DC link). These are naturally commutated, direct frequency converters that use naturally commutated thyristors. These are mainly used in high power applications up to tens of megawatts for frequency reduction.

Some of the applications of Cyclo-converter include high power AC drives, propulsion systems, high frequency induction heating, synchronous motors in sea and undersea vehicles, electromagnetic launchers, etc.

## EXPLAIN THE WORKING OF SINGLE-PHASE STEP UP & STEP DOWN CYCLO-CONVERTER.

### STEP-DOWN CYCLOCONVERTER

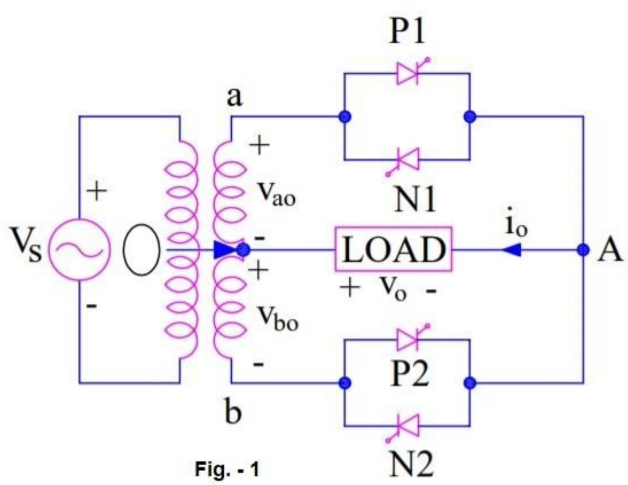
Step-down cycloconverter is a device which steps down the fixed frequency power supply input into some lower frequency. It is a frequency changer. If $f_s$ & $f_o$ are the supply and output frequency, then $f_o < f_s$ for this cycloconverter.

The most important feature of step-down cycloconverter is that it does not require force commutation. Line or Natural Commutation is used which is provided by the input AC supply.

Circuit Diagram:

There are two circuit configurations of a step-down cycloconverter: Mid-point and Bridge type**.** This article focuses on the mid-point type. The operation for continuous and discontinuous type of RL load is explained for mid-point type cycloconverter.

Figure below shows the circuit diagram of mid-point type cycloconverter. The positive direction of voltage and current are marked in the diagram.




Working of Step-down Cycloconverter:

The working principle of step-down cycloconverter is explained for discontinuous and continuous load current. The load is assumed to be comprised of resistance (R) & inductance (L).

**Discontinuous Load Current:**

For positive cycle of input AC supply, the terminal A is positive with respect to point O. This makes SCRs P1 forward biased. The forward biased SCR P1 is triggered at ωt = 0. With this, load current $i_o$ starts building up in the positive direction from A to O. Load current $i_o$ becomes zero at $\omega t = \beta > \pi$ but less than $(\pi+\alpha)$. Refer figure-2. The thyristor P1 is thus, naturally commutated at $\omega t = \beta$ which is already reversed biased after π.

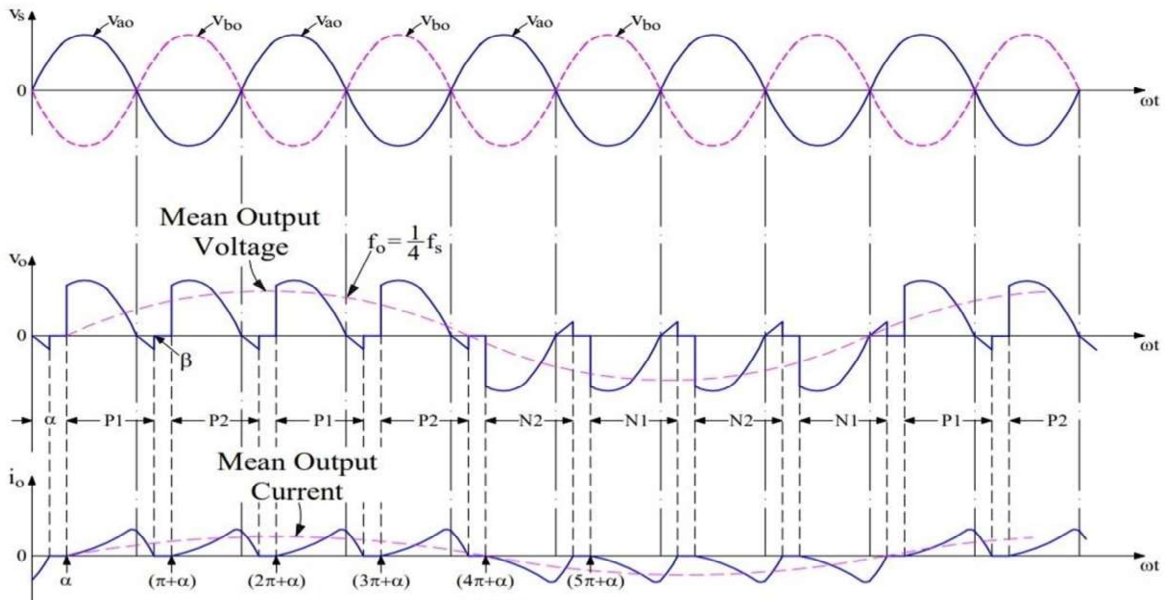


Fig.-2

After half a cycle, b is positive with respect to O. Now forward biased thyristor P2 is fired at $\omega t = (\pi+\alpha)$. Load current is again positive from A to O and builds up from zero as shown in figure-2. At $\omega t = (\pi+ \beta)$, $i_o$ decays to zero and P2 is naturally commutated. At $\omega t = (2\pi+\alpha)$, P is again turned ON. Load current in figure-2 is seen to be discontinuous.

After four positive half cycles of load voltage and load current, thyristor N2 is gated at $(4\pi+\alpha)$ when O is positive with respect to b. As N2 is forward biased, it starts conducting but the direction of load current is reverse this time i.e. it flows from O to A. After N2 is triggered, O is positive with respect to “a” but before N1 is fired, $i_o$ decays to zero and N2 is naturally commutated. Now when N1 is gated at $(5\pi+\alpha)$, $i_o$ again builds up but it decays to zero before thyristor N2 in sequence is again gated.

In this manner, four negative half cycles of load voltage and load current, equal to number of positive half cycles of load voltage & current, are generated. Now P1 is again triggered to fabricate four positive half cycles of load voltage and so on. It may be noted that, natural commutation is achieved for discontinuous current load.

Form figure-2, the waveform of mean load voltage & current may be noted. It is clear that the output frequency of load voltage & current is (¼) times of input supply frequency.

**STEP-UP CYCLOCONVERTER**

Working Principle of Step-up Cycloconverter:

The working principle of a step-up cycloconverter is based on switching of thyristors in a proper sequence. The thyristor acts as a power switch. These switches are arranged is a specific pattern

so that the output power is available for both the positive and negative half of the input power supply. Forced commutation technique is used to turn OFF the conducting thyristor.
Two circuit configurations are possible for step-up cycloconverter: Mid-point Type and Bridge Type**.** In this article, we will consider mid-point type of circuit arrangement for better understanding of working principle.
Circuit Diagram:
Figure below shows the circuit diagram of Mid-point step-up cycloconverter:

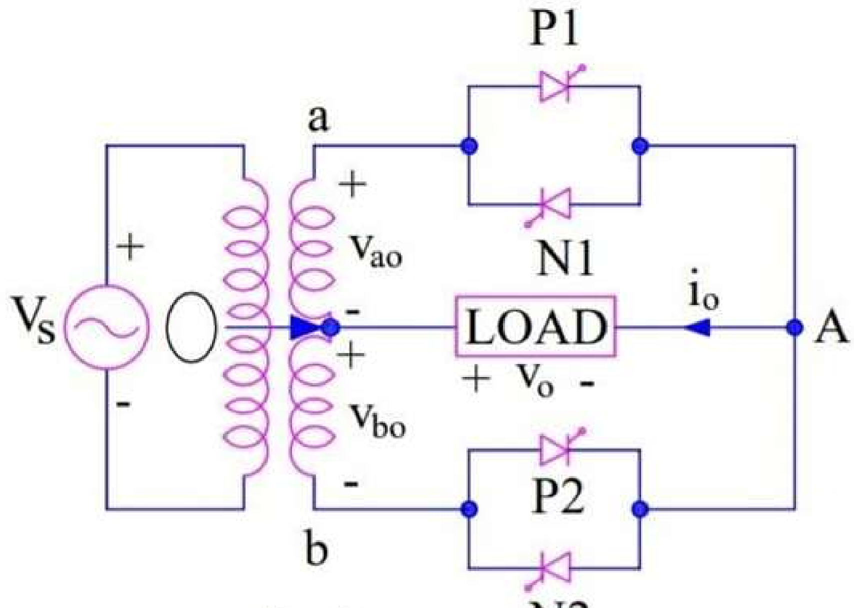


Fig. - 1

The circuit consists of a single phase transformer with mid tap on the secondary winding and four thyristors. Two of these thyristors P1 & P2 are for positive group. Here positive group means when either P1 or P2 conducts, the load voltage is positive. Other two thyristors N1 & N2 are for negative group. Load is connected between secondary winding mid-point O and terminal A. The load is assumed resistive for simplicity. Assumed positive direction for voltage and current are marked in the circuit diagram.

Operation of Step-up Cycloconverter:
During the positive half cycle of input supply voltage, positive group thyristors P1 & N2 are forward biased for $\omega t = 0$ to $\omega t = \pi$. As such SCR P1 is fired to turn it ON at $\omega t = 0$ such that load voltage is positive with terminal A positive and O negative. The load voltage, thus, follows the positive envelop of the input supply voltage. At some time instant $\omega t = \omega t_1$, the conducting thyristor P1 is force commutated and the forward biased thyristor N2 is fired to turn it ON. During the period N2 conducts, the load voltage is negative because O is positive & A is negative this time. The load or output voltage traces the negative envelop of the supply voltage. This is shown in figure below.

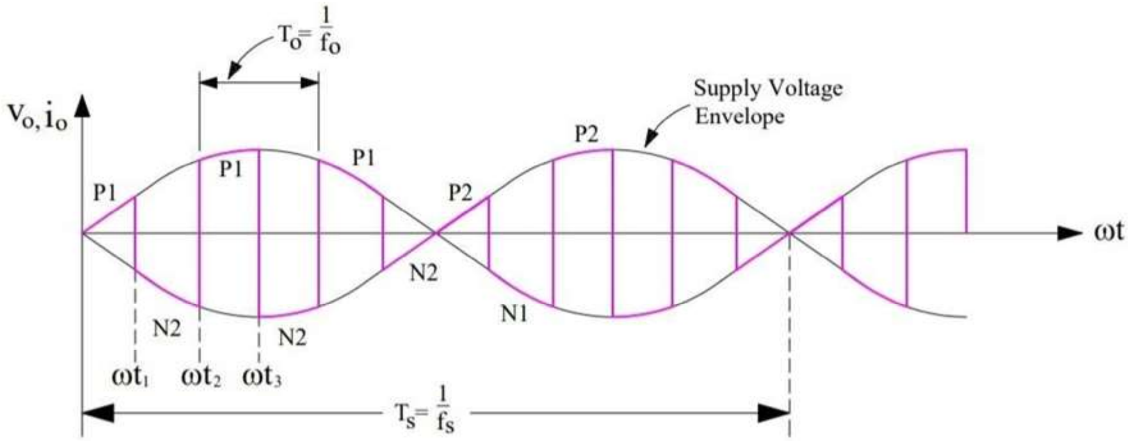


Fig. - 2

At $\omega t = \omega t_2$, N2 is force commutated and P1 is turned ON. The load voltage is now positive and follows the positive envelop of the supply voltage. At $\omega t = \pi$, terminal "b" is positive with respect to terminal "a"; both SCRs P2 & N1 are therefore forward biased from $\omega t = \pi$ to $\omega t = 2\pi$. AT $\omega t = \pi$, N2 is force commutated and forward biased SCR P2 is turned ON. The load voltage is positive and follows the positive envelop of supply voltage.

If the supply frequency is $f_s$ and output frequency is $f_o$, P2 will be force commutated at $\omega t = (1/2f_s) + (1/2f_o)$. Carefully note this from the waveform shown in the figure-2.

When P2 is force commutated, forward biased SCR N1 is turned ON. This time, the load voltage is negative and follows the negative envelop of the supply input.

In this manner, SCRs P1, N2 for the first half cycle; P2, N1 in the second half cycle and so on are switched alternately between positive and negative envelops at a high frequency. This results in output frequency $f_o$ more than the input supply frequency $f_s$. In our example of figure-2, note that there is a total of 6 cycles of output in one cycle of input supply. This means that frequency of output voltage is 6 times of input frequency i.e. $f_o = 6f_s$.

## APPLICATIONS OF CYCLO-CONVERTER.

Application of Cycloconverter:

The general use of cycloconverter is to provide either a variable frequency power from a fixed input frequency power as in AC motor speed control or a fixed frequency power from a variable frequency power as in aircraft or wind generators.

Some of the major applications of cycloconverter are as follows:

- Speed control of high power AC drives
- Induction heating
- Static VAR compensation
- It is used for converting variable speed alternator voltage to constant frequency output voltage for use as power supply in aircrafts or shipboards.

# 4. UNDERSTAND APPLICATIONS OF POWER ELECTRONIC CIRCUITS

## LIST APPLICATIONS OF POWER ELECTRONIC CIRCUITS.

- Our Daily Life: If we look around ourselves, we can find a whole lot of power electronics applications such as a fan regulator, light dimmer, air-conditioning, induction cooking, emergency lights, personal computers, vacuum cleaners, UPS (uninterrupted power system), battery charges, etc.
- Automotives and Traction: Subways, hybrid electric vehicles, trolley, fork-lifts, and many more. A modern car itself has so many components where power electronic is used such as ignition switch, windshield wiper control, adaptive front lighting, interior lighting, electric power steering and so on. Besides power electronics are extensively used in modern traction systems and ships.
- Industries: Almost all the motors employed in the industries are controlled by power electronic drives, for eg. Rolling mills, textile mills, cement mills, compressors, pumps, fans, blowers, elevators, rotary kilns etc. Other applications include welding, arc furnace, cranes, heating applications, emergency power systems, construction machinery, excavators etc.
- Defense and Aerospace: Power supplies in aircraft, satellites, space shuttles, advance control in missiles, unmanned vehicles and other defense equipments.
- Renewable Energy: Generation systems such as solar, wind etc. needs power conditioning systems, storage systems and conversion systems in order to become usable. For example solar cells generate DC power and for general application we need AC power and hence power electronic converter is used.
- Utility System: HVDC transmission, VAR compensation (SVC), static circuit breakers, generator excitation systems, FACTS, smart grids, etc.

## LIST THE FACTORS AFFECTING THE SPEED OF DC MOTORS.

According to the speed equation of a d.c. motor we can write,

$$N \propto \frac{E_b}{\phi}$$

or $$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.} \qquad \text{(i)}$$

where $R = R_a$ for shunt motor

$= R_a + R_{se}$. for series motor

The factors affecting DC control are therefore:

- The applied voltage
- The flux

- The voltage across an armature

Considering these factors, speed control can then be achieved through the following techniques:

- Flux control method: This is done by varying the current via the field winding, thus altering the flux.
- Rheostat control: changing the armature route resistance which also changes the applied voltage across the armature.
- Voltage method: changing the applied voltage

**SPEED CONTROL FOR DC SHUNT MOTOR USING CONVERTER.**

Speed Control of DC Shunt Motor

The power circuit diagram for speed control of the DC Shunt Motor is shown in the figure E.

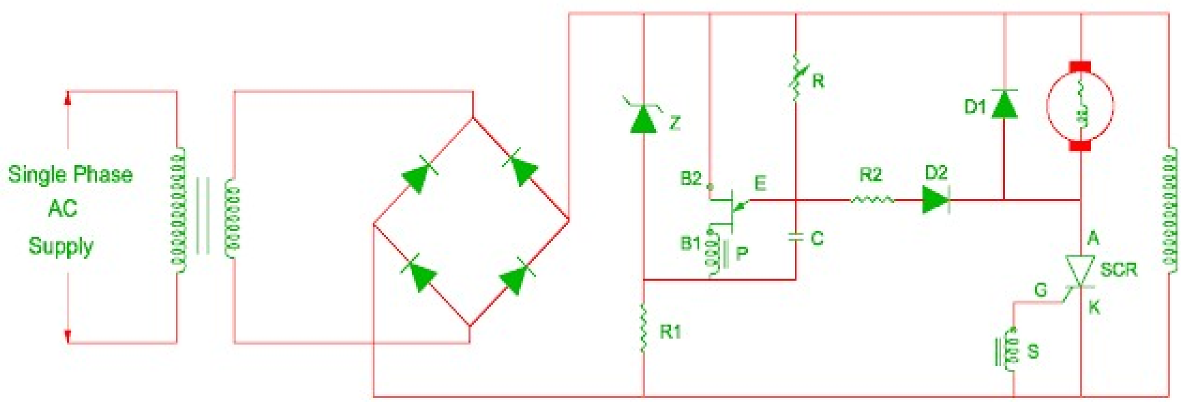



FIG E : Speed control of DC Shunt Motor

1. The function of the bridge rectifier is to converter alternating voltage in to direct voltage.
2. The zener diode clips the voltage and provides constant voltage.
3. The field winding of the DC shunt motor is connected across supply voltage.
4. The SCR is connected in series with the armature winding of the DC shunt motor.
5. The charging of capacitor is done through variable resistor R.
6. When the voltage across capacitor becomes equal to peak point voltage, the UJT turns on.
7. The discharging of capacitor is done through path C – EB1 – Primary of pulse transformer – C.
8. As soon as the pulse transformer primary energies, the SCR gets pulse through pulse transformer secondary.
9. Now the current passes through the armature winding of the DC motor.
10. The charging rate of the capacitor depends upon variable resistor R.
11. If the value of variable R is set minimum, the charging of capacitor done faster resulting UJT turns on in short time.

12. This will resulting the firing angle of the SCR decreases and DC motor speed increases.
13. If the value of resistor R set at maximum, the firing angle of SCR increases and DC motor speed decreases.
14. As the field winding gets constant voltage, the motor speed is directly proportional to back emf.
15. If the armature winding drop is neglected, the speed of the DC motor is directly proportional to armature voltage.
16. The speed of the DC motor is adjusted by the firing angle of the SCR.
17. When the UJT turns on, the diode D2 forward biases and diode D1 reverse biased therefore the charging of capacitor is done only through variable resistor R.
18. The diode D1 reverse biases when current passes through the armature winding.
19. As soon as the current passes through the armature winding becomes zero, the stored energy of armature winding dissipates through diode D1.

Speed Regulation

1. As the motor speed increases, the back emf also increases and diode D2 becomes forward biased in this condition.
2. As the charging path of capacitor and resistor R2 becomes parallel, the charging current of capacitor decreases and firing angle of SCR increases.
3. This will result the speed of motor decreases. If the motor speed decreases by any chance, the back emf decreases.
4. This will result in small current passes through shunt resistor R2 and firing angle of SCR decreases due to charging rate of capacitor increases.
5. The DC shunt motor speed increases due to decrease of firing angle.

SPEED CONTROL FOR DC SHUNT MOTOR USING CHOPPER.

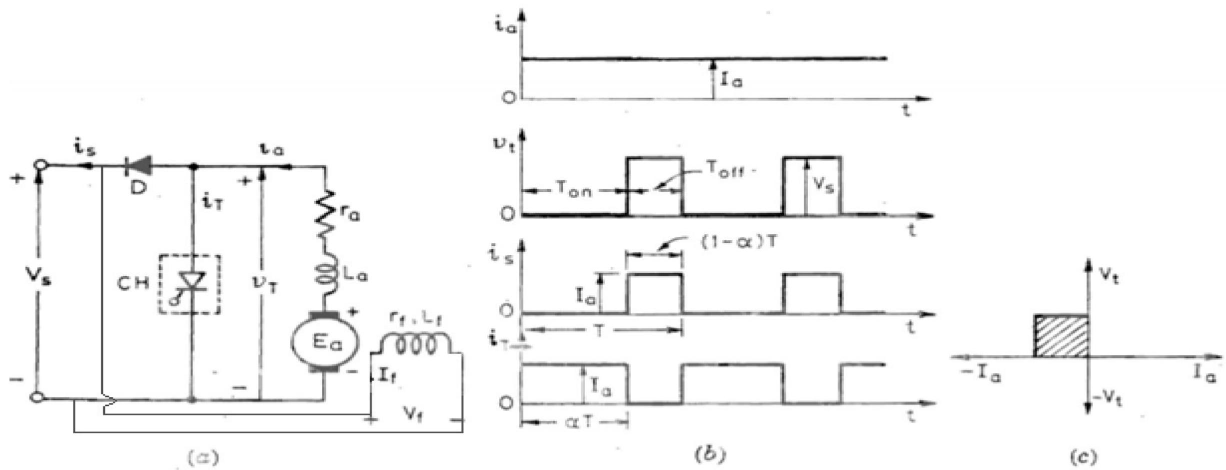
Chopper drive used for single quadrant regenerative braking control

In regenerative-braking control, the motor acts as a generator and the kinetic energy of the motor and connected load is returned to the supply.

During motoring mode, armature current Ia $=\frac{vt-Ea}{r_a}$, i.e. armature current is positive and the motor consumes power. In case load drives the motor at a speed such that average value of motor counter emf Ea ($=k_m.\omega_m$) exceeds Vt, Ia is reversed and power is delivered to the dc bus. The motor is then working as a generator in the regenerative braking mode.

The principle of regenerative braking mode is explained with the help of Fig.(a), where a separately-excited dc motor and a chopper are shown. For active loads, such as a train going down the hill or a descending hoist, let it be assumed that motor counter emf Ea is more than the source voltage Vs When chopper CH is on, current through armature inductance La rises as the armature terminals get short 'circuited through CH. Also, $v_t$ =0 during Ton. When chopper is turned off, Ea being more than source voltage Vs diode D conducts and the energy stored in armature inductance is transferred to the source. During $T_{off}$ $v_t$ $=V_s$ On the assumption of continuous and ripple free armature current, the relevant voltage and current waveforms are shown in Fig. (b). Regenerative braking control offers second quadrant operation as armature terminal voltage has the same polarity but the direction of armature current is reversed, Figs. (a) and (c). From the waveforms of Fig.(b), the following relations can be derived: The average voltage across chopper (or armature terminals) is

$$\mathbf{V_t = \frac{T_o}{T} \cdot V_s = (1\text{-}\alpha)\, Vs}$$




Regenerative braking of separately excited dc motor (a) circuit diagram (b)waveform (c)quadrant operation

Power generated by the motor

$$= V_t \cdot I_a = (1-\alpha)\, V_s \cdot I_a$$

Motor emf generated, $E_a = K_m\, \omega_m = V_t + I_a\, r_a$

$$= (1-\alpha)\, V_s + I_a\, r_a$$

Motor speed during regenerative braking,

$$\omega_m = \frac{(1-\alpha)\, V_s + I_a r_a}{K_m}$$


Motor speed during regenerative braking,

$$\omega_m = \frac{(1-\alpha)\, V_s + I_a r_a}{K_m}$$


When chopper is on, $E_a - I_a r_a - L_a \dfrac{di_a}{dt} = 0$

or $$(E_a - I_a r_a) = L_a \cdot \frac{di_a}{dt}$$

With chopper on, $L_a$ must store energy and current must rise, *i.e.* $\frac{di_a}{dt}$ must be positive or

$$(E_a - I_a r_a) \geq 0$$

When chopper is off, $E_a - I_a r_a - L_a \cdot \frac{di_a}{dt} = V_s$

or
$$V_s - (E_a - I_a r_a) = - L_a \cdot \frac{di_a}{dt}$$

With chopper off, $(E_a - I_a r_a)$ must be more than $V_s$ for regeneration purposes and therefore $[V_s - (E_a - I_a r_a)]$ must be negative. This is possible only if current decreases during off period, *i.e.* $\frac{di_a}{dt}$ in the above expression must be negative.

$$\therefore \quad [V_s - (E_a - I_a r_a)] \leq 0$$

$$- (E_a - I_a r_a) \leq (- V_s)$$

or
$$(E_a - I_a r_a) \geq V_s$$

Eqs. can be combined to give the conditions for controlling the power during regenerative braking as

$$0 \leq (E_a - I_a r_a) \geq V_s$$

Eq. gives the conditions for the two voltages and their polarity for the regenerative braking control of dc separately-excited motor.

Minimum braking speed is obtained when $E_a - I_a r_a = 0$

or
$$K_m \omega_{mn} = I_a r_a$$

$\therefore$ Minimum braking speed $\quad \omega_{mn} = \frac{I_a r_a}{K_m}$

Maximum possible braking speed is obtained when

$$E_a - I_a r_a = V_s$$

$\therefore$ Maximum braking speed, $\quad \omega_{mx} = \frac{V_s + I_a r_a}{K_m}$

Thus regenerative braking control is effective only when motor speed is less than $\omega_{mx}$ and more than $\omega_{mn}$. This can be expressed as

$$\omega_{mn} < \omega_m < \omega_{mx}$$

$$\frac{I_a r_a}{K_m} < \omega_m < \frac{V_s + I_a r_a}{K_m}$$

Therefore, the speed range for regenerative braking is $\frac{V_s + I_a r_a}{K_m} : \frac{I_a r_a}{K_m}$ or $(V_s + I_a r_a) : I_a r_a$.

Regenerative braking of chopper-fed separately-excited or self excited dc shunt motor is more stable, it is therefore discussed here. DC series motors, however, offer unstable operating characteristics during regenerative braking. As such, regenerative braking of chopper-controlled series motors is difficult.

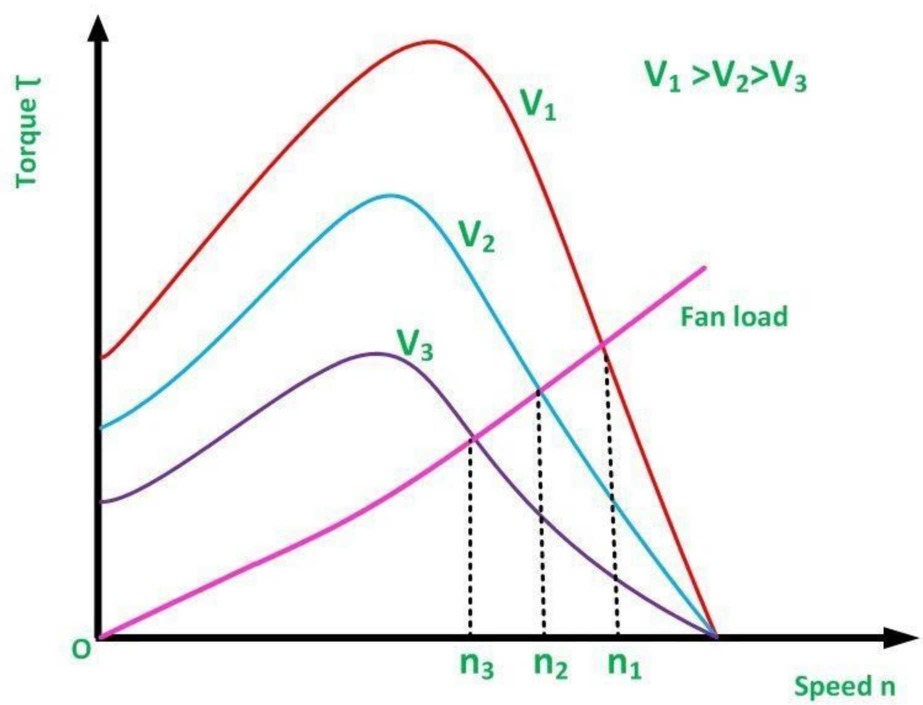
LIST THE FACTORS AFFECTING SPEED OF THE AC MOTORS

The factors that affect speed of the ac motors are

- Voltage
- Frequency
- Slip
- Current
- Rotor resistance

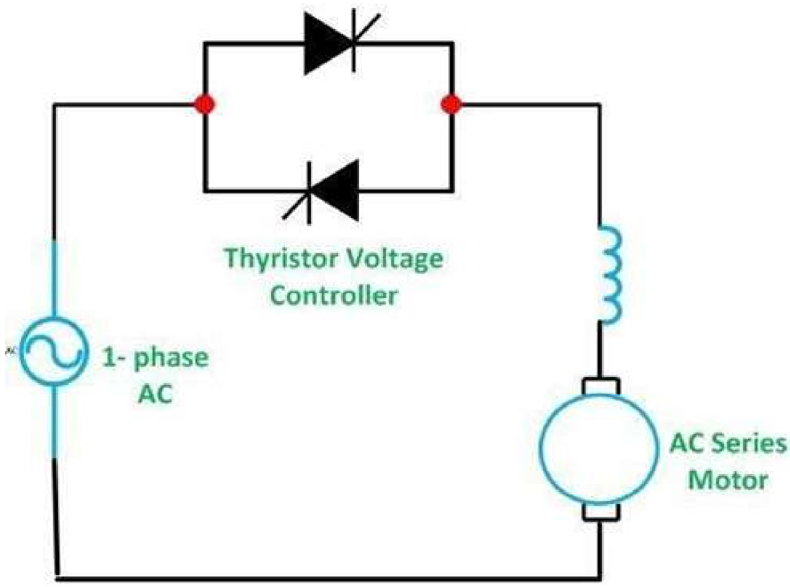
SPEED CONTROL OF INDUCTION MOTOR BY USING AC VOLTAGE REGULATOR.

The speed of a three-phase induction motor can be varied by varying the supply voltage. As we already know that the torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage. The variation in the supply voltage does not alter the synchronous speed of the motor. The Torque-Speed Characteristics of the three-phase induction motors for varying supply voltage and also for fan load are shown below:

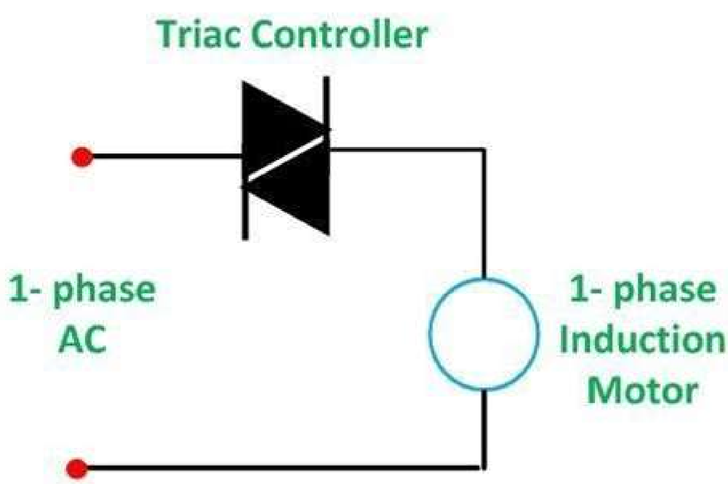



By varying the supplying voltage, the speed can be controlled. The voltage is varied until the torque required by the load is developed, at the desired speed. The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.
Hence, to reduce the speed for the same value of the same current, the value of the voltage is reduced and as a result, the torque developed by the motor is reduced. This stator voltage control method is suitable for applications where the load torque decreases with the speed.

Thyristor voltage controller method is preferred for varying the voltage. For a single phase supply, two thyristors are connected back to back as shown in the figure below:

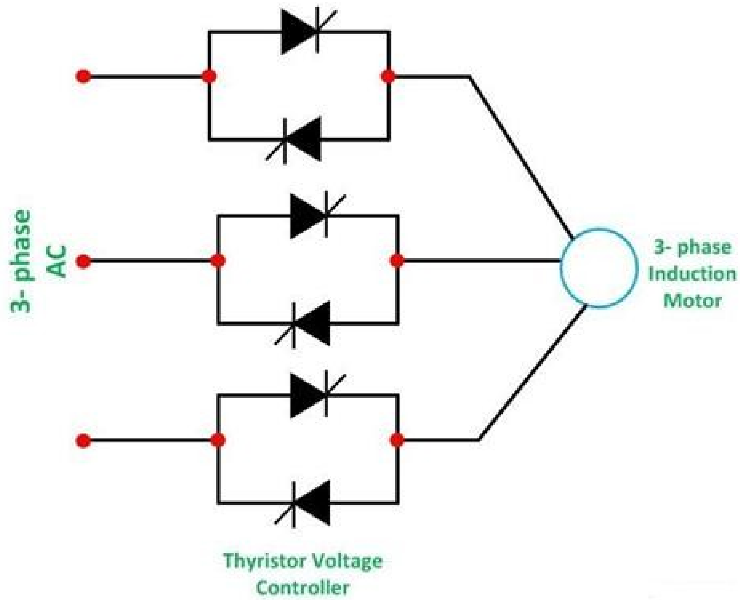



The domestic fan motors, which are single-phase, are controlled by a single-phase Triac Voltage Controller as shown in the figure below:




Speed control is obtained by varying the firing angle of the Triac. These controllers are known as Solid State fan regulators. As the solid-state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.

In the case of a three-phase induction motor, three pairs of thyristors are required which are connected back to back. Each pair consists of two thyristors. The diagram below shows the Stator Voltage Control of the three-phase induction motors by Thyristor Voltage Controller.




Each pair of the thyristor controls the voltage of the phase to which it is connected. Speed control is obtained by varying the conduction period of the Thyristor. For lower power ratings, the back-to-back thyristor pairs connected in each phase are replaced by the Traic.

Speed control of induction motor by using converters and inverters (V/F control).

For a 3-ph IM stator voltage per phase is given by

$v_i = \sqrt{2}\pi f_1 . N_{ph1} . \varphi . k_{w1}$

It is seen from above equation that if the ratio of supply voltage $V_1$ to supply frequency $f_1$ is kept constant, the air-gap flux remains constant. From Fig., the starting torque is given by

$$T_{e.st} = \frac{3}{\omega_s} \cdot \frac{V_1^2}{(r_1 + r_2)^2 + (x_1 + x_2)^2} \cdot r_2$$

As $(r_1 + r_2) << (x_1 + x_2)$ and $\omega_s = \frac{2\omega_1}{P}$, we get

$$T_{e \cdot st} = \frac{3P}{2\omega_1} \cdot \frac{V_1^2 \cdot r_2}{\omega_1^2 (l_1 + l_2)^2}$$

$$= \frac{3P}{2\omega_1} \cdot \left(\frac{V_1}{\omega_1}\right)^2 \cdot \frac{r_2}{(l_1 + l_2)^2}$$

maximum torque is given by

$$T_{e,m} = \frac{3}{\omega_s} \cdot \frac{V_1^2}{2(x_1 + x_2)}$$

$$= \frac{3P}{2\omega_1} \cdot \frac{V_1^2}{2 \cdot \omega_1 (l_1 + l_2)}$$

$$= \frac{3P}{4} \cdot \left(\frac{V_1}{\omega_1}\right)^2 \frac{1}{l_1 + l_2}$$

The Eq. shows that if $\frac{v1}{\omega 1}$, or air-gap flux $\varphi$, is kept constant, the maximum torque remains unaltered. Eq. indicates that starting torque inversely proportional to supply frequency $\omega_1$even if air-gap flux is kept constant. At low values of frequencies, the effect of resistances cannot be neglected as compared to the reactances. This has the effect of reducing the magnitude of maximum torque at lower frequencies as shown in Fig. In practice, at low frequencies, the supply voltage is increased to maintain the level of maximum torque. This method of speed control is also called volts / hertz control.

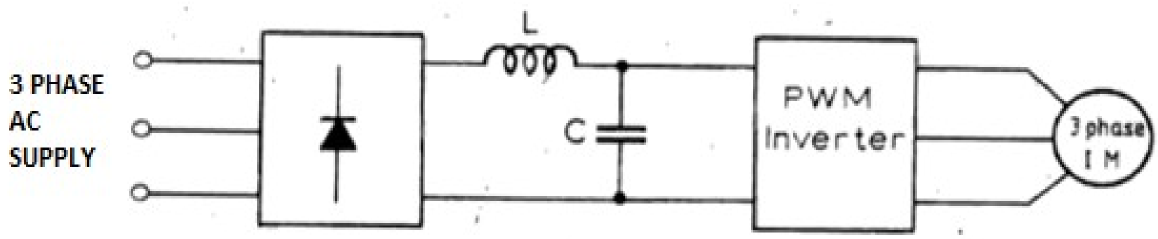
If stator reactance is neglected the slip at which maximum torque occurs is given by

$$s_m = \frac{r_2}{x_1 + x_2}$$

$$= \frac{r_2}{\omega_1 (l_1 + l_2)}$$

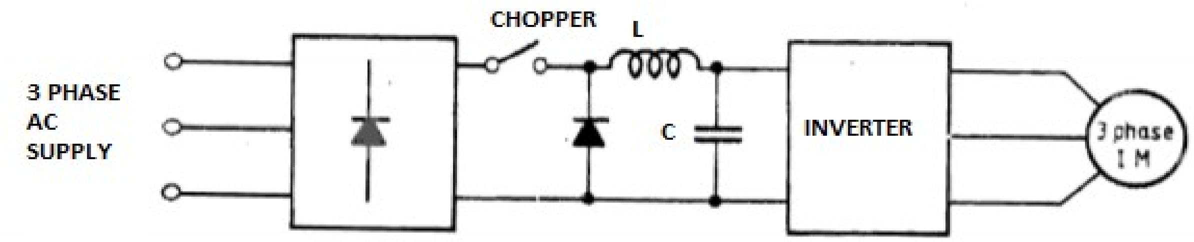
As the supply frequency ($\omega_1$ is reduced, the slip at maximum torque increases. In Fig.load torque $T_L$ for a certain load is also shown. It is seen from this figure that as both voltage and frequency are varied (usually below their rated values), speed of the drive can be controlled. The control of both voltage and frequency can be carried out (so as to keep $\frac{V}{f}$ constant through the use of three-phase inverters or cycloconverters. Inverters are used in low and medium power drives whereas cycloconverters are suitable for high-power drives like cement mills, locomotives etc.

Variable voltage and variable -frequency can be obtained from voltage-source inverters. Four such circuit configurations are shown in Fig.



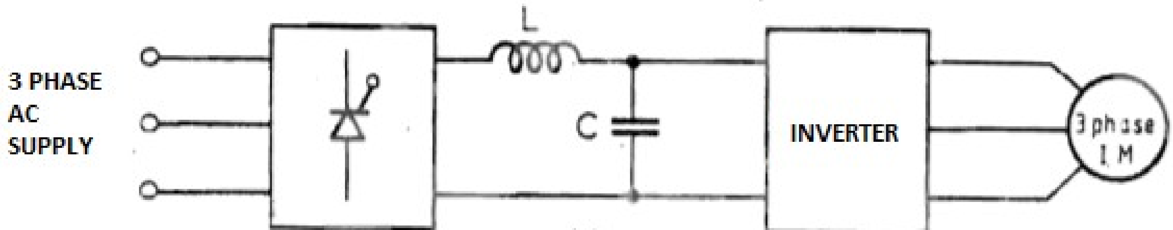

(a)

In Fig. Three-phase ac is converted to constant dc by diode rectifier. Voltage and frequency are both varied by PWM inverter. The circuitry between the rectifier and the inverter consists of an inductor L and capacitor C, called filter circuit. The function of filter circuit is to smooth dc input voltage to the inverter. This Circuitry in between rectifier and inverter is called dc link. In Fig. - regeneration is not possible because of diode rectifier. Also, inverter would inject harmonics into the 3-phase ac supply.



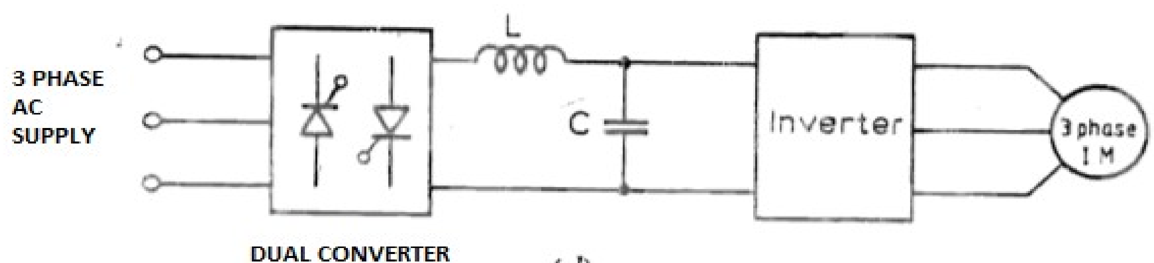

(b)

In Fig. three-phase ac is converted to dc by diode rectifier. Chopper varies the dc input voltage to the inverter and frequency is controlled by the inverter. Use of chopper reduces the harmonic injection into the ac supply. Regeneration is not feasible in the scheme of Fig.




(c)

Fig. uses a 3-phase controlled rectifier, dc link consisting of Land C and a force-commutated VSI. Voltage is regulated by controlled rectifier and frequency is varied within the inverter. Here regeneration is possible if three-phase full converter is used. Regeneration is also feasible in the scheme shown in Fig. below It uses a 3-phase dual -- converter, L-C filter and inverter. Level of dc input voltage to the inverter is regulated in dual converter whereas frequency is varied within the VSI inverter.




(d)

It may be observed from above that volt/hertz control offers speed control from standstill up to rated speed of IM. This method is similar to the armature-voltage control method used for the speed control of a dc motor.

## WORKING OF UPS WITH BLOCK DIAGRAM.

**Uninterruptible Power Supply | UPS**

In a UPS, the energy is generally stored in flywheels, batteries, or super capacitors. When compared to other immediate power supply system, UPS have the advantage of immediate protection against the input power interruptions. It has very short on-battery run time; however this time is enough to safely shut down the connected apparatus (computers, telecommunication equipment etc) or to switch on a standby power source.

UPS can be used as a protective device for some hardware which can cause serious damage or loss with a sudden power disruption. Uninterruptible power source, Battery backup and Flywheel back up are the other names often used for UPS. The available size of UPS units ranges from 200 VA which is used for a solo computer to several large units up to 46 MVA.

Major Roles of UPS

When there is any failure in main power source, the UPS will supply the power for a short time. This is the prime role of UPS. In addition to that, it can also able to correct some general power problems related to utility services in varying degrees. The problems that can be corrected are voltage spike (sustained over voltage), Noise, Quick reduction in input voltage, Harmonic distortion and the instability of frequency in mains.

Types of UPS

Generally, the UPS system is categorized into On-line UPS, Off- line UPS and Line interactive UPS. Other designs include Standby on-line hybrid, Standby-Ferro, Delta conversion On-Line.

Off-line UPS

This UPS is also called as Standby UPS system which can give only the most basic features. Here, the primary source is the filtered AC mains (shown in solid path in figure 1). When the power breakage occurs, the transfer switch will select the backup source (shown in dashed path in figure 1). Thus we can clearly see that the stand by system will start working only when there is any failure in mains. In this system, the AC voltage is first rectified and stored in the storage battery connected to the rectifier.

When power breakage occurs, this DC voltage is converted to AC voltage by means of a power inverter, and is transferred to the load connected to it. This is the least expensive UPS system and it provides surge protection in addition to back up. The transfer time can be about 25 milliseconds which can be related to the time taken by the UPS system to detect the utility voltage that is lost.

The block diagram is shown below.

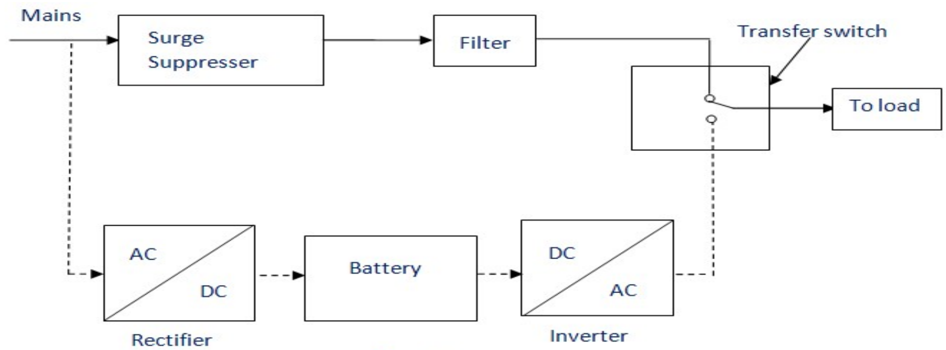


Figure 1

**On-line UPS**

In this **type of UPS**, double conversion method is used. Here, first the AC input is converted into DC by rectifying process for storing it in the rechargeable battery. This DC is converted into AC by the process of inversion and given to the load or equipment which it is connected (figure 2). This type of UPS is used where electrical isolation is mandatory. This system is a bit more costly due to the design of constantly running converters and cooling systems. Here, the rectifier which is powered with the normal AC current is directly driving the inverter. Hence it is also known as Double conversion UPS. The block diagram is shown below.

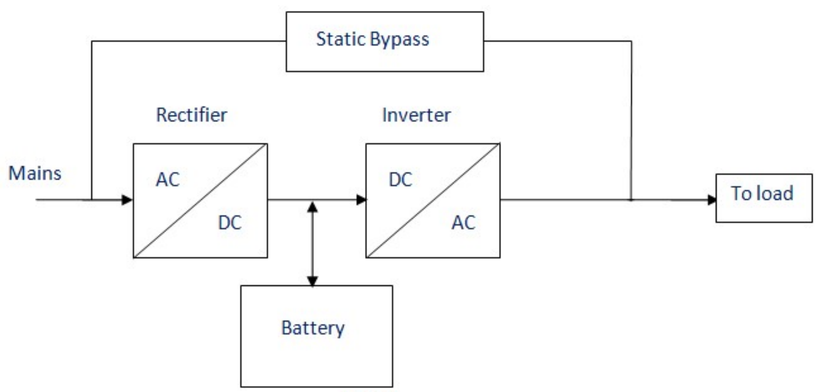


Figure 2

When there is any power failure, the rectifier have no role in the circuit and the steady power stored in the batteries which is connected to the inverter is given to the load by means of transfer switch. Once the power is restored, the rectifier begins to charge the batteries. To prevent the batteries from overheating due to the high power rectifier, the charging current is limited. During a main power breakdown, this UPS system operates with zero transfer time. The reason is that the backup source acts as a primary source and not the main AC input. But the presence of inrush current and large load step current can result in a transfer time of about 4-6 milliseconds in this system.

**Applications of a UPS**:

- Data Centers
- Industries
- Telecommunications

- Hospitals
- Banks and insurance
- Some special projects (events)

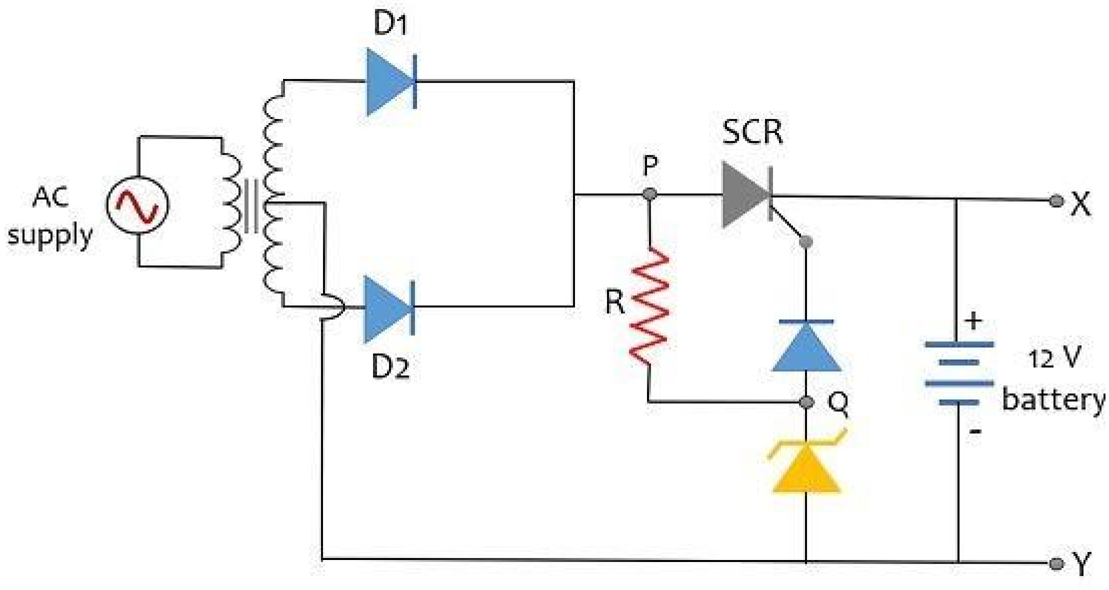
**BATTERY CHARGER CIRCUIT USING SCR WITH THE HELP OF A DIAGRAM**

An SCR-based battery charger makes use of the switching principle of the thyristor in order to get the specific output. The circuit includes a transformer, rectifier, and control circuit as its major elements.

As we have already discussed in the beginning that a small amount of ac or dc input voltage is needed for the purpose of charging the battery. So, the elements of the circuit help to provide the desired voltage to charge the battery.

Working of Battery Charger circuit using SCR

The figure below represents the circuit of a battery charger incorporating an SCR:




Battery Charger Circuit using SCR

Here, an ac voltage signal of value 230 V, 50 Hz is applied as input and the load is a 12 V battery that is required to be charged.

Following are the circuit elements:

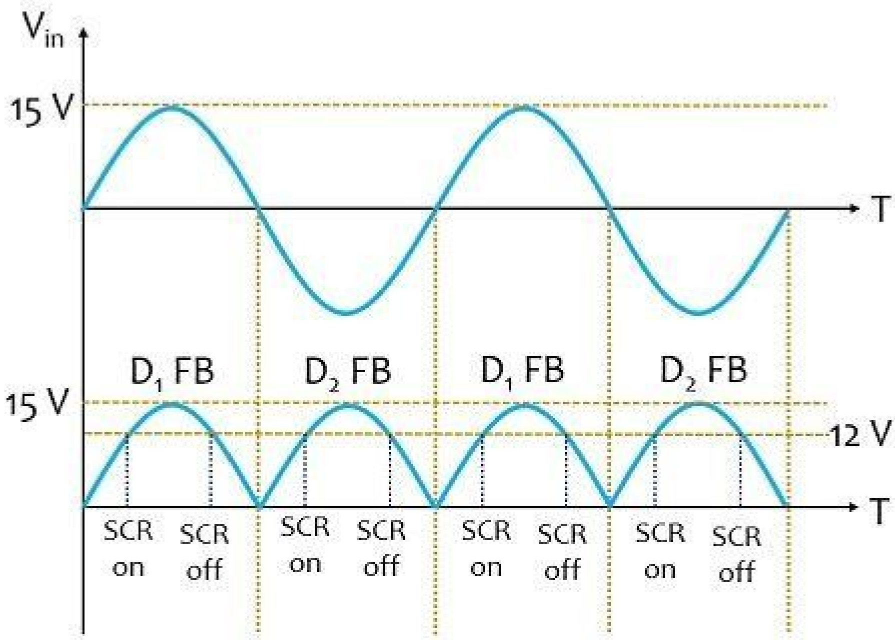
- AC supply
- Step down transformer
- Rectifier circuit
- SCR
- Zener diode as a voltage regulator
- Battery to be charged

Let us now understand how the above-given circuit operates.

So, initially, 230 V ac supply is provided to the step-down transformer which converts the high voltage given at the input of the primary winding into a low voltage which is obtained at the output of the secondary winding. So, here the voltage obtained at the other side of the transformer is 15V with respect to neutral.

From the circuit, it is clearly shown that the transformer forms connection with the rectifier circuit, hence the output of the transformer will be provided to the rectifier circuit. As we have an ac input signal, so let us understand how the rectifier circuit operates when the two halves of the ac signal are applied.

Initially, when the positive half of the ac input signal is applied then the diode $D_1$ in the above-given configuration will be forward biased and will conduct however, $D_2$ will be in reverse biased condition thus will not conduct. Conversely, when the negative half of ac input is applied then $D_1$ will not conduct but $D_2$ will be in conducting state, this is clearly shown in the waveform representation given below:




So, the rectifier circuit will provide rectified output i.e., the dc voltage at terminal P.

Here we have used a Zener diode with breakdown voltage of 10 V as a voltage regulator to regulate the voltage level of the circuit. Therefore, terminal Q will be at 10 V due to the presence of the Zener diode.

As the terminal voltage at P which is nothing but the rectified voltage is comparatively more than at terminal Q thus, this makes the SCR forward biased, allowing it to conduct and due to this current will start flowing through the load i.e., the **12 V battery**. And we have already discussed in the beginning that when current flows through the battery then the cells present within it stores the energy. In this way, the battery gets charged.

However, in case, the rectified voltage is less than that of terminal voltage at Q then automatically SCR will come in a reverse-biased state, getting it turned off and no flow of current through the battery will take place further.

Thus, we can say that here the SCR is acting as a switch that controls the voltage fed to the battery. Now, the question arises, once the battery gets fully charged how the circuit will operate. So, basically what happens within the circuit is as the rectified voltage here is 15 V, so once the battery gets fully charged (suppose it reaches 14.5 V) then the remaining value of the voltage at terminal P will be insufficient to cause further conduction through the SCR because now the rectified voltage will be less than the voltage at terminal Q. This will not allow current to reach the battery further and resultantly the charging circuit will get deactivated.

Basically, this comparison between rectified voltage and the charging potential is made using a comparator circuit. Once the charging potential falls below a certain value then the charging circuit will automatically get activated and again the charging of the battery will take place.

It is to be noted here that the value of the breakdown voltage of the Zener diode and the transformer in the circuit depends on the charging potential of the battery. Thus, the potential at which the battery will be charged will decide the value of these two circuit parameters.

Drawbacks of Battery charger circuit using SCR

This charging is a quite time taking process.

The rectifier circuit for ac to dc conversion, do not remove ac ripples as the filter circuit is absent here.

The process of charging and discharging is slow due to the presence of a half-wave rectifier.

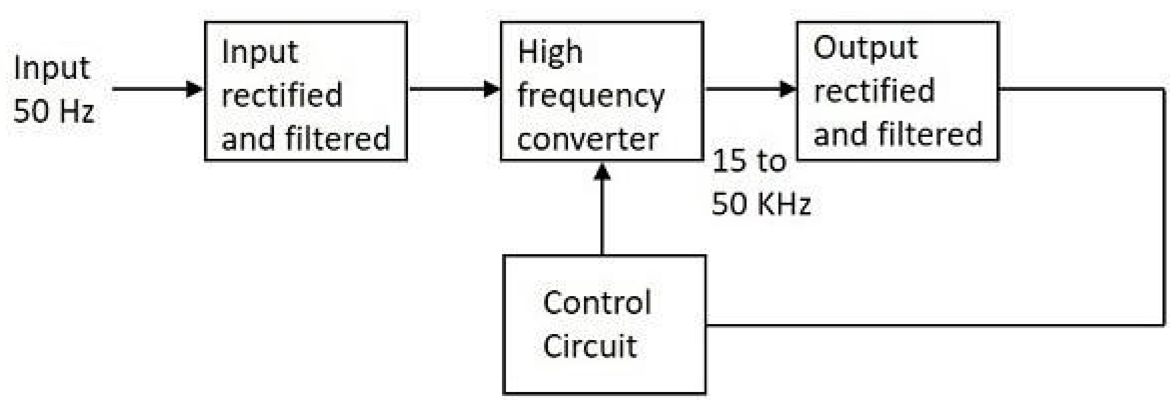
This is only suitable for charging the batteries with a low to medium ampere-hour rating.

## BASIC SWITCHED MODE POWER SUPPLY (SMPS) - EXPLAIN ITS WORKING & APPLICATIONS

A switched-mode power supply (switched power supply,) is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently.

Working

The working of SMPS can be understood by the following figure.




Let us try to understand what happens at each stage of SMPS circuit.

Input Stage

The AC input supply signal 50 Hz is given directly to the rectifier and filter circuit combination without using any transformer. This output will have many variations and the capacitance value of the capacitor should be higher to handle the input fluctuations. This unregulated dc is given to the central switching section of SMPS.

Switching Section

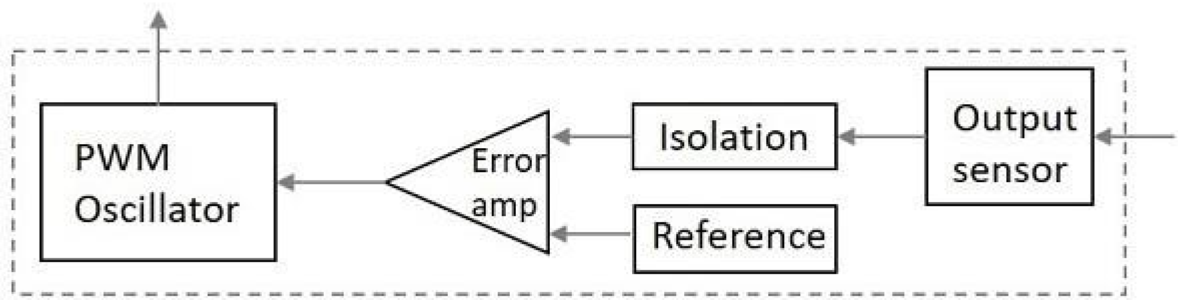
A fast switching device such as a Power transistor or a MOSFET is employed in this section, which switches ON and OFF according to the variations and this output is given to the primary of the transformer present in this section. The transformer used here are much smaller and lighter ones unlike the ones used for 60 Hz supply. These are much efficient and hence the power conversion ratio is higher.

Output Stage

The output signal from the switching section is again rectified and filtered, to get the required DC voltage. This is a regulated output voltage which is then given to the control circuit, which is a feedback circuit. The final output is obtained after considering the feedback signal.

Control Unit

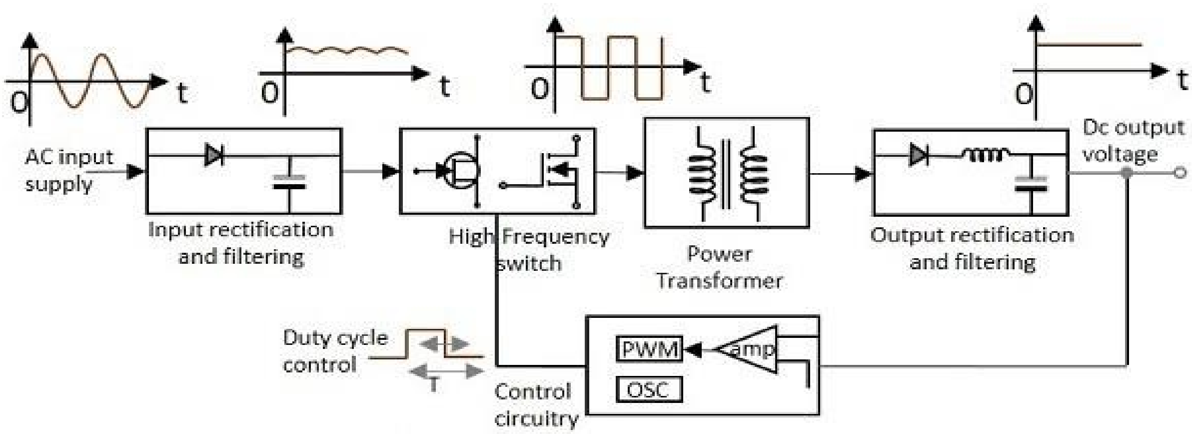
This unit is the feedback circuit which has many sections. Let us have a clear understanding about this from The following figure.




The above figure explains the inner parts of a control unit. The output sensor senses the signal and joins it to the control unit. The signal is isolated from the other section so that any sudden spikes should not affect the circuitry. A reference voltage is given as one input along with the signal to the error amplifier which is a comparator that compares the signal with the required signal level.

By controlling the chopping frequency the final voltage level is maintained. This is controlled by comparing the inputs given to the error amplifier, whose output helps to decide whether to increase or decrease the chopping frequency. The PWM oscillator produces a standard PWM wave fixed frequency.

We can get a better idea on the complete functioning of SMPS by having a look at the following figure.




Functional block diagram of SMPS

The SMPS is mostly used where switching of voltages is not at all a problem and where efficiency of the system really matters. There are few points which are to be noted regarding SMPS. They are

SMPS circuit is operated by switching and hence the voltages vary continuously.

The switching device is operated in saturation or cut off mode.

The output voltage is controlled by the switching time of the feedback circuitry.

Switching time is adjusted by adjusting the duty cycle.

The efficiency of SMPS is high because, instead of dissipating excess power as heat, it continuously switches its input to control the output.

**Disadvantages**

- There are few disadvantages in SMPS, such as
- The noise is present due to high frequency switching.
- The circuit is complex.
- It produces electromagnetic interference.

**Advantages**

- The advantages of SMPS include,
- The efficiency is as high as 80 to 90%
- Less heat generation; less power wastage.
- Reduced harmonic feedback into the supply mains.
- The device is compact and small in size.
- The manufacturing cost is reduced.
- Provision for providing the required number of voltages.

**Applications**

There are many applications of SMPS. They are used in the motherboard of computers, mobile phone chargers, HVDC measurements, battery chargers, central power distribution, motor vehicles, consumer electronics, laptops, security systems, space stations, etc.

**Types of SMPS**

SMPS is the Switched Mode Power Supply circuit which is designed for obtaining the regulated DC output voltage from an unregulated DC or AC voltage. There are four main types of SMPS such as

DC to DC Converter

AC to DC Converter

Fly back Converter

Forward Converter

# 5. PLC AND ITS APPLICATIONS

## INTRODUCTION OF PROGRAMMABLE LOGIC CONTROLLER (PLC)

### The Need for PLCs

PLC is used in the fully automated industries or plants or process, the actual processes handled and controlled by the controllers which are nothing but the programming logic controllers that means PLC plays a very important role in automation section.

PLCs constantly monitor the state of the systems through input devices and generate the control actions according to the logic given in the user program.

It is a heart of control systems, PLC monitors the state of the system through field input devices, feedback signals and based on the feedback signal PLC determine the type of action to be carried out at field output devices.

PLC provides easy and economic solution for many automation tasks like

- Operates control and monitoring.
- Co-ordination and communication.
- PID computing and control.
- Logic / sequence control.

### Programmable Logic Controller

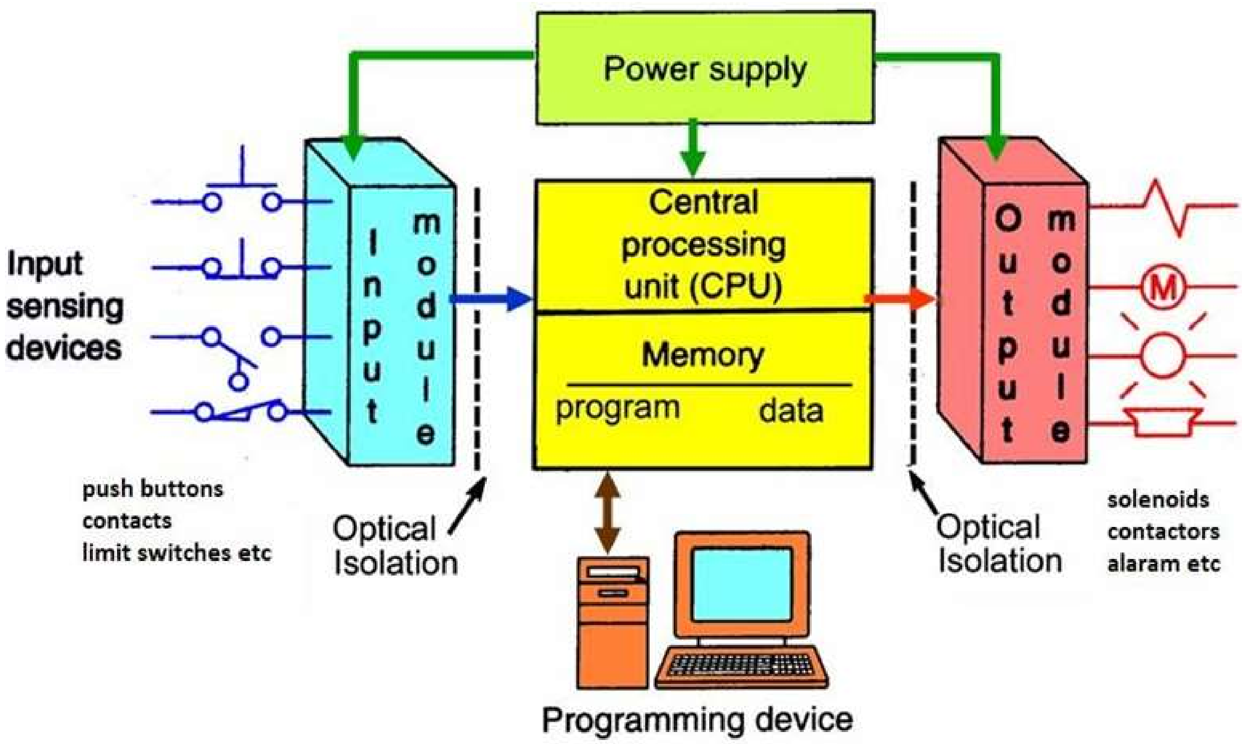
A programmable logic controller (PLC) is a specialized computer used to control machines and process.

It uses a programmable memory to store instructions and specific functions that include On/Off control, timing, counting, sequencing, arithmetic, and data handling

## ADVANTAGES OF PLC

- Flexible
- Faster response time
- Less and simpler wiring
- Solid-state - no moving parts
- Modular design - easy to repair and expand
- Handles much more complicated systems
- Sophisticated instruction sets available
- Allows for diagnostics “easy to troubleshoot”
- Less expensive

**DIFFERENT PARTS OF PLC BY DRAWING THE BLOCK DIAGRAM AND PURPOSE OF EACH PART OF PLC.**




The block diagram of programming logic controller (PLC) is shown in above figure. The PLC has following basic sections are,

**Processor section (CPU)**

The processor section is brain of PLC which consists of RAM, ROM, logic solver and user memory. The central processing unit is heart of PLC. CPU controls monitors and supervises all operation within PLC. The CPU makes decision and executes control instructions based on the program instruction in memory.

**Input and output module**

The input module is a mediator between input devices and central processing unit (CPU) which is used to convert analog signal into digital signal.

The output module is a mediator between output devices and central processing unit (CPU) which is convert digital signal into analog signal.

**Power supply**

Power supply is provided to the processor unit, input and output module unit. Power supply may be integral or separately mounted unit. Most of the PLC operates on 0 volts DC and 24 volts.

**Memory section**

The memory section is the area of the CPU in which data and information is stored and retrieved. Data Memory is used to store numerical data required in math calculation, bar code data etc. User memory contains user's application program.

**Programming device**

Programming devices are dedicated devices used for loading the user program into the program memory or edit it and to monitor the execution of the program of the PLC. It is also used to troubleshoot the PLC ladder logic program. Hand held terminal (HHT) or dedicated terminal or personal computer are programming devices commonly used in most of the PLCs.

## APPLICATIONS OF PLC

- In machining, packaging, material handling, automated assembly etc.
- In medical instruments and technologies
- In industrial manufacturing
- In Nano technology and robotics
- In automatic transfer switch
- In Traffic light Signal system
- It is used in civil applications such as washing machine, elevators working and traffic signals control.
- It is used to reducing the human control allocation of human sequence given to the technical equipments that is called **Automation**.
- It is used in batch process in chemical, cement, food and paper industries are sequential in nature, requiring time or event based decisions.

## LADDER DIAGRAM

Ladder Diagram is a graphical programming language that you use to develop software for programmable logic controllers (PLCs). The most elementary objects in Ladder Diagram programming are contacts and coils, intended to mimic the contacts and coils of electromechanical relays.

Contacts and coils are discrete programming elements, dealing with Boolean (1 and 0; on and off; true and false) variable states.

Each contact in a Ladder Diagram PLC program represents the reading of a single bit in memory, while each coil represents the writing of a single bit in memory.

Discrete input signals to the PLC from real-world switches are read by a Ladder Diagram program by contacts referenced to those input channels.

**DESCRIPTION OF CONTACTS AND COILS IN THE FOLLOWING STATES I) NORMALLY OPEN II) NORMALLY CLOSED III) ENERGIZED OUTPUT IV) LATCHED OUTPUT V) BRANCHING**

Normally Open and Normally Closed electrical contacts make up electrical switches, relays, circuit breakers, and most any other electrical component that switches something on/off or can be switched on/off.

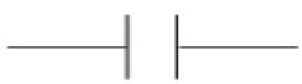
IMPORTANT CONCEPT:

Closed = Current flow

Open = No current flow

What is normally? This is simply the state that the contact is in when something else is not affecting it. If it is a relay then it is not energized. If it is a switch, then it is off. If it is a high limit such as a temperature alarm then the current temperature is below the limit.

**NORMALLY OPEN** - Is a contact that does not flow current in its normal state. Energizing it and switching it on will close the contact, causing it to allow current flow.



Normally Open
(NO)

**Normally closed** - Is a contact that flows current in its normal state. Energizing it and switching it on will open the contact, causing it to not allow current flow.

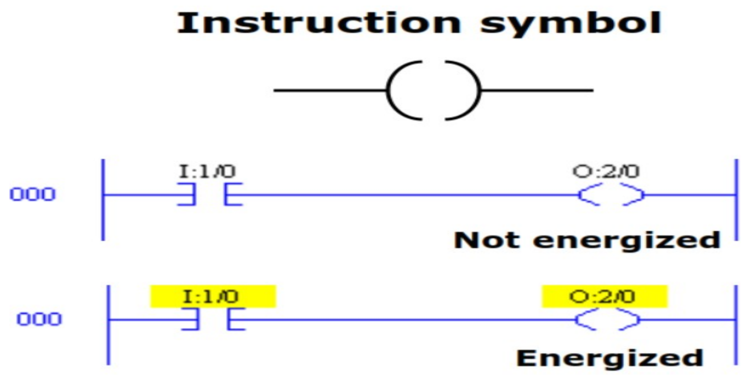
Normally Closed
(NC)

**III) ENERGIZED OUTPUT**

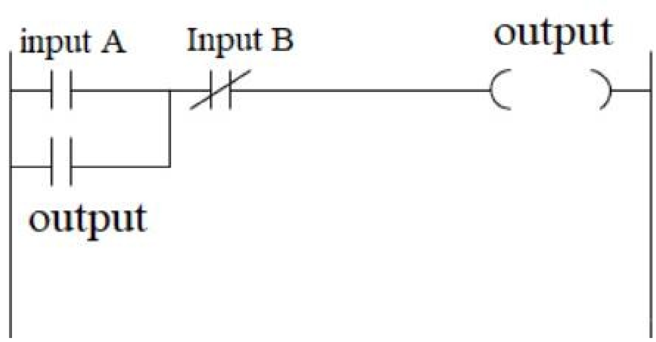
The OTE, also known as Output Energize, instruction will energize a single bit of data if the input leading to it is true. It's a fundamental instruction used in Programmable Logic Controllers (PLCs). This instruction will be found on the right side within a ladder logic structure and turn a bit to a HIGH state if the preceding instructions evaluate to true. If the same instructions evaluate to false, the OTE instruction will set the specified bit to a LOW state.

This Output energize (OTE) instruction is usually used in conjunction with XIC or XIO or any other input instruction in PLC.

If the logic preceding the OTE instruction is true (1), the OTE instruction will be energized.




**IV) LATCHED OUTPUT**
The latching is used where the output must be activated even after the entry ceases.




A simple example of such a situation is a motor, which is started by pressing a button switch. Although the switch contacts do not remain closed, it is required that the motor continue to run until a stop button switch is pressed. The latching used to stay the motor run until the push button is pressed again.
Circuits that are characteristic given the previous conditions are often needed in logic control. In this series the output is latched by using the output contact itself, so even though the input has changed, the output condition is fixed:

When there is an exit, another set of contacts associated with the exit is closed. These contacts form an OR logic gate system with the input contacts. Therefore, even if the A input is opened, the circuit will keep the output energized. The only way to release the output is to activate the normally closed contact B.

**BRANCHING IN LADDER LOGIC**
When two or more instructions are connected in parallel, it is called a branch. Ladder logic circuits almost always contain rungs with branches, and many have levels of branches. A branch level is assigned for each branch that is connected either in series or parallel.
**1. SERIES BRANCH:**

In the series branch, inputs or outputs are connected in the series.

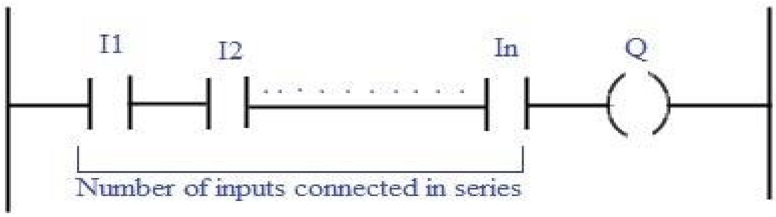



Figure: Representation of the Series Branch

**2. PARALLEL BRANCH**

In the parallel branch, inputs or outputs are connected parallelly.

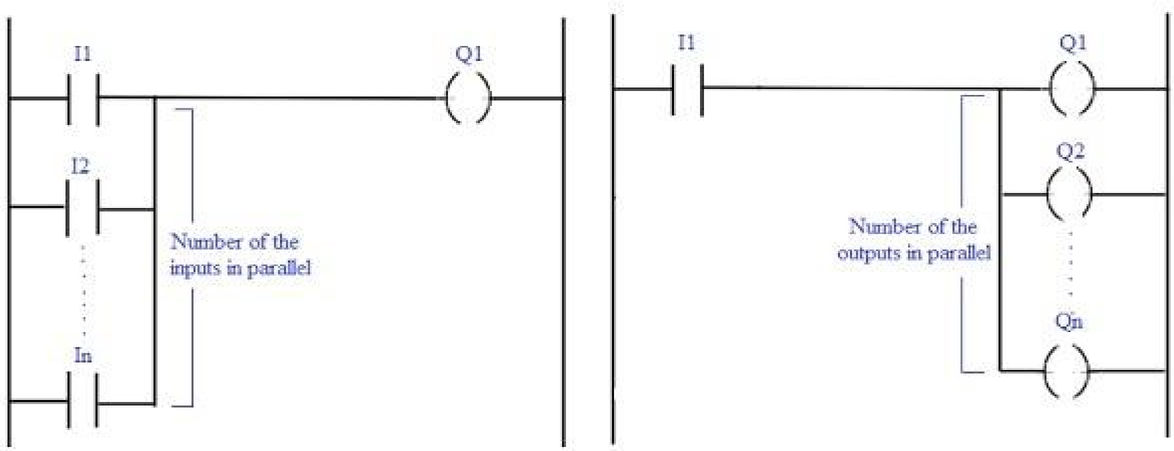


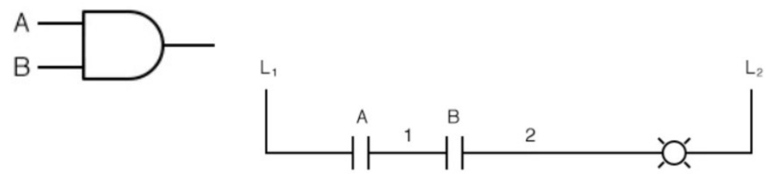

Figure: Representation of the Parallel Branch

**LADDER DIAGRAMS FOR I) AND GATE II) OR GATE AND III) NOT GATE.**

We can mimic the AND logic function by wiring the two contacts in series Now, the lamp energizes only if contact A and contact B are simultaneously actuated.

A path exists for current from wire L1 to the lamp (wire 2) if and only if both switch contacts are closed.

| A | B | Output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

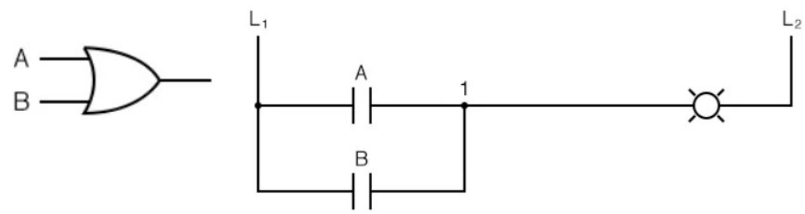



II) OR GATE

The lamp will come on if either contact A or contact B is actuated, because all it takes for the lamp to be energized is to have at least one path for current from wire L1 to wire 1.

What we have is a simple OR logic function, implemented with nothing more than contacts and a lamp.

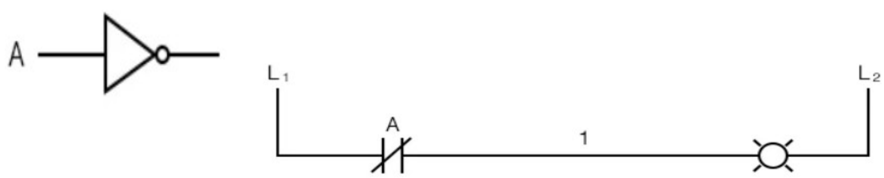
| A | B | Output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |




III) NOT GATE.

The logical inversion, or NOT, function can be performed on a contact input simply by using a normally-closed contact.

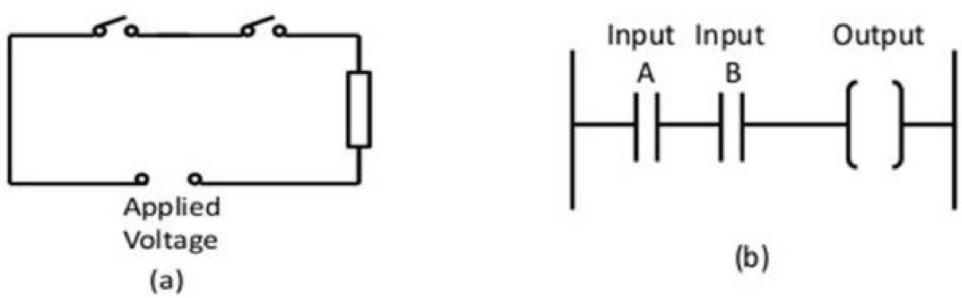
| A | Output |
|---|---|
| 0 | 1 |
| 1 | 0 |




Now, the lamp energizes if the contact is not actuated, and de-energizes when the contact is actuated.

**LADDER DIAGRAMS FOR COMBINATION CIRCUITS USING NAND, NOR, AND, OR AND NOT**

**AND Gate:**



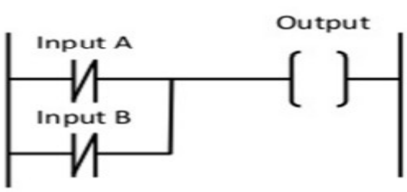
**OR Gate:**


(a) (b)

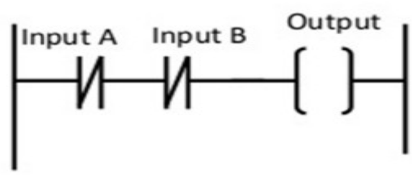
**NOT Gate:**


(a) (b)

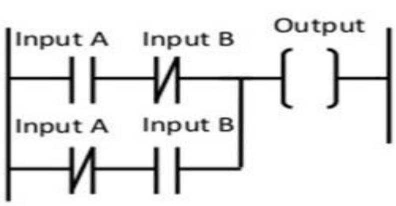
**NAND Gate:**



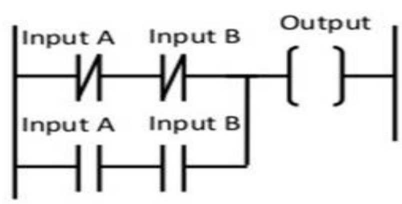

**NOR Gate**



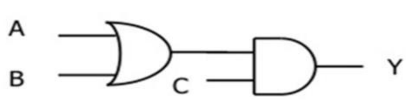

**XOR Gate:**

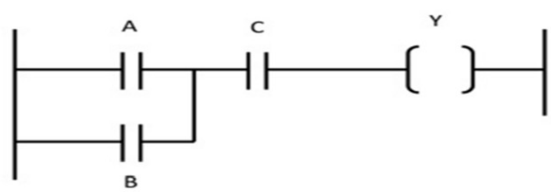



**X-NOR Gate**

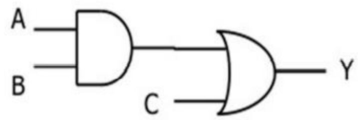


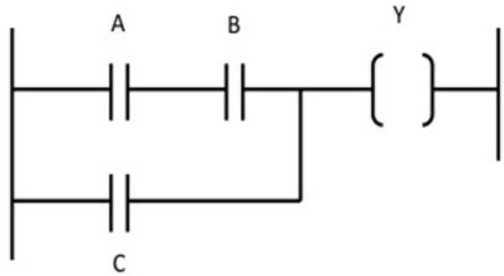

Draw Ladder diagram for given logic diagram



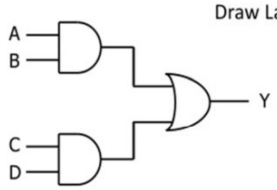



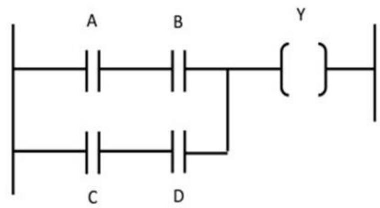
Draw Ladder diagram for given logic diagram



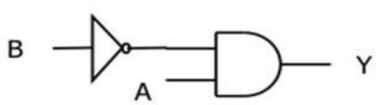




Draw Ladder diagram for given logic diagram



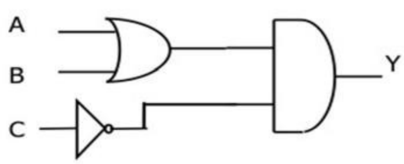



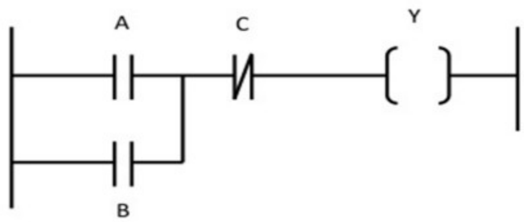

Draw Ladder diagram for given logic diagram





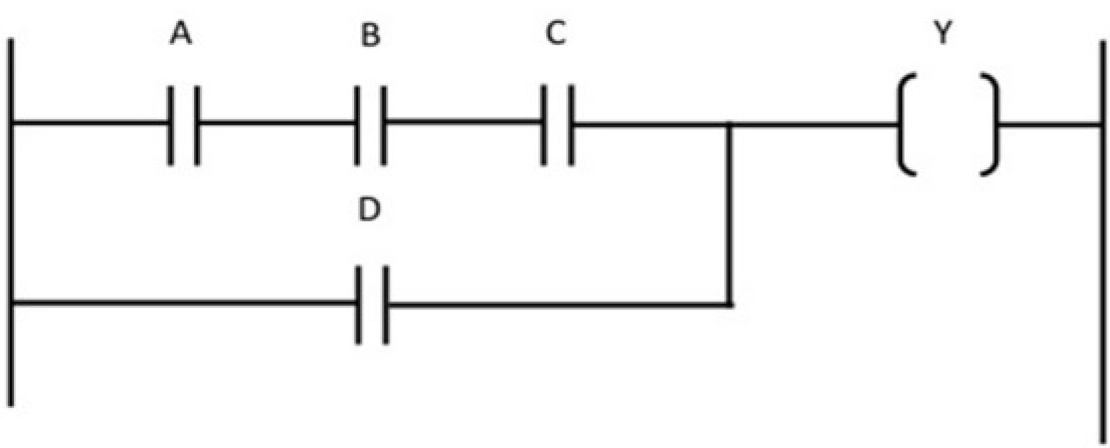
Draw Ladder diagram for given logic diagram



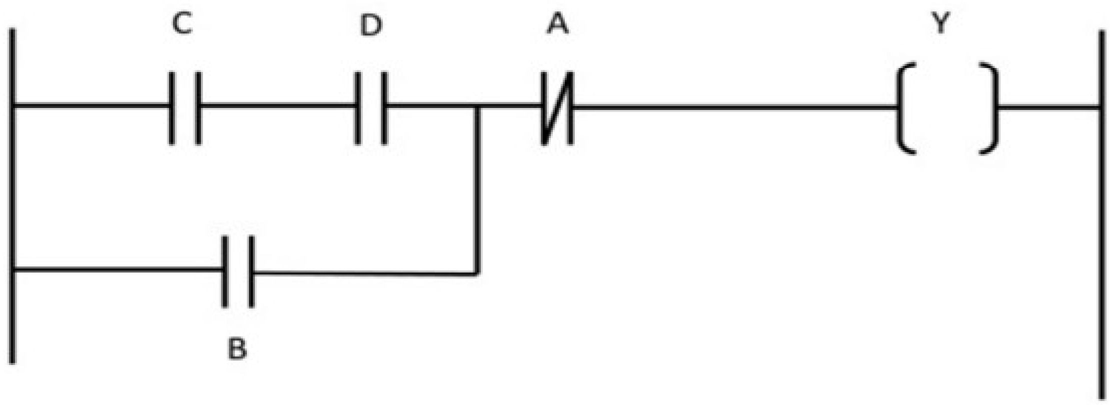

## Draw Ladder diagram for given Boolean Expression

$$Y = ABC + D$$



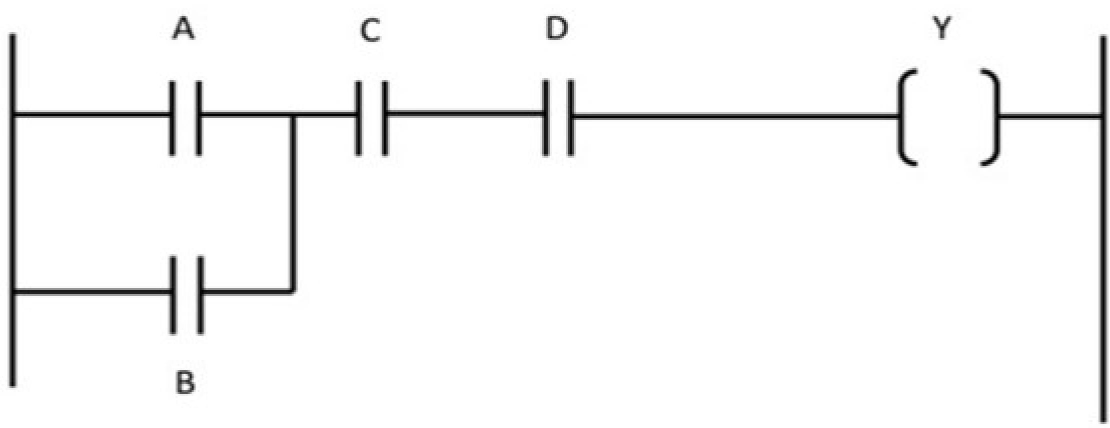
Draw Ladder diagram for given Boolean Expression

$$Y = \overline{A}(B + CD)$$



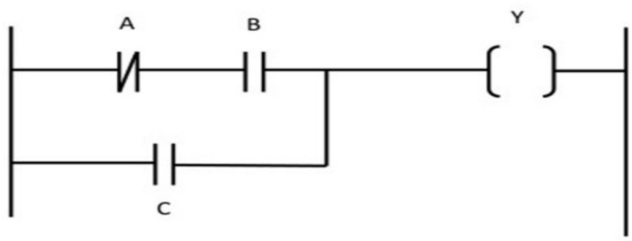

Draw Ladder diagram for given Boolean Expression

$$Y = (A + B)CD$$



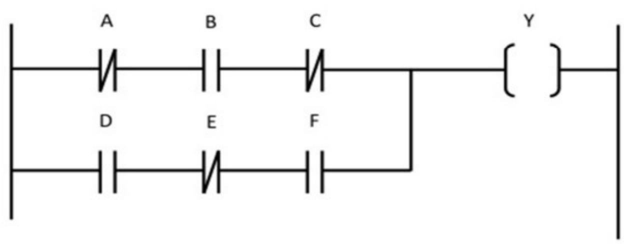

Draw Ladder diagram for given Boolean Expression

$$Y = \overline{A}B + C$$



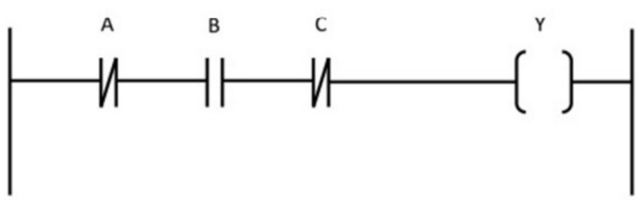

Draw Ladder diagram for given Boolean Expression

$$Y = (\overline{A}B\overline{C}) + (D\overline{E}F)$$




Draw Ladder diagram for given Boolean Expression

$$Y = (\overline{A} + B) + (\overline{A} + B + \overline{C})$$




**TIMERS-I) T ON II) T OFF AND III) RETENTIVE TIMER**

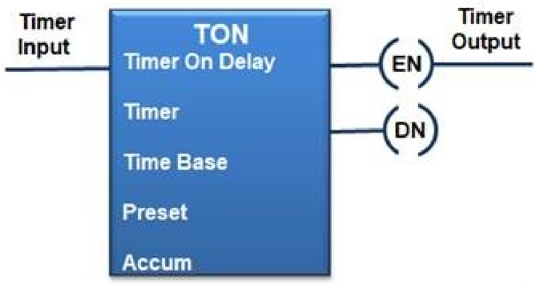
1. On Timer (TON)

What is TON?

TON is called ‘On Delay Timer’.

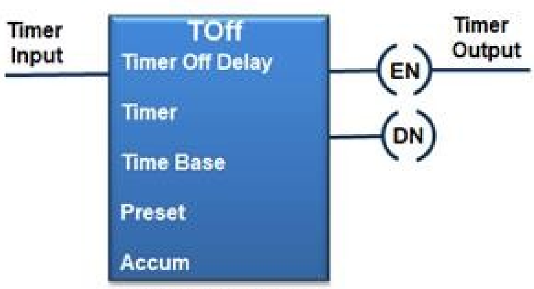
An on-delay timer (TON) is a programming instruction which use to start momentary pulses for a set period of time.

Let’s see, a simple construction of the AB PLC On-delay timer programming instruction.



On Delay PLC Timer

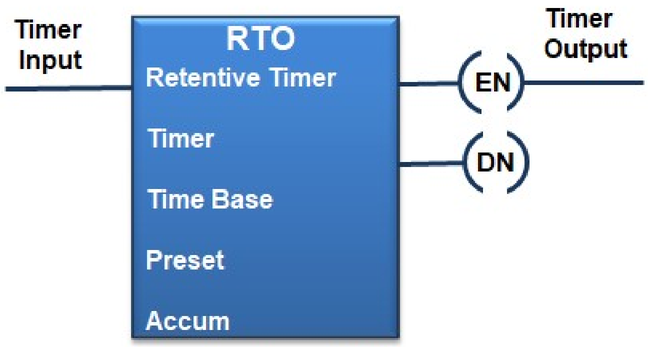
In the LD programming, when an On-delay timer is energized (True), it delays turning 'on' the timer's output.
This output will be 'on' until the timer's preset time value is reached.off delay PLC timer instruction. It helps to activate the output (like machine or process) contact based on the delay time.
Example: Running Electric Motor after 10 seconds.
– If you press the button (NC), it starts the momentary pulse. After the 10 seconds, the motor will be 'On'.
**2. Off Timer (TOFF)**
What is TOFF?
TOFF is also known as an 'Off-Delay Timer'.
A off-delay (TOF) timer is a PLC programming instruction which use to switch off the output or system after a certain amount of time.
See here, a basic structure of AB PLC Off delay timer programming instruction.



Off Delay PLC Timer

In PLC programming, when the off-delay timer is energized (True), it immediately turns 'on' its output. The output will be 'on' till it reaches the setting time.
When it reaches preset time, the output turns 'off'. Due to the turning 'off' condition, the timer is de-energized (False).
It helps to delay the shut down of machinery or process in automation industries.
Example: Stop electric motor after the 10 seconds.
– Firstly, you should switch press (NC), the motor will 'on' for the 10 seconds. After 10 seconds, the motor will automatically stop (NO).
This is the main function of the off-delay timer.

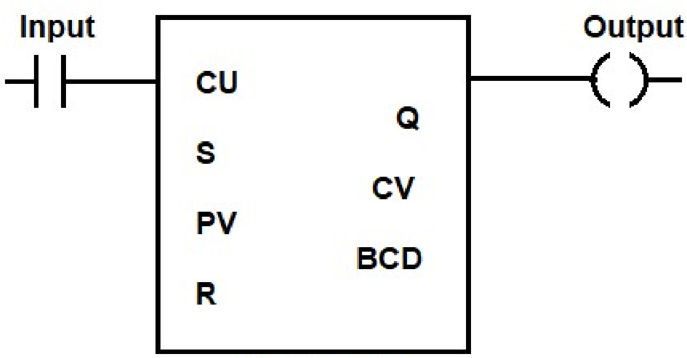
**3. Retentive Timer On/Off (RTO)**
The main function of the RTO is used to hold or store the set (accumulated) time.
RTO is used in the case when there is a change in the rung state, power loss, or any interruption in the system.
In the AB PLC, retentive timer instruction looks like this.



Retentive Timer On/Off

**COUNTERS-CTU, CTD**

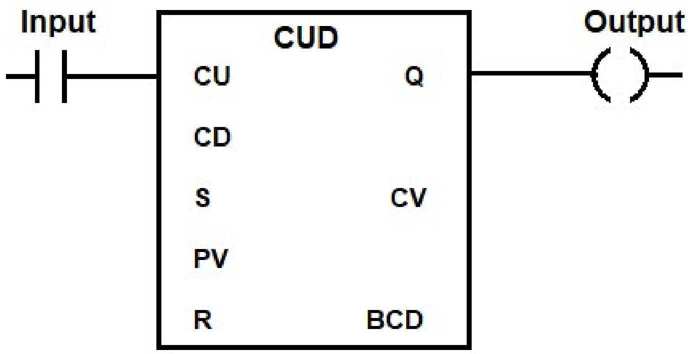
**Up Counter**
Up counter counts from zero to the preset value. Basically, it increases the pulse or number.
Up counter is known as the '**CTU**' or '**CNT**' or '**CC**' or '**CTR**'.
**Up counter function block diagram:**



Up Counter

We can also set the initial and target value as an input to the counter.
Here, the up-counter in PLC can count the value from the initial value to the target value. This initial value must be less than the target value. Most of the time, it is set as zero.

**Down Counter**
The down counter counts from the preset value to zero. It decreases the pulse or number.
Down counter is shortly known as the '**CTD**' or '**CD**'.
Down counter function block diagram:



Up-Down Counter

The down counter counts from target value to the initial value by decreasing it. This initial value must be less than the target value.

**Counter Instruction Addressing for Siemens PLC**

In Siemens PLC, up, down and up-down counters are used. These three PLC counters require some important factors

- S – Set the value of a counter.
- Q – Output of the counter.
- R- Reset value of the counter.
- PV- Preset counter value.
- CV – Count Variable.
- BCD – Current count in binary decimal code.
- Preset counter value (PV) and Count Variable (CV) require the same addressing format. The standard addressing format of the PV and CV in LD.

Summary of PLC Counter Function

- The basic counter function is to count the digital signal pulse or binary system.
- Different PLC brands offer a different range of counter values.
- Counters work as per the supported mode.
- Counter operates in up mode, down mode, bidirectional mode, and quadrature mode.
- Up counting starts from the zero or initial value to the target value.
- Down counting starts from target value down to the initial value.

**LADDER DIAGRAMS USING TIMERS AND COUNTERS**

**LADDER DIAGRAMS USING TIMERS**

In many of the PLC control tasks, there is a need to control the time an example of this will be using a PLC to control a motor. The motor would require to be controlled to operate for a certain interval, and that's why PLCs have timers and the timers are built-in devices in a PLC. By using he internal CPU clock the timer would count the time. Different PLC timers are programmed in different ways, so we can consider a timer to act as a relay with coils, which would open or close when it is energized according to the pre-set time.

**Timer instructions**

The timer instructions are the output instructions which is used to time the intervals for which the rung conditions are true or false. The timer accuracy will be depended upon the microprocessor which is being used. The timer instruction is composed of two values and they are

- **Accumulated value** – This is a current number of time-based intervals that have been counted from the moment when the timer is energized.
- **Preset value** – This value is set by the programmer, if the preset value is less than or equal to the accumulated value then a status bit is set and this bit is to control an output device.
- Each timer is composed of two status bit
- **Timer enable-bit** – This bit will be set if the rung condition to the left of the timer instruction is true and when this bit is set then the accumulated value will be incremented on each time base interval till it reaches the preset value.
- **Done bit** – This bit will be set if the preset value and the accumulated value are equal and it will be reset if the rung condition is false.

**Timer working**

The timer will be activated if the execution condition is started and it will be reset if the execution condition stops or goes OFF. If the execution condition keeps ongoing or if it is long enough for the timer to time down to zero. Then the completion flag will be turned ON and it will remain ON till the execution condition is completed or turn off.

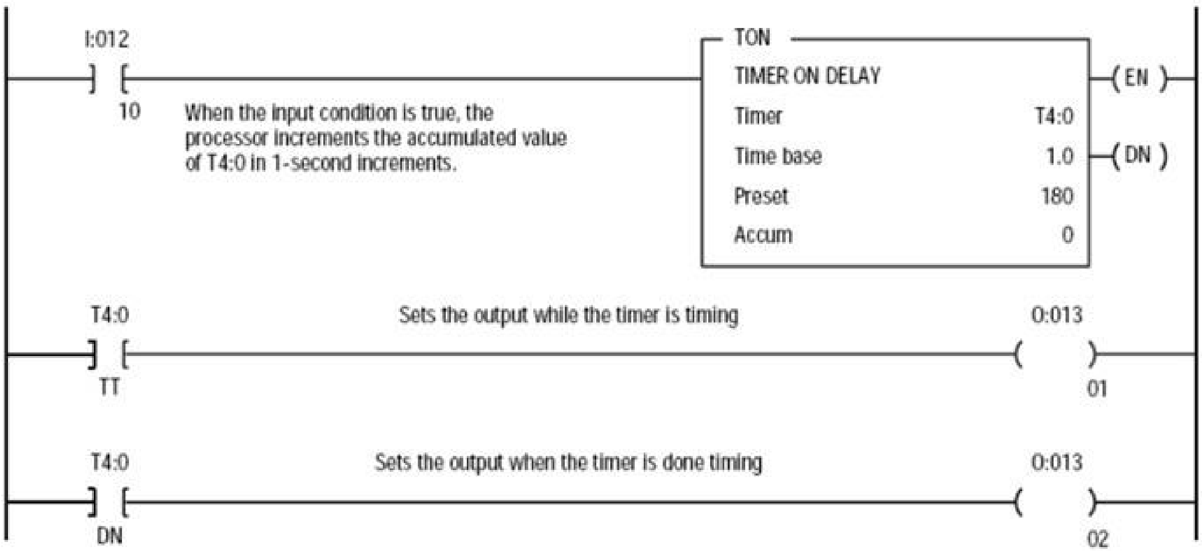
The address of the timer is unique in the PLC memory, the timer instruction is one element and the timer element is composed of 16-bits. The word zero will cover the status bits and it has three state bits such as EN, TT, and DN. The word one is for the preset value and the word two is for the accumulated value.

Types of timers

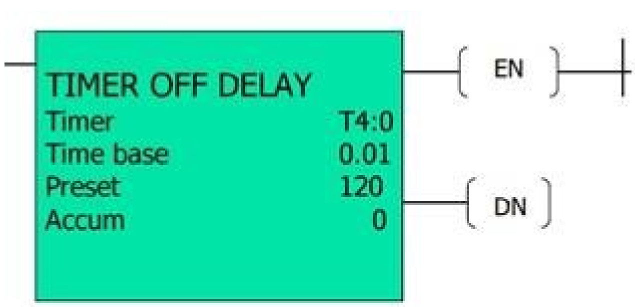
We can see different types of timers in a PLC

**ON delay timer**

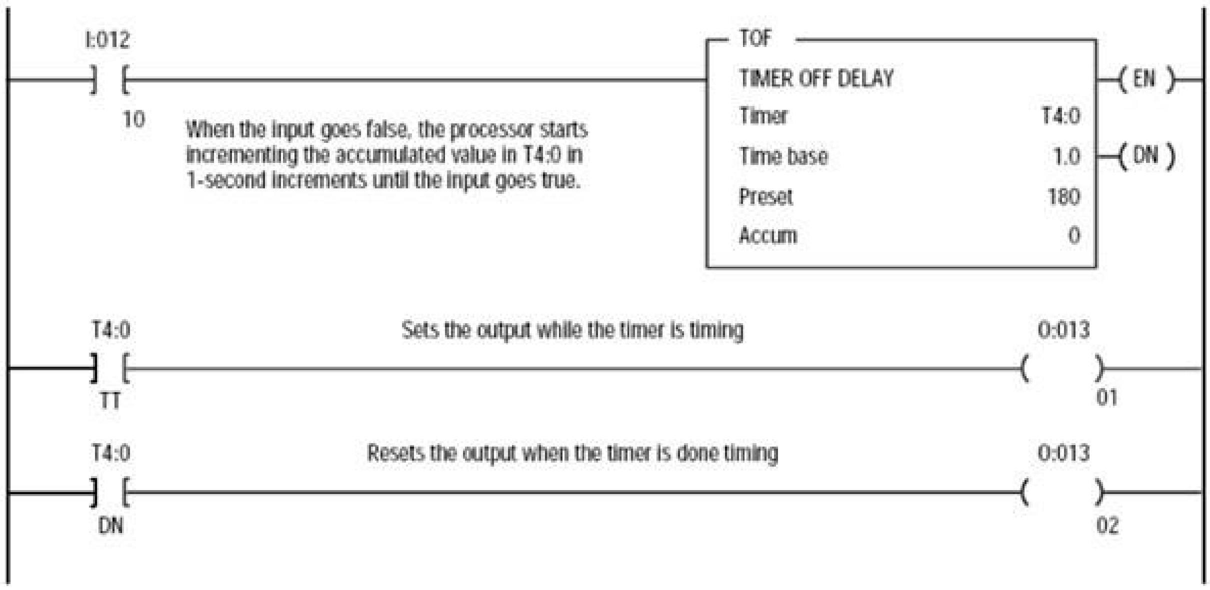
This type of timer can be seen in small PLC's and this timer would be on after a particular time delay. This is widely used for PLC programming we can also create other timer functions by using an on-delay timer. So this timer would delay the turning ON time in a system. This type of timer would count the time base interval if the instruction is true. So if the rung condition becomes true then the on delay timer instructions will start to count the time base intervals. So if the rung conditions stay true then the timer would adjust its accumulated value during each evaluation till it reaches the preset value. So when the rung condition becomes false then the accumulated value is reset. The three timer bits EN, TT, and DN can be used as rung conditions.




**OFF delay timer**




This is the exact opposite of the on delay timer; this timer would delays the turning off. So these timers are on for a fixed period of time before turning off. The output will be turned off after a delay, so when this timer is turned on then the output is also turned on. So if the output needs to be turned off then it needs to be turned on in the beginning. So this timer won't be activated before we turn the input off again, so if we do that the timer will start the count after the delay and the output will be turned off.



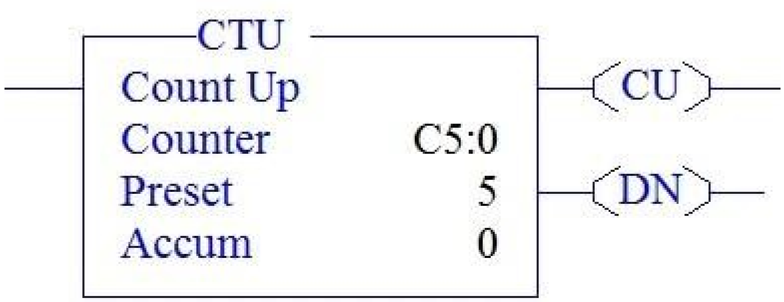

Pulse timer

This timer is not used widely in a PLC it can be very helpful for some PLC operations. The pulse timer is used to generate the pulse and it will be of a specific length. The pulse timer can be activated by turning on the input and when it is turned on then the timer would start counting the time. So basically a pulse timer can switch on or off for a fixed period of time.

**LADDER DIAGRAMS USING COUNTERS**

To study the working of **Up Counter PLC program** in Allen Bradley Programmable Logic Controller (PLC).

## Up Counter

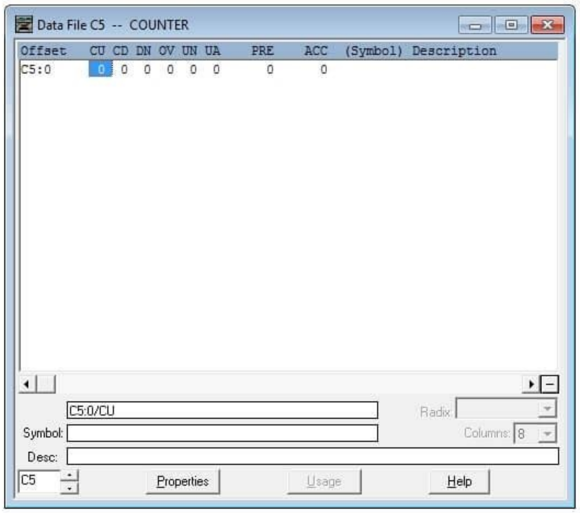



In the above picture, there are totally three parameter,

**COUNTER: C4:0 –** Counter File name (Timer C5:0, C5:1, C5:2…)

**PRESET –PRE:** Limit value of COUNT-Up to how much it should count

**ACCUMULATOR –ACC:** Running Value of counter when condition turn ON.

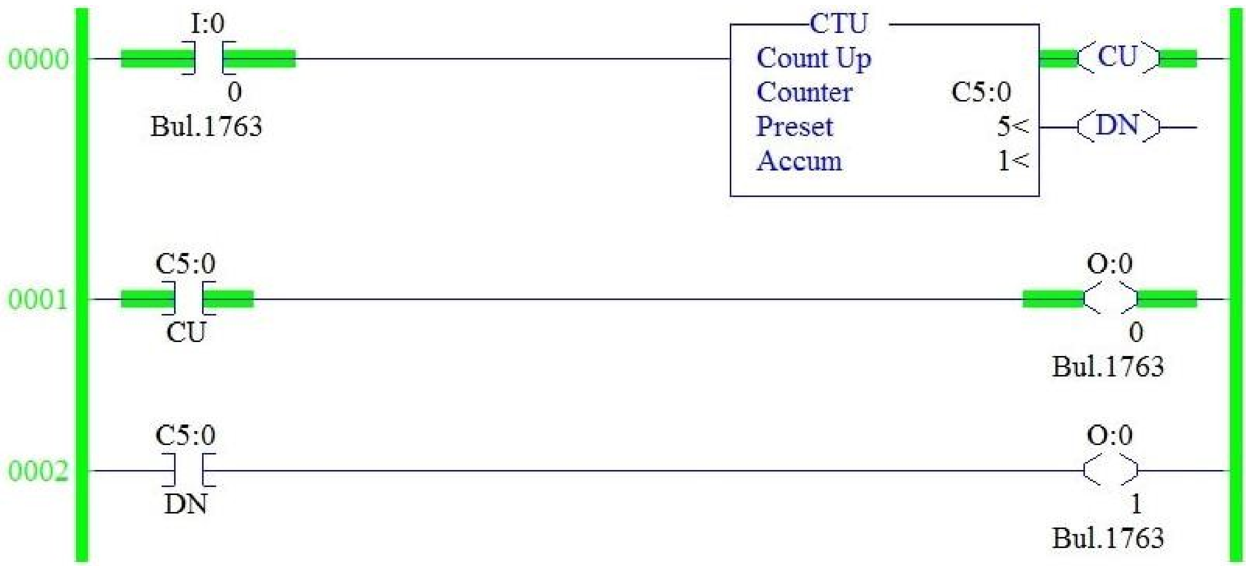



From the data file, along with preset and accumulator, we have few more bits,
CU: Count up Bit-whenever the counter is enable makes this bit to go ON.
DN: Done Bit-When accumulator value reached preset value, done bit turns to ON.
OV: Over Flow Bit-When accumulator value reached the limit value (32767),it rolls back to -32767 for the upcoming counter operation, Overflow bit turns ON, in this condition.

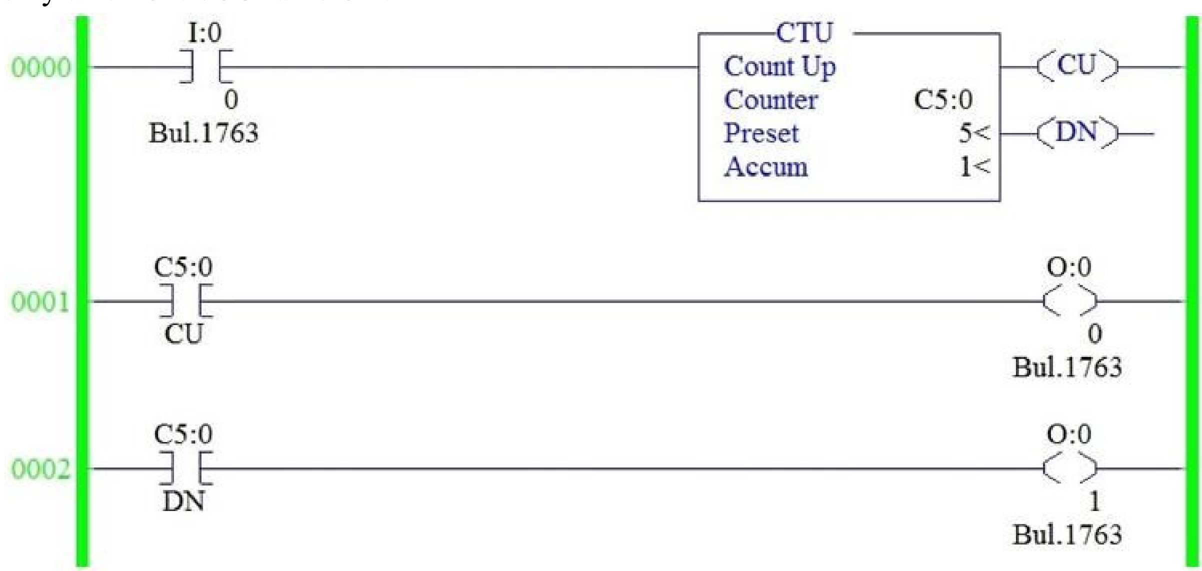
Notes:
UA-Update Accumulator Value-Only used when high speed counters are used in the program.
CD & UN-Used for down Counter Function.

## Up Counter Description Using PLC Program

I:0/0 is used to give input to counter and Preset value is set to 5.
Counter Count up Bit (C5:0/CU)
In the below Ladder logic,
Rung 000 – Having condition input I:0/0 which gives input to counter to perform counter function.
Rung 0001 – Having Counter CU Bit which enable only when counter is in function or when input to the counter turns ON.

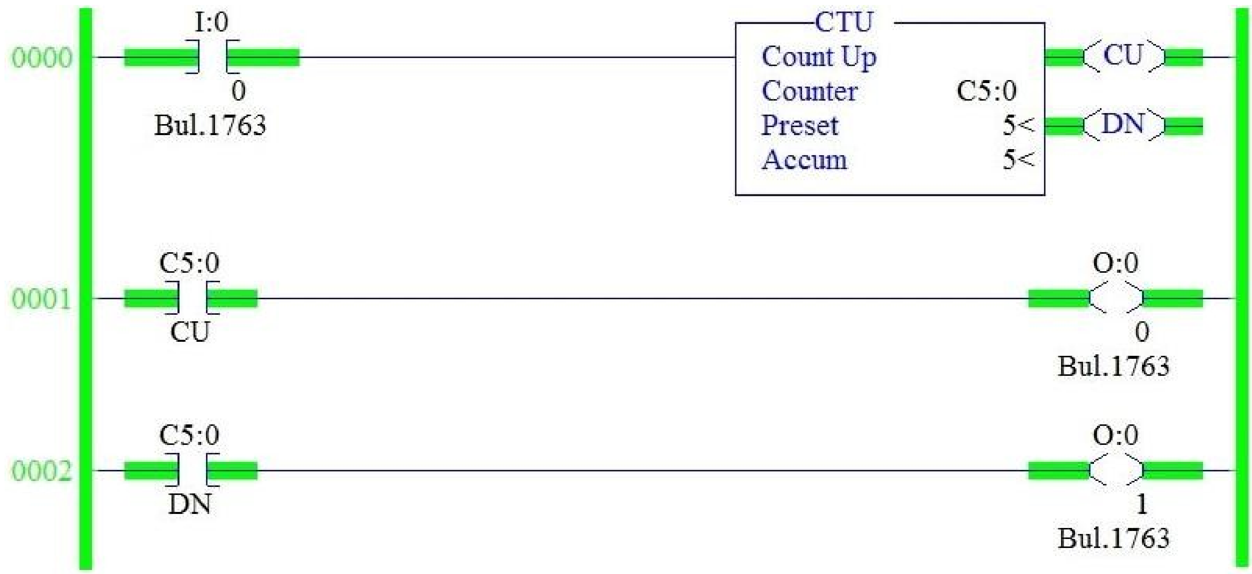



In the below ladder Logic,
When input to the counter turn OFF (I:0/0),Counter CU bit turns OFF. Output O:0/0 turns ON only when C5:0/CU turns ON.



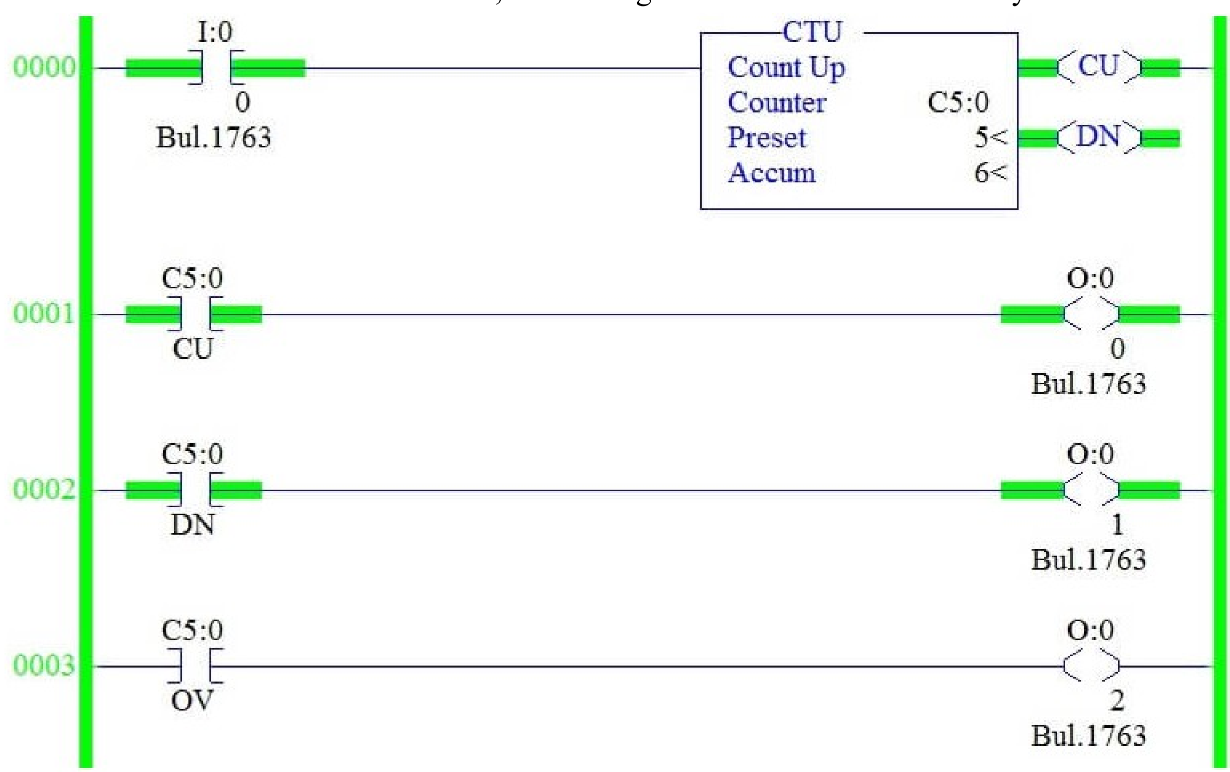

## Counter Done Bit (C5:0/DN)

In the Below Ladder Logic,
When accumulator value reaches the Preset, Counter Done bit (Cu5:0/DN) turns ON.




In the below ladder Logic,

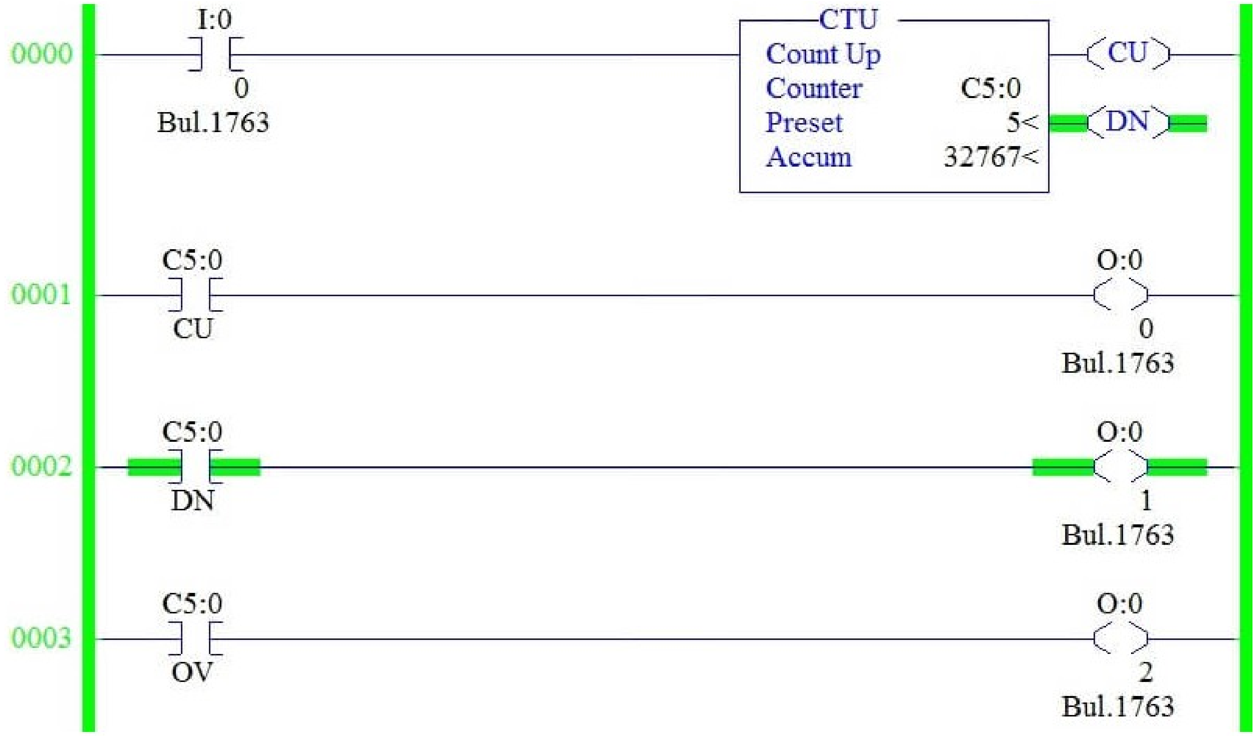
Done bits remains in the ON condition, even though accumulator value runs beyond Preset.




Counter Overflow Bit (C5:0/OV)

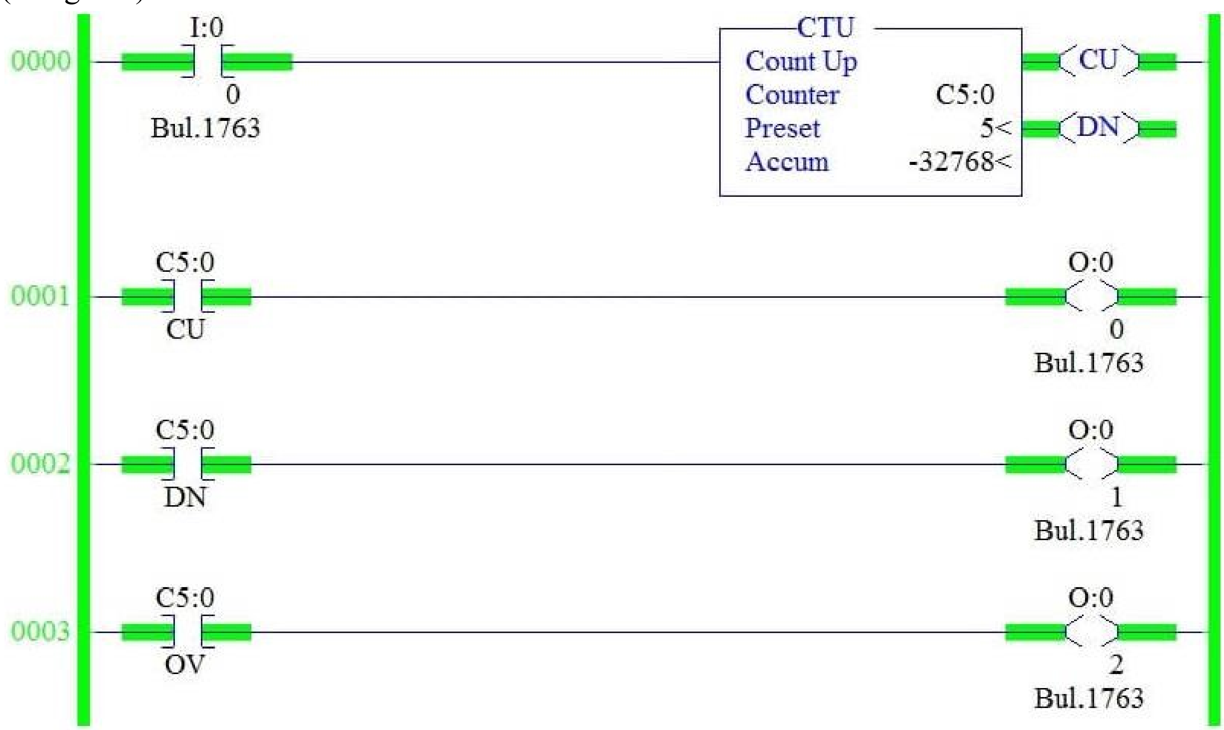
In the Below Ladder Logic,

Counter accumulator value overflows when accumulator value reaches 32767 in Allen Bradley PLC Programming.




In the below ladder Logic,

When we turn ON the I:0/0 for the 32768 time, accumulator value rolls back to -32768 and start counting from -32767 to 32767.Counter Overflow bit turns ON when this condition happen (Rung 003).



## Conclusion:

We can use this explanation to understand the working of Up Counter function in Allen Bradley Programmable Logic Controller (PLC).

**PLC INSTRUCTION SET**

**Naming Convention**

During the development of a PLC program, we must use specific names to identify the inputs, outputs, memory flags, timers, and counters.

PLC manufacturers use a variety of approaches in naming the inputs, outputs and other resources.

A typical naming convention is to identify inputs with the letter “I” and outputs with the letter “O”, followed by a 1-digit number that identifies the slot number and a 2-digit number that identifies the position of the input or output in the slot.

**For example:**

- I1:00 refers to the first input of slot 1
- O2:00 refers to the first output of slot 2.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For example:

- I1:00 refers to the first input of slot 1
- O2:00 refers to the first output of slot 2.


**Examine if Closed (XIC)**

If the input device is ON or closed, then the corresponding bit in the data memory (input image) is set to true, thus allowing (conceptually) the energy to flow from its left side to its right-hand side.

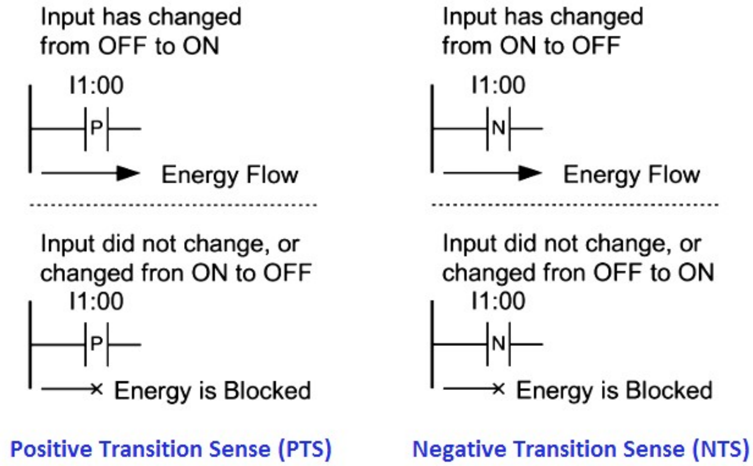
Otherwise, it is set to false, thus blocking the energy.

**Examine if Open (XIO)**

If the input device is OFF or Open, then the corresponding bit in the data memory (input image) is set to true, thus allowing (conceptually) the energy to flow from its left side to its right-hand side.

Otherwise, it is set to false, thus blocking the energy.

Input Transition Sensing Instructions



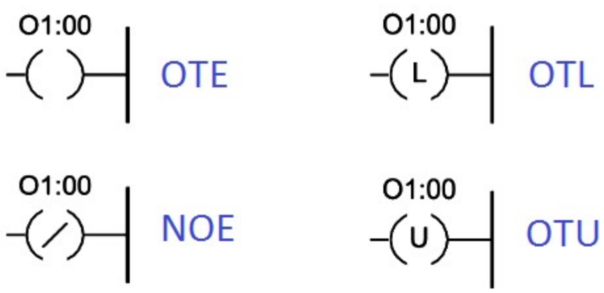

**Positive Transition Sense (PTS)**

The condition of the right link is ON for one ladder rung evaluation when a change from OFF to ON at the specified input is sensed.

**Negative Transition Sense (NTS)**

The condition of the right link is ON for one ladder rung evaluation when a change from ON to OFF at the specified input is sensed.

## Output Instructions




**Output Energize (OTE)**

If the condition of the left link of the OTE is ON then the corresponding bit in the output data memory is set. The device wired to this output is also energized.

Negative Output Energize (NOE)

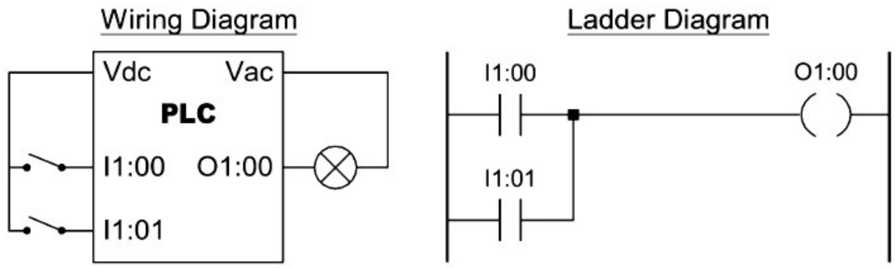
If the condition of the left link of the OTE is OFF then the corresponding bit in the output data memory is set. The device wired to this output is also energized.

**Output Latch/Set and Output Unlatch/Reset (OTL), (OTU)**

If the condition of the left link of the OTL is momentary ON then the corresponding bit in the output data memory is set, and remains set even if the condition switches to the OFF state. The output will remain set until the condition of the left link of the OTU is momentary ON.

Basic Logic Functions

Two Input OR Function

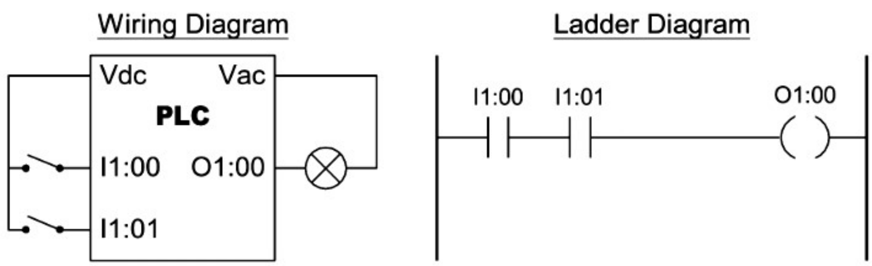



Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | OFF |
| OFF | ON | ON |
| ON | OFF | ON |
| ON | ON | ON |

The output is ON if any of the two inputs is ON.

Two Input AND Function

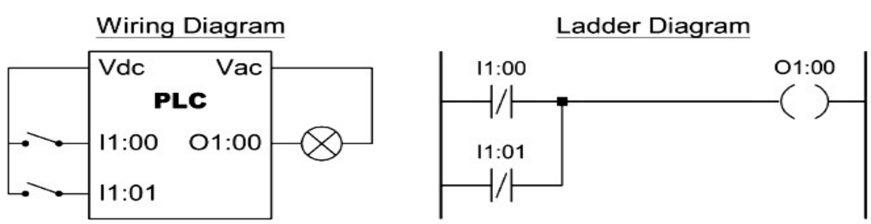



Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | OFF |
| OFF | ON | OFF |
| ON | OFF | OFF |
| ON | ON | ON |

The output is ON if both of the two inputs are ON.

Two Input NAND Function

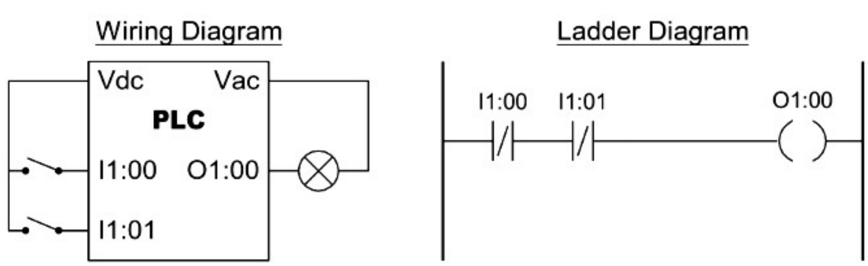



Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | ON |
| OFF | ON | ON |
| ON | OFF | ON |
| ON | ON | OFF |

The output is ON if any of the two inputs is OFF.

# Two Input NOR Function

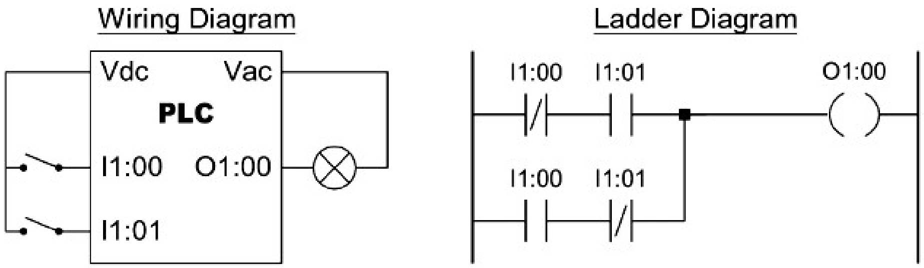



Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | ON |
| OFF | ON | OFF |
| ON | OFF | OFF |
| ON | ON | OFF |

The output is ON if both of the two inputs are OFF.

Two Input EXOR Function

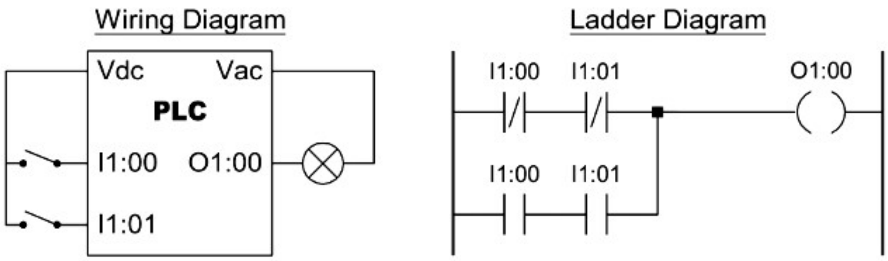



Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | OFF |
| OFF | ON | ON |
| ON | OFF | ON |
| ON | ON | OFF |

The output is ON if any of the two inputs is ON, but not both.

Two Input EXNOR Function



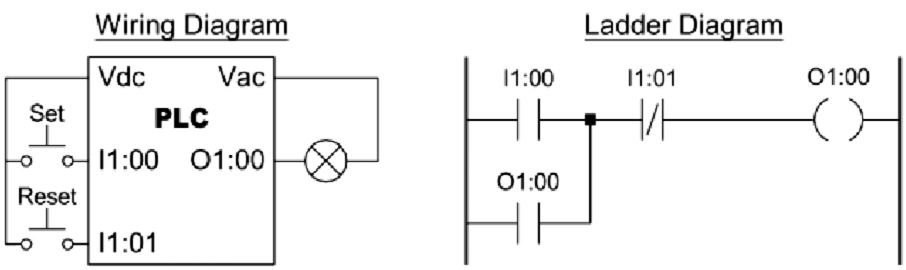

Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | ON |
| OFF | ON | OFF |
| ON | OFF | OFF |
| ON | ON | ON |

The output is ON if both of the two inputs are either OFF or ON.

Set/Reset Latch Instructions

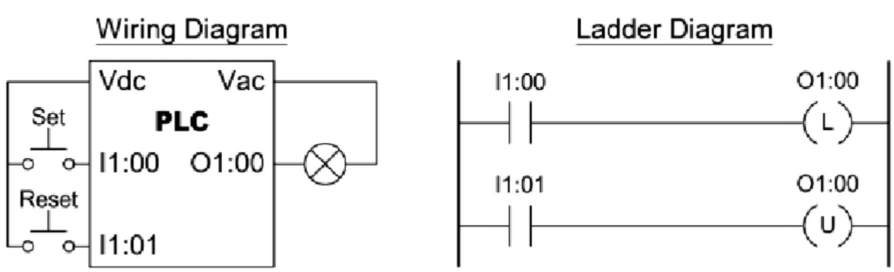
# Set/Reset Latch using a Hold-in contact




Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | O1:00' |
| OFF | ON | OFF |
| ON | OFF | ON |
| ON | ON | OFF-? |

Set/Reset Latch using Latch/Unlatch outputs




Truth Table

| I1:00 | I1:01 | O1:00 |
|---|---|---|
| OFF | OFF | O1:00' |
| OFF | ON | OFF |
| ON | OFF | ON |
| ON | ON | OFF-? |

Notes:

- O1:00’ means that the output is unchanged
- If both inputs are ON then normally the output is OFF, since the Unlatch rung appears last in the ladder diagram.

**Timer Instructions**

Timer Instructions are output instructions used to time intervals for which their rung conditions are true (TON), or false (TOF).

These are software timers. Their resolution and accuracy depend on a tick timer maintained by the microprocessor.

Each timer instruction has two values (integers) associated with it:

- Accumulated Value (ACC): This is the current number of ticks (time-base intervals) that have been counted from the moment that the timer has been energized.
- Preset Value (PR): This is a predetermined value set by the programmer. When the accumulated value is equal to, or greater than the preset value, a status bit is set. This bit can be used to control an output device.

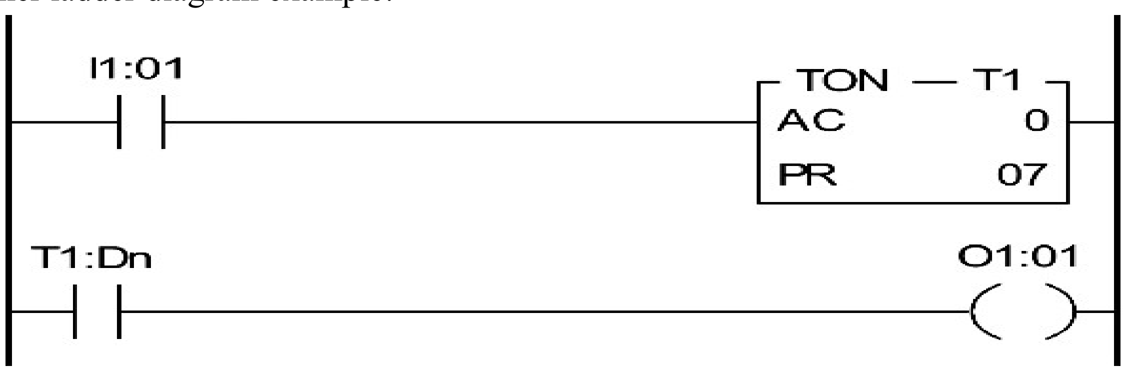
Each timer is associated with two status bits:

- Timer Enable Bit (EN): This bit is set when the rung condition to the left of the timer instruction is true. When this bit is set, the accumulated value is incremented on each time-base interval, until it reaches the preset value.
- Done Bit (DN): This bit is set when the accumulated value is equal to the preset value. It is reset when the rung condition becomes false.

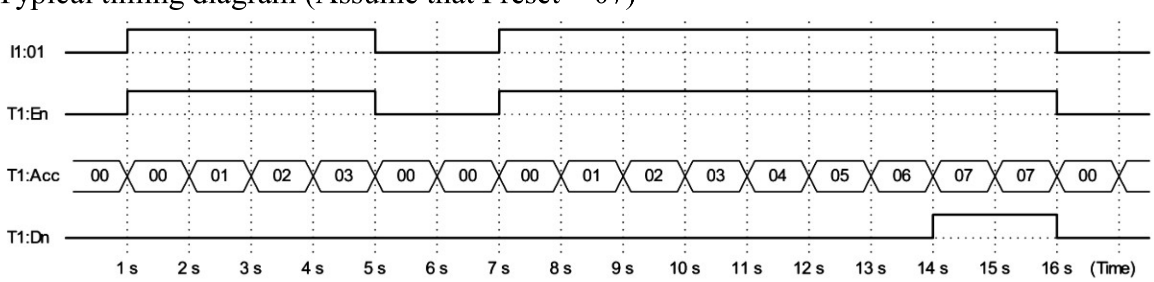
**Timer On-Delay (TON) Instruction**

The TON instruction begins to count when its input rung conditions are true. The accumulated value is reset when the input rung conditions become false.

Timer ladder diagram example:



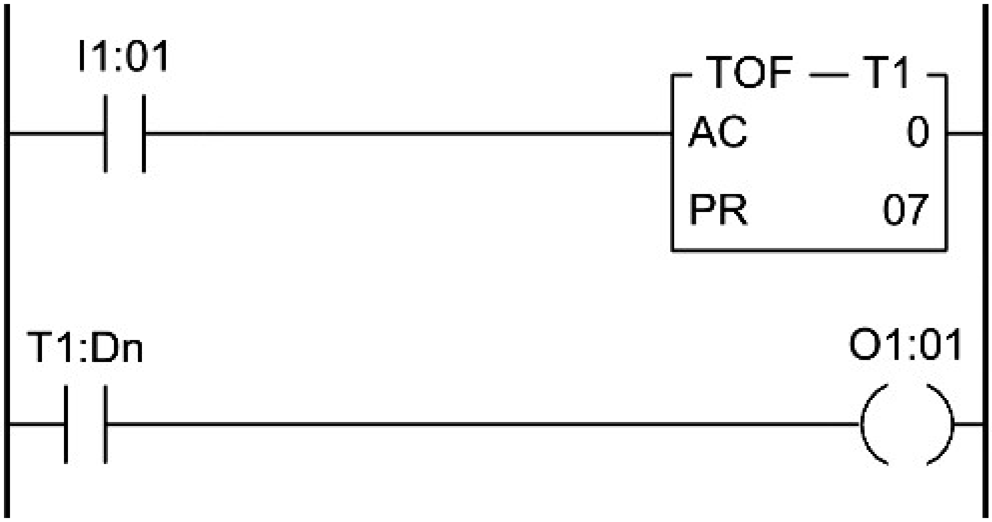

Typical timing diagram (Assume that Preset = 07)



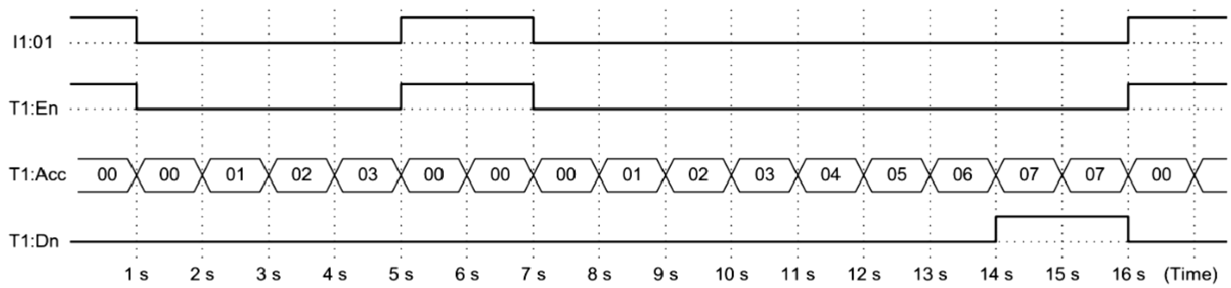

# Timer Off-Delay (TOF) Instruction

The TOF instruction begins to count when its input rung makes a true-to-false transition, and continues counting for as long as the input rung remains false. The accumulated value is reset when the input rung conditions become false.

Timer ladder diagram example:



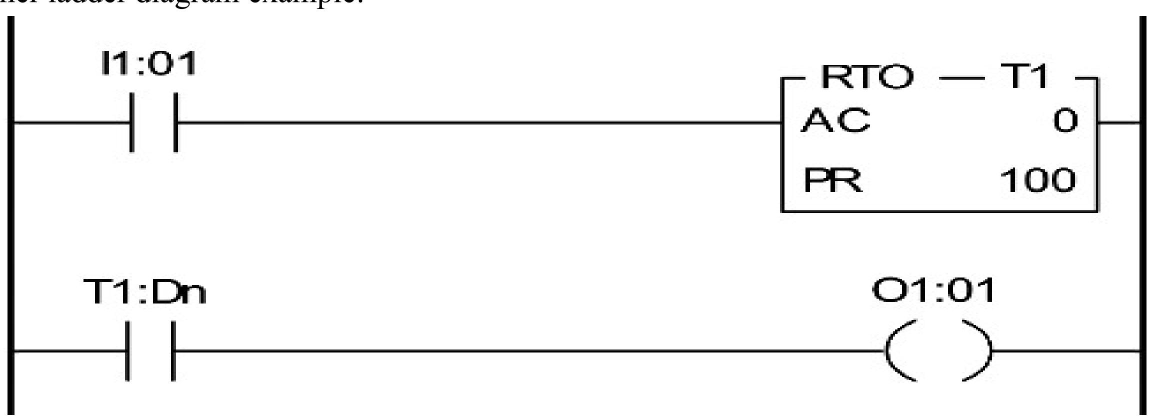

Typical timing diagram (Assume that Preset = 07)



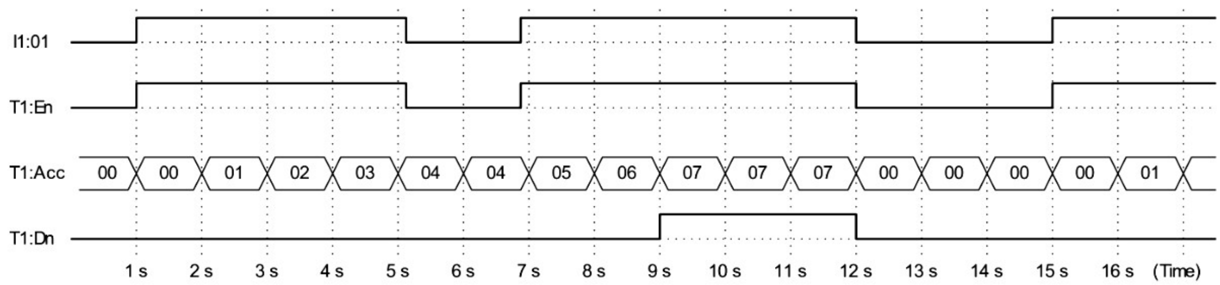

**Retentive Timer (RTO) Instruction**

The RTO instruction begins to count when its input rung conditions are true. The accumulated value is retained when the input rung conditions become false, and continues counting after the input rung conditions become true.

Timer ladder diagram example:




Typical timing diagram (Assume that Preset = 07)




**Counter Instructions**

Counter Instructions are output instructions used to count false-to-true rung transitions. These transitions are usually caused by events occurring at an input.

These counters can be UP (incrementing) or DOWN (decrementing).

Each counter instruction has two values (integers) associated with it:

- Accumulated Value (ACC): This is the current number of the counter. The initial value is zero.
- Preset Value (PR): This is a predetermined value set by the programmer. When the accumulated value is equal to, or greater than the preset value, a status bit is set. This bit can be used to control an output device.

Each counter is associated with two status bits:

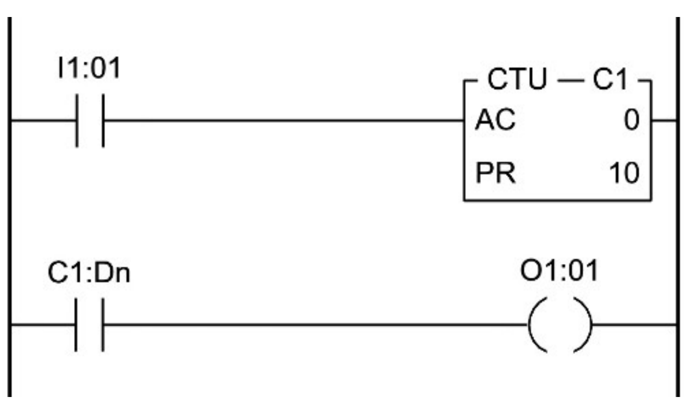
- Counter Enable Bit (EN): This bit is set when a false-to-true rung condition to the left of the counter instruction is detected.
- Done Bit (DN): This bit is set when the accumulated value is equal to the preset value. It is reset when the rung condition becomes false.

The maximum count value is 9999*. After a maximum count is reached, the counters reset and start counting from zero.

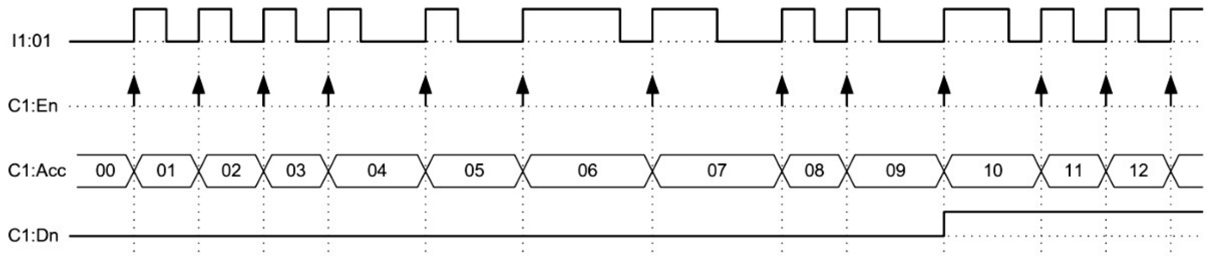
Count-up (CTU) Instruction

The CTU instruction increments its accumulated value on each false-to-true transition at its input, starting from 0.

Counter ladder diagram example:



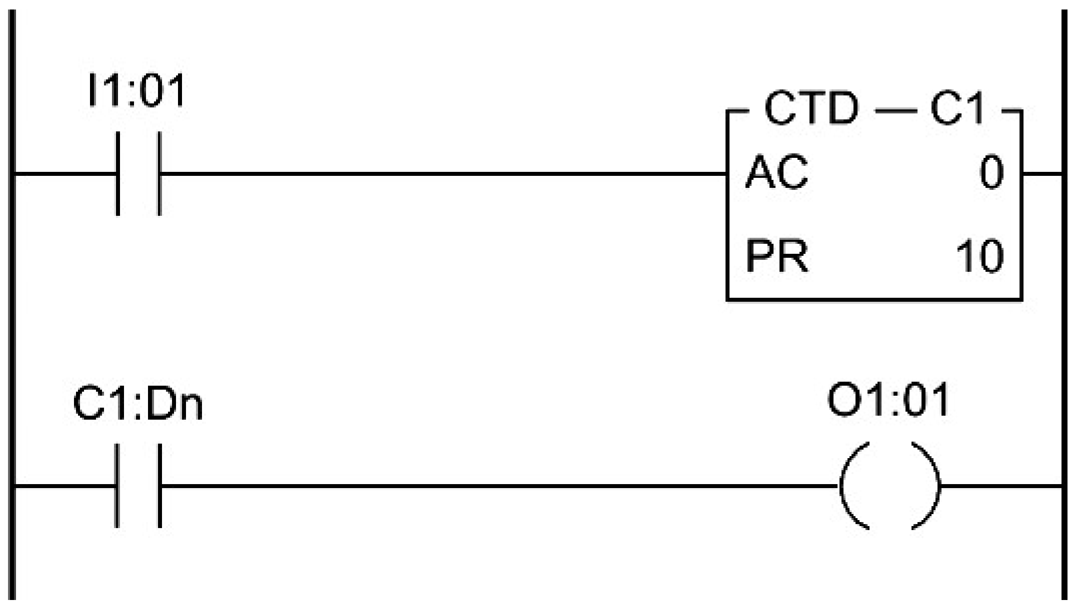
Typical timing diagram (Assume that Preset = 10)



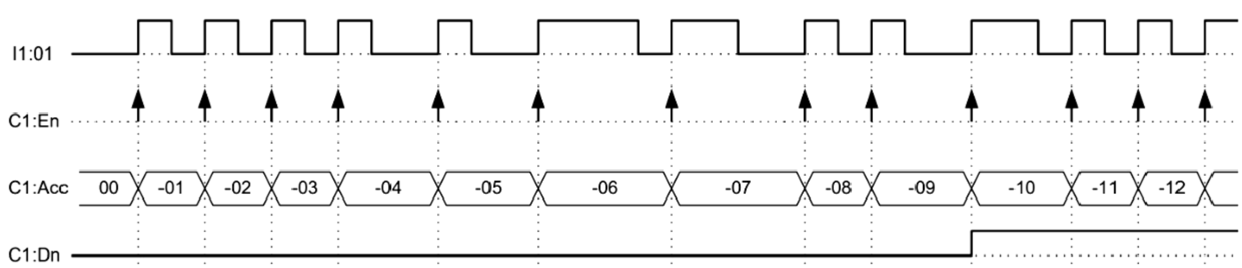

## Count-down (CTD) Instruction

The CTD instruction decrements its accumulated value on each false-to-true transition at its input, starting from 0.

## Counter ladder diagram example:




Typical timing diagram (Assume that Preset = -10)




The Reset (RES) Instruction

The RES instruction resets timing and counting instructions.

When the RES instruction is enabled it resets the following:

Counters:

- Accumulated value
- Counter Done Bit
- Counter Enabled Bit

Timers:

- Accumulated value
- Timer Done Bit
- Timer Timing Bit
- Timer Enable Bit

Reset ladder diagram example:


Some other PLC Instructions are :

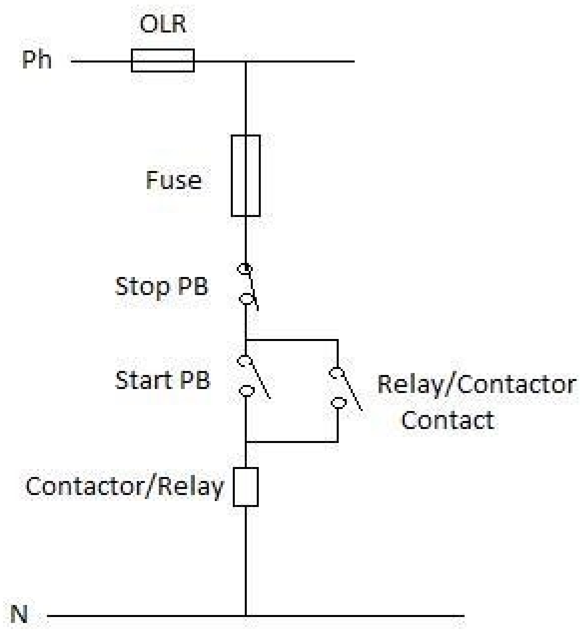
- Relay-type (Basic) instructions: I, O, OSR, SET, RES, T, C
- Data Handling Instructions:
- Data move Instructions: MOV, COP, FLL, TOD, FRD, DEG, RAD (degrees to radian).
- Comparison instructions: EQU (equal), NEQ (not equal), GEQ (greater than or equal), GRT (greater than).
- Mathematical instructions.
- Continuous Control Instructions ( PID instructions ).
- Program flow control instructions: MCR (master control reset), JMP, LBL, JSR, SBR, RET, SUS, REF
- Specific instructions:
- BSL, BSR (bit shift justify/right), SQO (sequencer output), SQC (sequencer compare), SQL (sequencer load).
- High-speed counter instructions: HSC, HSL, RES, HSE
- Communication instructions: MSQ, SVC
- ASCII instructions: ABL, ACB, ACI, ACL, CAN

**LADDER DIAGRAMS FOR FOLLOWING (I) DOL STARTER AND STAR-DELTA STARTER (II) STAIR CASE LIGHTING (III) TRAFFIC LIGHT CONTROL (IV) TEMPERATURE CONTROLLER**

**(I) DOL STARTER AND STAR-DELTA STARTER**

Working of Direct-On-Line (DOL) starter:

One method of starting electric motors is using direct on line (DOL) or across the line starter. In this method full line voltage is applied to the motor terminals. This is simplest type of motor starter. An electrical wiring diagram for single phase DOL starter is shown below.



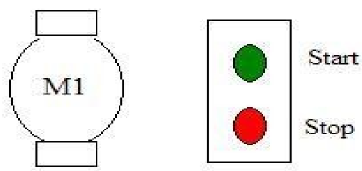

Control Circuit for DOL Starter

A DOL motor starter contains fuse and over load relay (OLR) for protection purpose. The starter can be contain momentary contact or maintained contact push buttons. The example considered here is momentary contact push buttons. For starting purpose normally open (NO) push button is preferred whereas normally closed (NC) push button is used to stop the motor.

The excessive supply voltage drop causing high inrush current is the criteria to limit the use of DOL starter. Conveyor motors, water pumps are the applications where DOL starters are used.

Procedure

Problem Statement: To start a motor using DOL starter. The simple P&I; diagram for this problem is as below.




Listing of Input and Output devices:

Inputs: PB1- To start the motor

PB2- To stop the motor

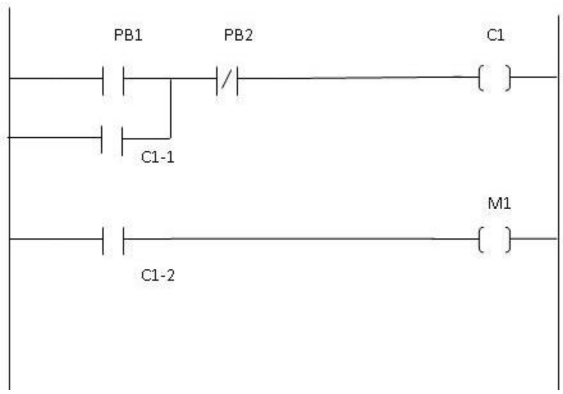
Output: M1- Motor

Sequence of Events :
1. When Start push button (PB1) is pressed, Motor (M1) has to start.
2. If Start pushbutton (PB1) is released and Stop pushbutton (PB2) is not pressed, Motor (M1) should remain on.
3. When Stop push button (PB2 is pressed, Motor (M1) has tol stop.
4. If stop push button is released and start is not pressed (released) motor should remain off.

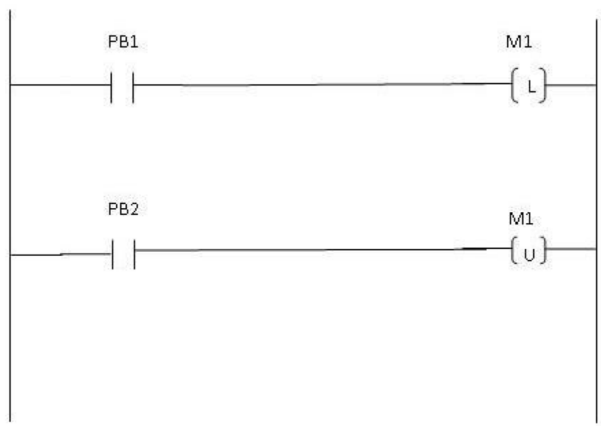
The Boolean equation to represent this sequence is

$$M1 = PB1.\overline{PB2}$$

The ladder diagram to implement these equations is shown below.




As the momentary contact push buttons are used here, the condition of PB1 is maintained through contact of coil C1. This contact is called as latching contact. The same sequence of event can be executed by using latch and unlatch instruction in the following way.




**STAR-DELTA STARTER**

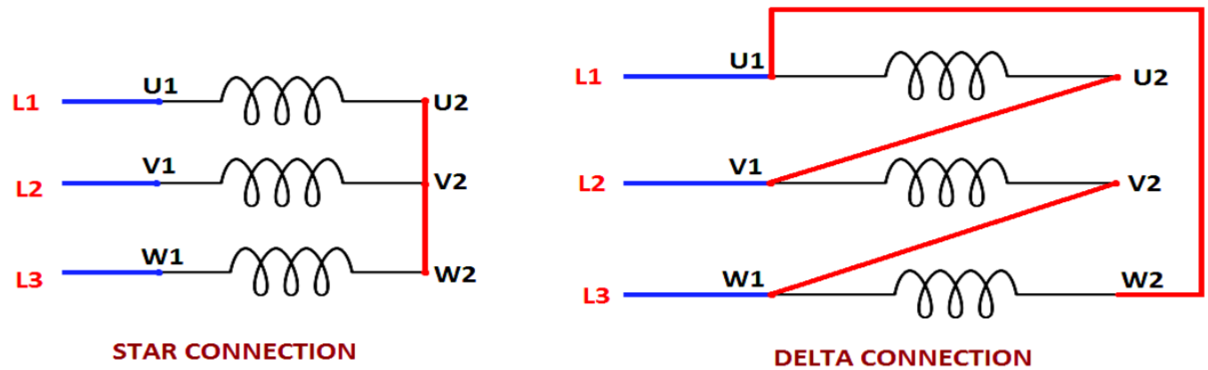
When electric motor is started, it draws a high current typical 5-6 times greater than normal current. In DC motors there is no back emf at starting therefore initial current is very high as compared to the normal current.

To protect the motor from these high starting currents we use a star and delta starter.

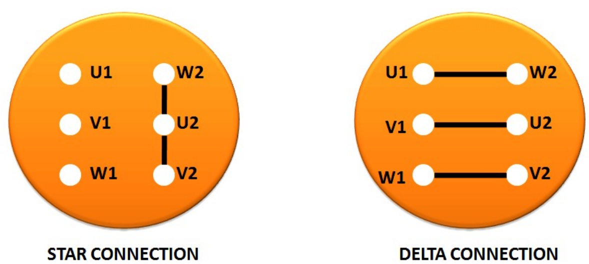
Simply in Star connection, supply voltage to motor will be less. so we use star connection during starting of the motor, after motor running we will change the connection form star to delta to gain full speed of the motor.

**Star Delta Motor Starter**

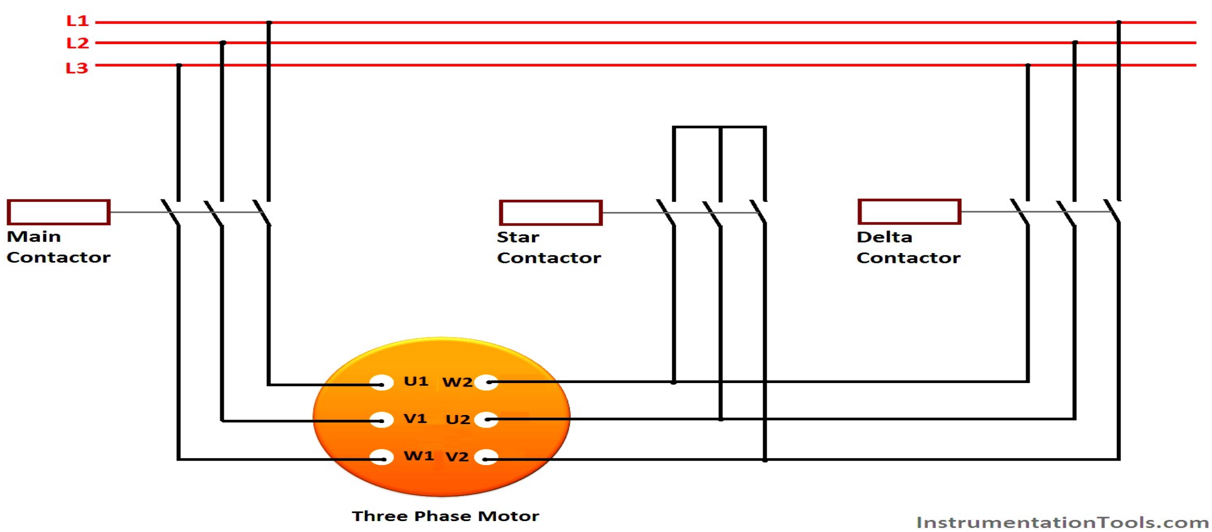
The following figure shows the winding connections in star and delta configuration one by one.



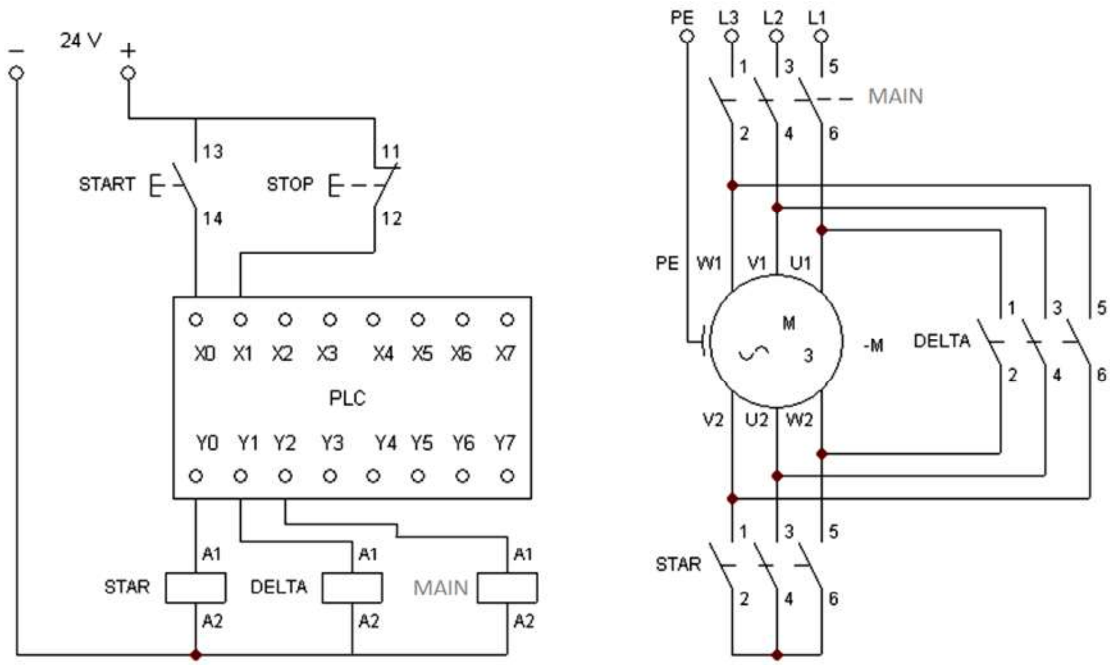

It can be seen that in star connection, one end of all three windings are shorted to make star point while other end of each winding is connected to power supply.It can be seen that in star connection, one end of all three windings are shorted to make star point while other end of each winding is connected to power supply. In delta configuration, the windings are connected such that to make a close loop. The connection of each winding is shown in above figure. In actual motor the three phase connections are provided in the following order as shown




So in order to make winding connection in star and delta style in practical motor, the connection is shown above.

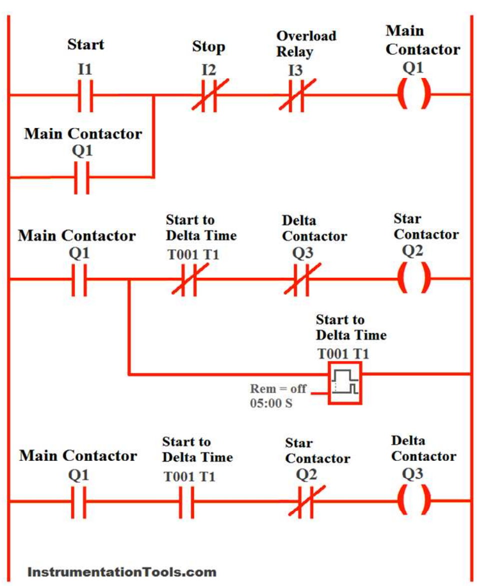


Main contractor is used to supply power to the windings. It must be turned on all the time. Initially the star contactor is closed while delta contactor is open It makes the motor windings in star configuration. When the motor gains speed, the star contactor is opened while delta contactor is closed turning the motor windings into delta configuration. The contactors are controlled by using PLC. The following section of PLC tutorial will explain the ladder programming for star delta motor starter.PLC program for star delta motor starter:




## PLC Ladder Logic

STAR-DELTA MOTOR STARTER LADDER LOGIC



Rung 1 Main contractor :

The main contactor depends upon the normally open input start push button (I1), normally closed stop button (I2) and normally closed overload relay. It means that Main contactor will only be energized if start button is pressed, while stop is not pressed and overload relay is not activated. A normally open input named (Q1) is added in parallel to the start button I1.By doing so, a push button is created which means that once motor is started, it will be kept started even if start button is released

Rung 2 Star contactor:

Star contactor depends upon main contractor, normally close contacts of timer (T1), and normally close contacts of output delta contactor (Q3).So star contactor will only be energized if main contactor is ON, time output is not activated and delta contactor is not energized.

Timer T1:

Timer T1 measures the time after which the winding connection of star delta starter is to be changed. It will start counting time after main contractor is energized.

Rung 3 Delta contactor:

Delta contactor will be energized when main contactor (Q1) is energized, timer T1 is activated and star contactor (Q3) is de-energized.

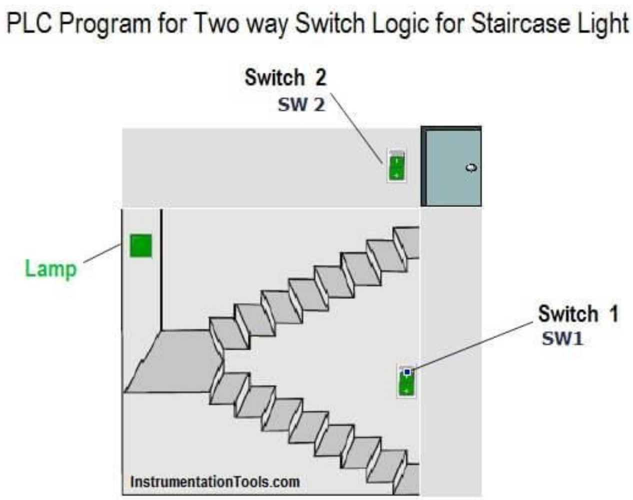
**(ii) Stair case lighting**

This is PLC Program for Two ways switch logic for staircase light in house

**PLC Two Way Switch Logic**

- In duplex type house there are ground floor and first floor and sometimes second floor also.
- Sometimes people need to go from ground floor to first floor or from first floor to ground floor by staircase provided in house.
- But in staircase there is no sunlight so people need a lamp/light to see the steps of the staircase easily.
- Here we are using a simple PLC to control this lamp using two switches, one switch at ground floor and second switch at first floor to control one lamp as shown in below figure.
- Note : we can also build the circuit using simple relays/switches also. This article only for understanding the basic concept of 2 way switch using a PLC Ladder Logic.

Problem Diagram




**Problem Solution**

We will solve this problem by simple automation. As shown in figure consider one simple house with one floor and staircase is provided in the house.

Here we will set lighting system for the users to switch ON/OFF the light whether they are on bottom of the stair or at top.

We will provide separate switch for each floor as shown in above figure.

## List of inputs/outputs

**Digital Inputs**

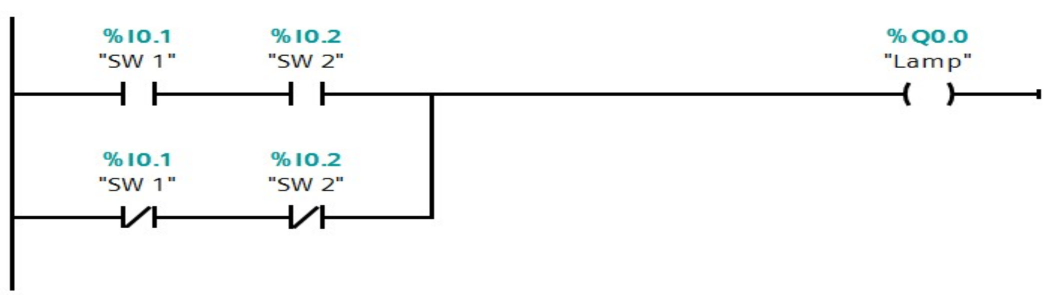
SW1: I0.1

SW2: I0.2

**Digital Outputs**

Lamp: Q0.0

PLC Ladder diagram for two ways switch logic




**Program Description**

- For this application, we used S7-1200 PLC and TIA portal software for programming.

- In above program, we have added two NO contacts of SW 1 (I0.1) and SW 2 (I0.2) in series and NC contacts of SW1 (I0.1) and SW2 (I0.2) in parallel of this series SW1 & SW2 NO Contacts.
- If the status of the bottom switch (SW1) and status of the top switch (SW2) are same then lamp will be ON. And if either status of the bottom or top switch is different from other then lamp (Q0.0) will be OFF.
- When lamp (Q0.0) is OFF then user can ON the lamp by changing status of any switch. Also user can turn OFF the lamp by changing the status of one of the two switches.

**Runtime Test Cases**

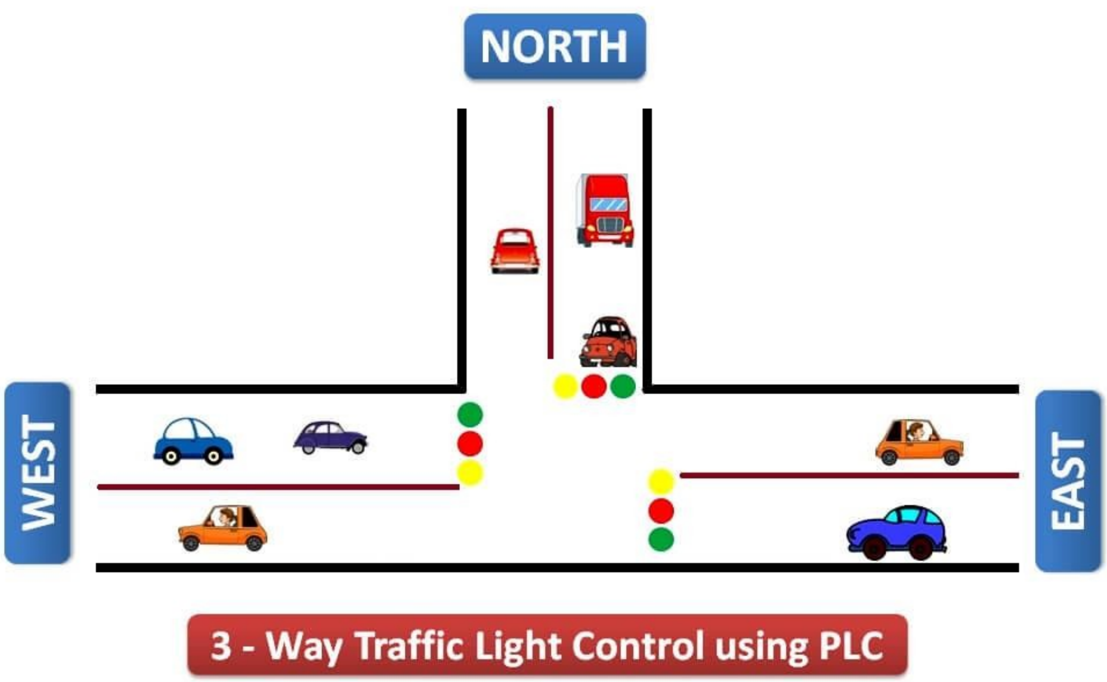
PLC Program for Two Way Switch Logic

| Inputs | Outputs | Physical Elements |
|---|---|---|
| I0.1=1 & I0.2=1 | Q0.0=1 | Lamp on |
| I0.1=0 & I0.2=0 | Q0.1=1 | Lamp on |
| I0.1=0 & I0.2=1 | Q0.1=0 | Lamp off |
| I0.1=1 & I0.2=0 | Q0.1=0 | Lamp off |

**(iii)** Traffic light Control

We most often come across a three-way traffic jam in our city. This **PLC program** gives the solution to control heavy traffic jams using programmable logic control.

**Traffic Light Control using PLC**



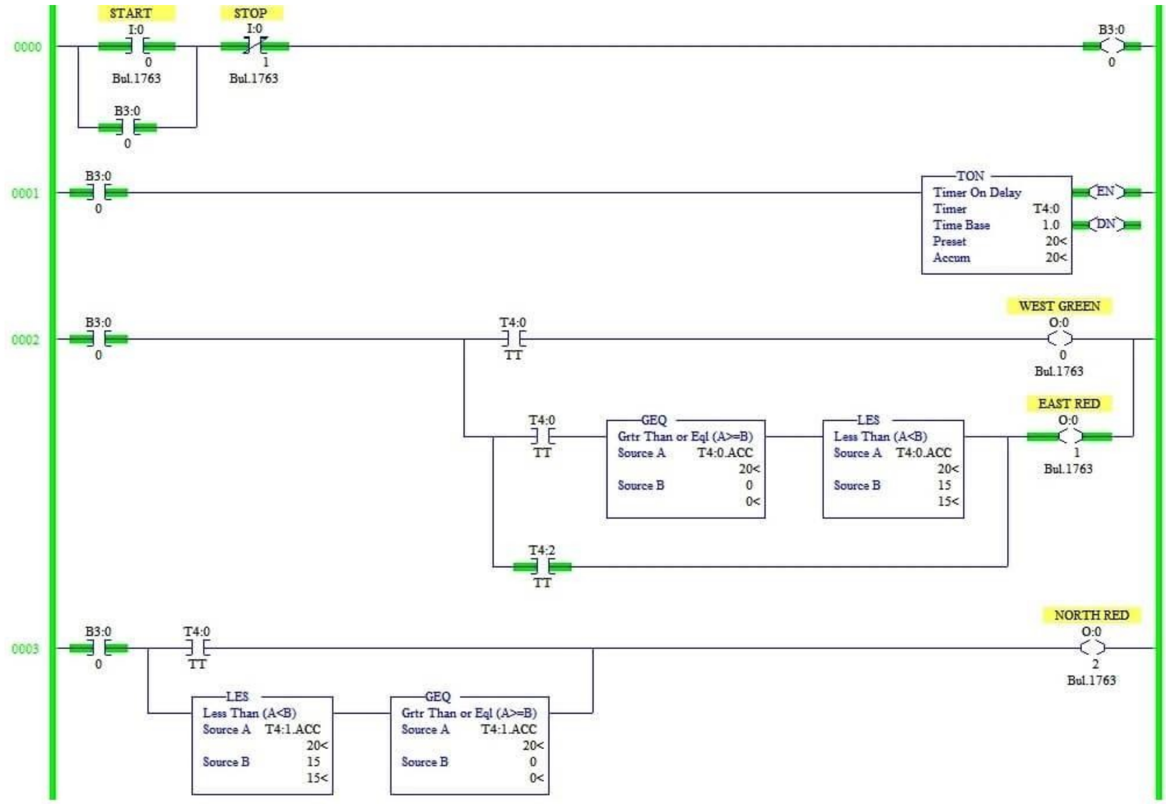
Problem Solution

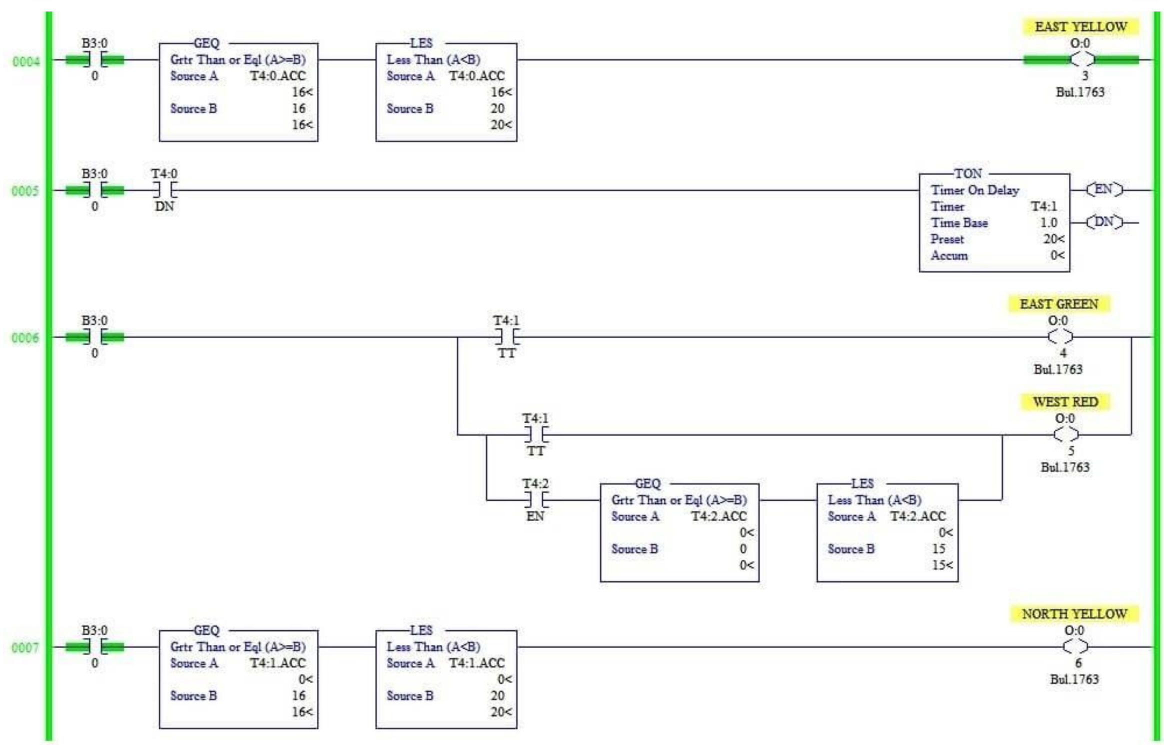
- They are so many ways to write a program for traffic light control ex: sequencer output method but in this normal input, outputs and timers are used.
- Timers are used to give time delay for output to turn ON and OFF.
- Reset coil is used at the end to run the program continuously.
- Comparator blocks are used to reduce the number of timers used.
- Program done in AB RSLogix 500 Software.

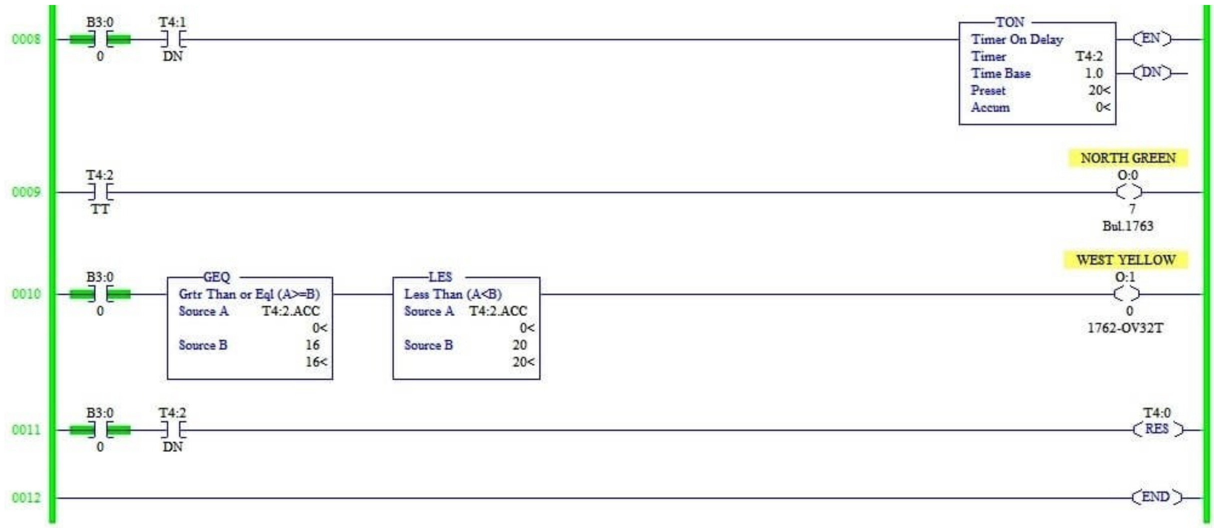
List of Inputs and Outputs for Traffic Control System

| S.no | Address | Name | Input/Output |
|---|---|---|---|
| 1 | I:0/0 | Start | Input |
| 2 | I:0/1 | Stop | Input |
| 3 | B3.0 | Memory | Memory |
| 4 | O:0/0 | West Green | Output |
| 5 | O:0/1 | East Red | Output |
| 6 | O:0/2 | North Red | Output |
| 7 | O:0/3 | East yellow | Output |
| 8 | O:0/4 | East Green | Output |
| 9 | O:0/5 | West Red | Output |
| 10 | O:0/6 | North Yellow | Output |
| 11 | O:0/7 | North Green | Output |
| 12 | O:1/0 | West Yellow | Output |

PLC Program for 3-way Traffic control System


0000
START
I:0
0
Bul.1763
STOP
I:0
1
Bul.1763
B3:0
0
B3:0
0
0001
B3:0
0
TON
Timer On Delay
Timer T4:0
Time Base 1.0
Preset 20<
Accum 20<
EN
DN
0002
B3:0
0
T4:0
TT
WEST GREEN
O:0
0
Bul.1763
T4:0
TT
GEQ
Grtr Than or Eql (A>=B)
Source A T4:0.ACC
20<
Source B 0
0<
LES
Less Than (A<B)
Source A T4:0.ACC
20<
Source B 15
15<
EAST RED
O:0
1
Bul.1763
T4:2
TT
0003
B3:0
0
T4:0
TT
NORTH RED
O:0
2
Bul.1763
LES
Less Than (A<B)
Source A T4:1.ACC
20<
Source B 15
15<
GEQ
Grtr Than or Eql (A>=B)
Source A T4:1.ACC
20<
Source B 0
0<


0004
B3:0
0
GEQ
Grtr Than or Eql (A>=B)
Source A T4:0.ACC
16<
Source B 16
16<
LES
Less Than (A<B)
Source A T4:0.ACC
16<
Source B 20
20<
EAST YELLOW
O:0
3
Bul.1763
0005
B3:0
0
T4:0
DN
TON
Timer On Delay
Timer T4:1
Time Base 1.0
Preset 20<
Accum 0<
EN
DN
0006
B3:0
0
T4:1
TT
EAST GREEN
O:0
4
Bul.1763
T4:1
TT
WEST RED
O:0
5
Bul.1763
T4:2
EN
GEQ
Grtr Than or Eql (A>=B)
Source A T4:2.ACC
0<
Source B 0
0<
LES
Less Than (A<B)
Source A T4:2.ACC
0<
Source B 15
15<
0007
B3:0
0
GEQ
Grtr Than or Eql (A>=B)
Source A T4:1.ACC
0<
Source B 16
16<
LES
Less Than (A<B)
Source A T4:1.ACC
0<
Source B 20
20<
NORTH YELLOW
O:0
6
Bul.1763




Below tabular column gives the Steps or sequence of outputs to turn ON.

| S.NO | EAST | WEST | NORTH |
|---|---|---|---|
| 1 | R | G | R |
| 2 | Y | G | R |
| 3 | G | R | R |
| 4 | G | R | Y |
| 5 | R | R | G |
| 6 | R | Y | G |

PLC Logic Description for 3-way Traffic Control System

RUNG000:

This is a Latching rung to operate the system through Master Start and Stop PB.

RUNG001 and RUNG0002:

Starting the timer to turn ON first output West Green so east and west should be in red. Comparators in Parallel rung are used to turn OFF East red after 15 sec. Timer T4:2 timing bit in parallel contact used to turn ON East red again in 5th and 6Th Step. (Refer Above Tabular column for clarification)

RUNG 0003:

Turning ON North Red up to 3rd step using T4:0 and T4:1's timer timing bit and comparator blocks.

Rung 0004:

Turn ON East yellow for 5 sec using comparator blocks. (Step 2nd)

Rung 0005-0006-0007-0008-0009-0010 :

The same procedures followed to turn ON further outputs. ( Refer Tabular column for a sequence of operation)

RUNG 0011:
Reset coil is turned ON using T4:2‘s done bit to restart the cycle from beginning
The program runs continuously until STOP PB is pressed

**(IV) TEMPERATURE CONTROLLER**

PLC Temperature Control : In a vessel there are Three Heaters which are used to control the temperature of the vessel.

PLC Temperature Control Programming

We are using Three Thermostats to measure the temperature at each heater. Also another thermostat for safety shutoff in case of malfunction or emergency or to avoid over temperatures. All these heaters have different set points or different temperature ranges where heaters can be turned ON accordingly (below table shows the temperature ranges).

- A temperature control system consists of four thermostats. The system operates three heating units. The thermostats (TS1/TS2/TS3/TS4 are set at 55°C, 60°C, 65°C and 70°C.
- Below 55°C temperature, three heaters (H1,H2,H3) are to be in ON state
- Between 55°C – 60°C two heaters (H2,H3) are to be in ON state.
- Between 60°C – 65°C one heater (H3) is to be in ON state.
- Above 70°C all heaters are to be in OFF state, there is a safety shutoff (Relay CR1) in case any heater is operating by mistake.
- A master switch turns the system ON and OFF.

Solution:

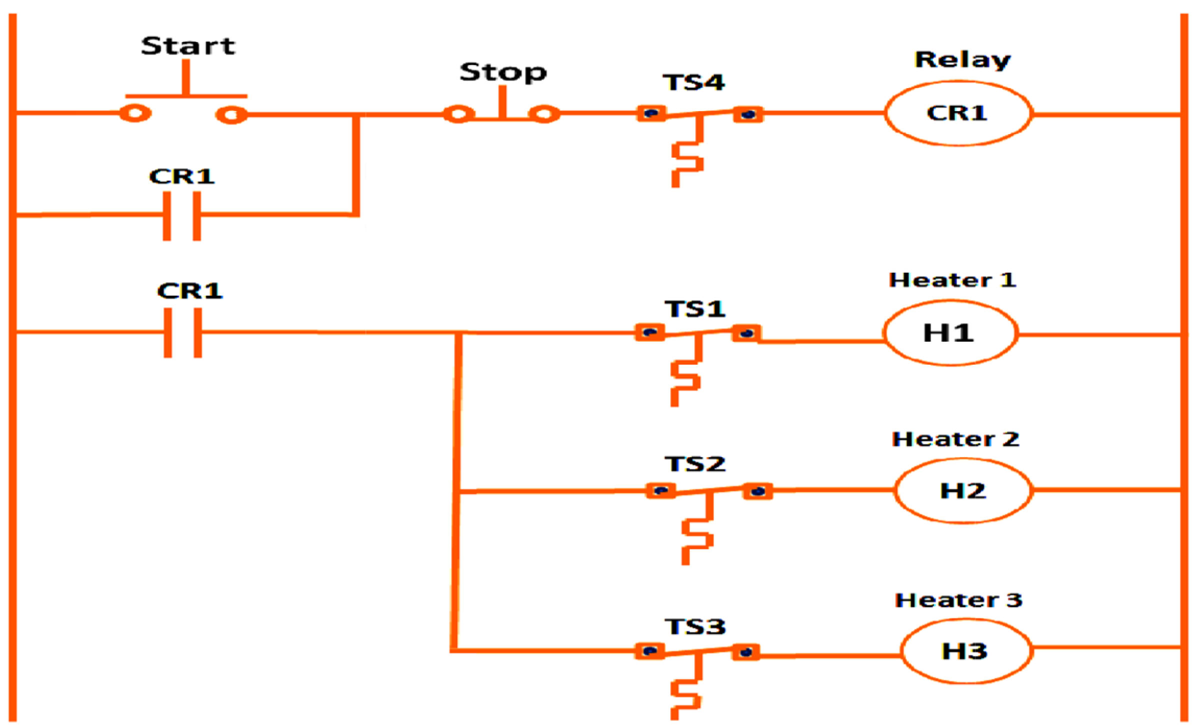
- There are four thermostats; assume them be in NC state when the set point is not reached.
- Let there be a control relay (CR1) to work as a safety shutoff.
- Master Switch: The Start switch is NO and Stop switch NC type.

The below table shows the temperature ranges where Thermostats (TS1,TS2,TS3,TS4) status will be indicated as per the temperature value.

Also the Heaters (H1, H2, H3) status in which either those Heaters will be ON or OFF as per the temperature value.

| Temperature | Thermostats | Heater 1 | Heater 2 | Heater3 |
|---|---|---|---|---|
| Below 55°C | TS1 Closed<br>TS2 Closed<br>TS3 Closed<br>TS4 Closed | ON | ON | ON |
| 55°C-60°C | TS1 Open<br>TS2 Closed<br>TS3 Closed<br>TS4 Closed | OFF | ON | ON |
| 60°C-65°C | TS1 Open<br>TS2 Open<br>TS3 Closed<br>TS4 Closed | OFF | OFF | ON |
| 65°C-70°C | TS1 Open<br>TS2 Open<br>TS3 Open<br>TS4 Closed | OFF | OFF | OFF |
| Above 70°C | TS1 Open<br>TS2 Open<br>TS3 Open<br>TS4 Open | OFF | OFF | OFF |

## PLC Ladder Logic



Ladder Logic Operation :

First Rung:

It has START button (default NO contact) and STOP button (default NC contact). A Relay CR1 is used to control the heaters depending on the thermostats status.

A Thermostat TS4 is connected in between STOP & Relay; if TS4 activated (means TS4 contact changes from NC to NO) then all heaters will be OFF.

An NO contact of Relay CR1 is used across the START button in order to latch or hold the START command.

Second Rung:

Second Rung:

An NO contact of Relay CR1 is used to control the Heaters (H1, H2, H3) with the thermostats (TS1,TS2,TS3) status.

After giving START command, This NO contact becomes NC contact. if temperature below 55 Deg C, TS1, TS2 & TS3 will be in Close Status so all heaters will be ON.

If Temperature is in between 55 to 60 Deg C, Then TS1 will be Open, so Heater H1 will be OFF.

Then, if temperature in between 60 to 65 Deg C then TS2 also be Open, so Heater H2 will be OFF

if temperature in between 65 to 70 Deg C then TS3 also be Open, so Heater H3 will be OFF

There is a safety Shutoff which is used to avoid any malfunctions of Thermostats or to avoid over temperatures.

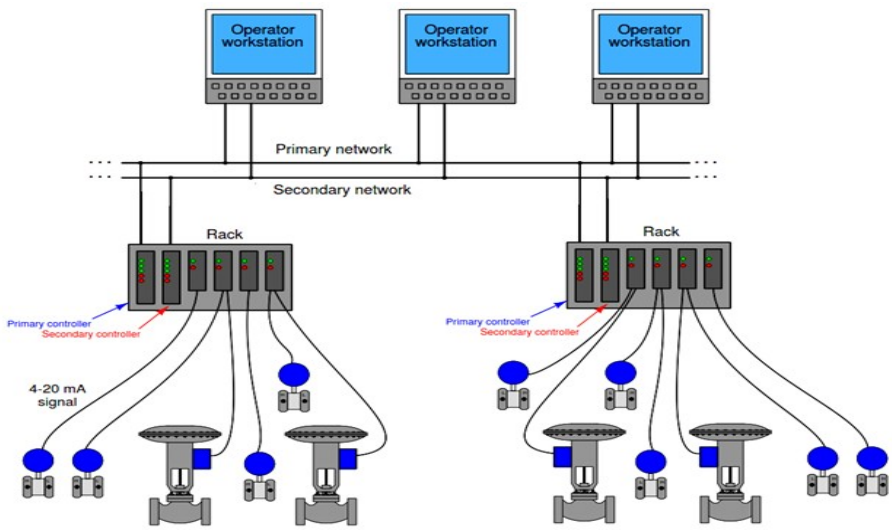
if temperature reaches above 70 Deg C then TS4 will activates and de-energizes the Relay, thus all Heaters will be turned OFF.

Note: Here Heaters H1, H2, H3 are either Relays or Contactors we energizing. so an NO contact of these relays are connected to Electrical Heater feeder circuits (MCC).These Electrical Feeder circuits will be controlled as per these signals and accordingly the heaters will be either ON or OFF.

**SPECIAL CONTROL SYSTEMS- BASICS DCS & SCADA SYSTEMS**

## Distributed Control Systems (DCS)

The following illustration shows a typical distributed control system (DCS) architecture:




Each “rack” contains a microprocessor to implement all necessary control functions, with individual I/O (input/output) “cards” for converting analog field instrument signals into digital format, and vice-versa. Redundant processors, redundant network cables, and even redundant I/O cards address the possibility of component failure.

DCS processors are usually programmed to perform routine self-checks on redundant system components to ensure availability of the spare components in the event of a failure.

If there ever was a total failure in one of the “control racks” where the redundancy proved insufficient for the fault(s), the only PID loops faulted will be those resident in that rack, not any of the other loops throughout the system.

Likewise, if ever the network cables become severed or otherwise faulted, only the information flow between those two points will suffer; the rest of the system will continue to communicate data normally.

Thus, one of the “hallmark” features of a DCS is its tolerance to serious faults: even in the event of severe hardware or software faults, the impact to process control is minimized by design.

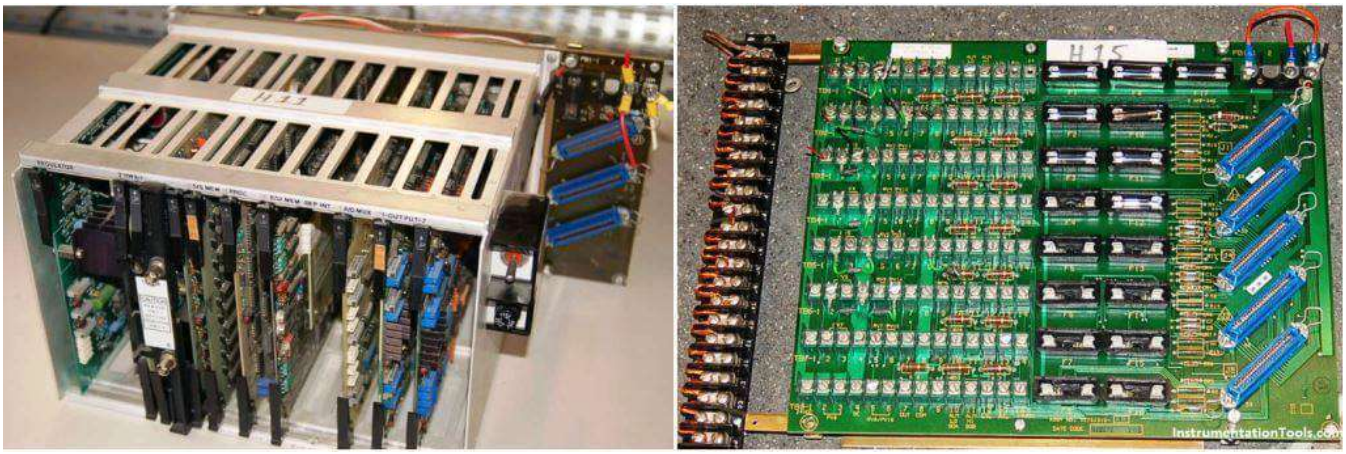
One of the very first distributed control systems in the world was the Honeywell TDC2000 system (Note 1) , introduced in 1975. By today’s standards, the technology was crude, but the concept was revolutionary.

Note 1: To be fair, the Yokogawa Electric Corporation of Japan introduced their CENTUM distributed control system the same year as Honeywell.

Each rack (called a “box” by Honeywell) consisted of an aluminum frame holding several large printed circuit boards with card-edge connectors. A “basic controller” box appears in the left-hand photograph.

The right-hand photograph shows the termination board where the field wiring (420 mA) connections were made. A thick cable connected each termination board to its respective controller box:

DCS Hardware



Controller redundancy in the TDC2000 DCS took the form of a “spare” controller box serving as a backup for up to eight other controller boxes. Thick cables routed all analog signals to this spare controller, so that it would have access to them in the event it needed to take over for a failed controller.

The spare controller would become active on the event of any fault in any of the other controllers, including failures in the I/O cards.

Thus, this redundancy system provided for processor failures as well as I/O failures. All TDC2000 controllers communicated digitally by means of a dual coaxial cable network known as the “Data Hiway.” The dual cables provided redundancy in network communications.

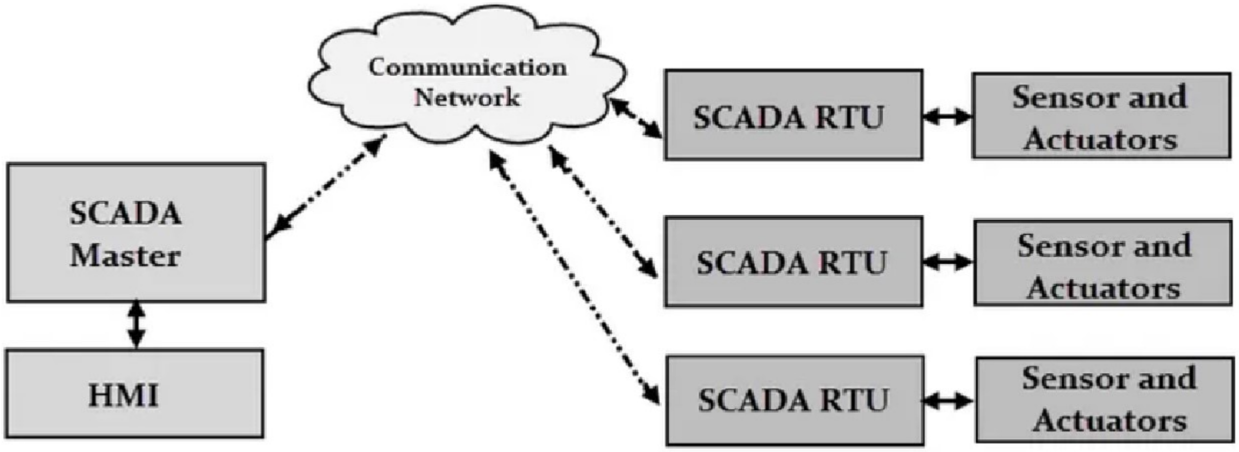
**SCADA SYSTEMS**

SCADA stands for “Supervisory Control and Data Acquisition”. SCADA is a type of process control system architecture that uses computers, networked data communications and graphical Human Machine Interfaces (HMIs) to enable a high-level process supervisory management and control.

SCADA systems communicate with other devices such as programmable logic controllers (PLCs) and PID controllers to interact with industrial process plant and equipment.

SCADA systems form a large part of control systems engineering. SCADA systems gather pieces of information and data from a process that is analyzed in real-time (the “DA” in SCADA). It records and logs the data, as well as representing the collected data on various HMIs.

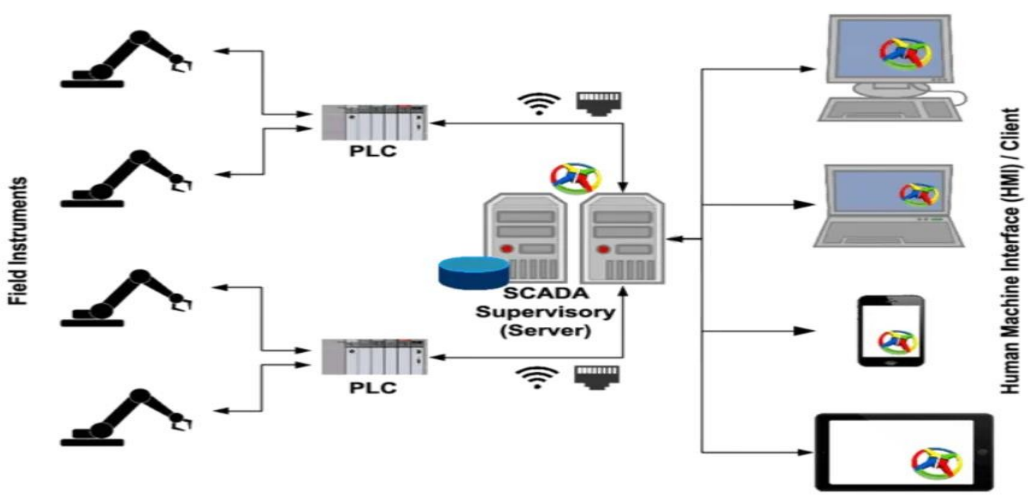
This enables process control operators to supervise (the “S” in SCADA) what is going on in the field, even from a distant location. It also enables operators to control (the “C” in SCADA) these processes by interacting with the HMI.




Supervisory Control and Data Acquisition systems are essential to a wide range of industries and are broadly used for the controlling and monitoring of a process. SCADA systems are prominently used as they have the power to control, monitor, and transmit data in a smart and seamless way. In today's data-driven world, we are always looking for ways to increase automation and make smarter decisions through the proper use of data – and SCADA systems are a great way of achieving this.

SCADA systems can be run virtually, which allows the operator to keep a track of the entire process from his place or control room. Time can be saved by using SCADA efficiently. One such excellent example is, SCADA systems are used extensively in the Oil and Gas sector. Large pipelines will be used to transfer oil and chemicals inside the manufacturing unit.

Hence, safety plays a crucial role, such that there should not be any leakage along the pipeline. In case, if some leakage occurs, a SCADA system is used to identify the leakage. It infers the information, transmits it to the system, displays the information on the computer screen and also gives an alert to the operator.




SCADA Architecture

Generic SCADA systems contain both hardware and software components. The computer used for analysis should be loaded with SCADA software. The hardware component receives the input data and feds it into the system for further analysis.

SCADA system contains a hard disk, which records and stores the data into a file, after which it is printed as when needed by the human operator. SCADA systems are used in various industries and manufacturing units like Energy, Food and Beverage, Oil and Gas, Power, Water, and Waste Management units and many more.

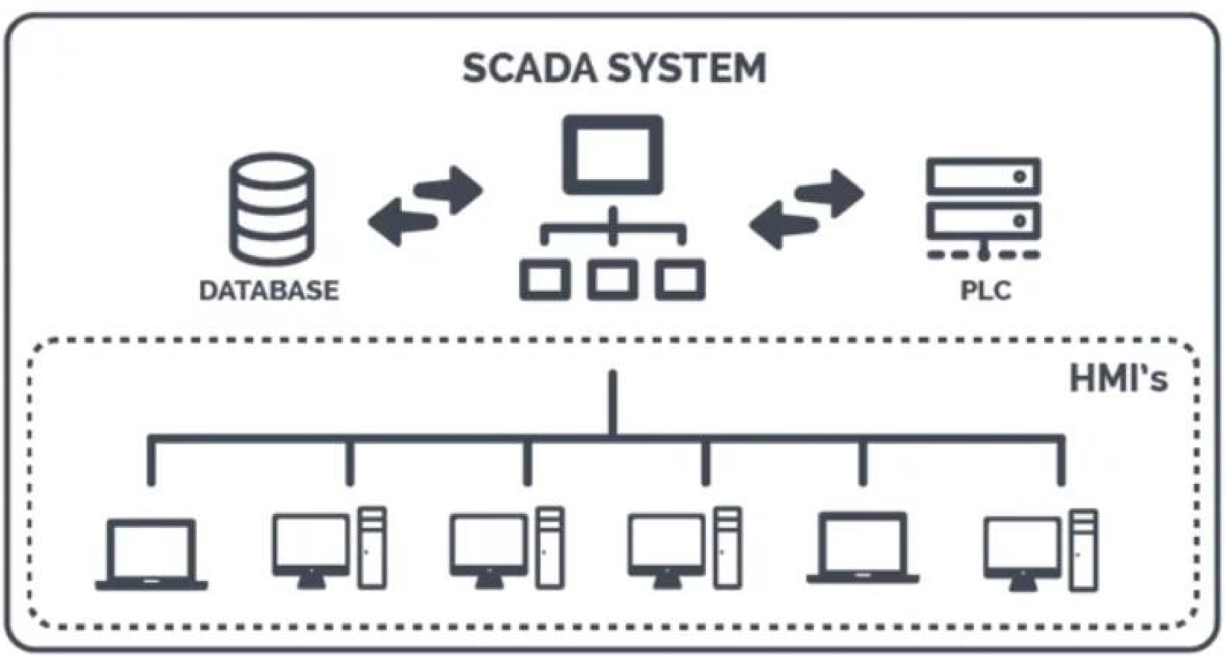
SCADA Basics

Objectives of SCADA

- Monitor: SCADA systems continuously monitor the physical parameters
- Measure: It measures the parameter for processing
- Data Acquisition: It acquires data from RTUs (Remote Terminal Units), data loggers, etc
- Data Communication: It helps to communicate and transmit a large amount of data between MTU and RTU units
- Controlling: Online real-time monitoring and controlling of the process
- Automation: It helps for automatic transmission and functionality

The SCADA systems consist of hardware units and software units. SCADA applications are run using a server. Desktop computers and screens act as an HMI which are connected to the server. The major components of a SCADA system include:

- Master Terminal Unit (MTU)
- Remote Terminal Unit (RTU)
- Communication Network (defined by its network topology)



Master Terminal Unit (MTU)
MTU is the core of the SCADA system. It comprises a computer, PLC and a network server that helps MTU to communicate with the RTUs. MTU begins communication, collects and saves data, helps to interface with operators and to communicate data to other systems.

Remote Terminal Unit (RTU)
Being employed in the field sites, each Remote Terminal Unit (RTU) is connected with sensors and actuators. RTU is used to collect information from these sensors and further sends the data to MTU. RTUs have the storage capacity facility.

So, it stores the data and transmits the data when MTU sends the corresponding command. Recently developed units are employed with sophisticated systems that utilize PLCs as RTUs. This helps for direct transfer and control of data without any signal from MTU.

Remote terminal unit

Communication Network
In general, network means connection. When you tell a communication network, it is defined as a link between RTU in the field to MTU in the central location. The bidirectional wired or wireless communication channel is used for networking purposes. Various other communication mediums like fiber optic cables, twisted pair cables, etc. are also used.
Functions of SCADA Systems
In a nutshell, we can tell the SCADA system is a collection of hardware and software components that allows the manufacturing units to perform specific functions. Some of the important functions include

- To monitor and gather data in real-time
- To interact with field devices and control stations via Human Machine Interface (HMI)
- To record systems events into a log file
- To control manufacturing process virtually
- Information Storage and Reports

**COMPUTER CONTROL–DATA ACQUISITION, DIRECT DIGITAL CONTROL SYSTEM (BASICS ONLY)**

DATA ACQUISITION SYSTEMS

Definition

Data acquisition is the process of real world physical conditions and conversion of the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition and data acquisition systems (abbreviated with the acronym DAS) typically involves the conversion of analog waveforms into digital values for processing.

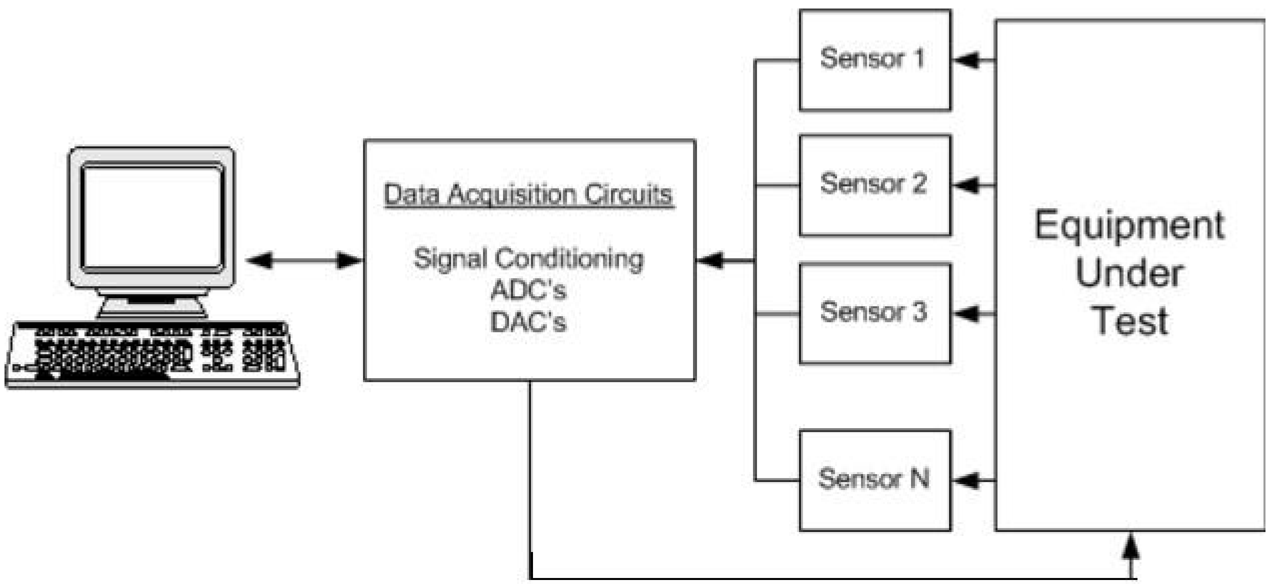
The components of data acquisition systems include:

i) Sensors that convert physical parameters to electrical signals.

ii) Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values.

iii) Analog-to-digital converters, which convert conditioned sensor signals to digital values.

**Diagram**




Fundamental elements of data acquisition system

Explanation

Data acquisition is the process of extracting, transforming, and transporting data from the source systems and external data sources to the data processing system to be displayed, analyzed, and stored.

A data acquisition system (DAQ) typically consist of transducers for asserting and measuring electrical signals, signal conditioning logic to perform amplification, isolation, and filtering, and other hardware for receiving analog signals and providing them to a processing system, such as a personal computer.

Data acquisition systems are used to perform a variety of functions, including laboratory research, process monitoring and control, data logging, analytical chemistry, tests and analysis of physical phenomena, and control of mechanical or electrical machinery.

Data recorders are used in a wide variety of applications for imprinting various types of forms, and documents.

Data collection systems or data loggers generally include memory chips or strip charts for electronic recording, probes or sensors which measure product environmental parameters and are connected to the data logger.

Hand-held portable data collection systems permit in field data collection for up-to-date information processing.

Source

Data acquisition begins with the physical phenomenon or physical property to be measured.

Examples of this include temperature, light intensity, gas pressure, fluid flow, and force.

Regardless of the type of physical property to be measured, the physical state that is to be measured must first be transformed into a unified form that can be sampled by a data acquisition system.

The task of performing such transformations falls on devices called sensors.

A sensor, which is a type of transducer, is a device that converts a physical property into a corresponding electrical signal (e.g., a voltage or current) or, in many cases, into a corresponding electrical characteristic (e.g., resistance or capacitance) that can easily be converted to electrical signal.

The ability of a data acquisition system to measure differing properties depends on having sensors that are suited to detect the various properties to be measured. There are specific sensors for many different applications.

DAQ systems also employ various signal conditioning techniques to adequately modify various different electrical signals into voltage that can then be digitized using an Analog-to-digital converter (ADC).

Signals

Signals may be digital (also called logic signals sometimes) or analog depending on the transducer used. Signal conditioning may be necessary if the signal from the transducer is not suitable for the DAQ hardware being used.

The signal may need to be amplified, filtered or demodulated.

Various other examples of signal conditioning might be bridge completion, providing current or voltage excitation to the sensor, isolation, and linearization. For transmission purposes, single ended analog signals, which are more susceptible to noise can be converted to differential signals. Once digitized, the signal can be encoded to reduce and correct transmission errors.

DAQ hardware

DAQ hardware is what usually interfaces between the signal and a PC. It could be in the form of modules that can be connected to the computer's ports (parallel, serial, USB, etc.) or cards connected to slots (S-100 bus, Apple Bus, ISA, MCA, PCI, PCI-E, etc.) in the mother board.

Usually the space on the back of a PCI card is too small for all the connections needed, so an external breakout box is required. The cable between this box and the PC can be expensive due to the many wires, and the required shielding

DAQ cards often contain multiple components (multiplexer, ADC, DAC, TTL-IO, high speed timers, RAM). These are accessible via a bus by a microcontroller, which can run small programs.

A controller is more flexible than a hard wired logic, yet cheaper than a CPU so that it is alright to block it with simple polling loops.

The fixed connection with the PC allows for comfortable compilation and debugging. Using an external housing a modular design with slots in a bus can grow with the needs of the user.

Not all DAQ hardware has to run permanently connected to a PC, for example intelligent stand-alone loggers and oscilloscopes, which can be operated from a PC, yet they can operate completely independent of the PC.

**DAQ software**

DAQ software is needed in order for the DAQ hardware to work with a PC. The device driver performs low-level register writes and reads on the hardware, while exposing a standard API for developing user applications.

A standard API such as COMEDI allows the same user applications to run on different operating systems, e.g. a user application that runs on Windows will also run on Linux and BSD.

**Advantages**

Reduced data redundancy

Reduced updating errors and increased consistency

Greater data integrity and independence from applications programs

Improved data access to users through use of host and query languages

Improved data security

Reduced data entry, storage, and retrieval costs

Facilitated development of new applications program

**Disadvantages**

Database systems are complex, difficult, and time-consuming to design Substantial hardware and software start-up costs

Damage to database affects virtually all applications programs

Extensive conversion costs in moving form a file-based system to a database system Initial training required for all programmers and users

**Applications**

Temperature measurement

Recommended application software packages and necessary toolkit

Prewritten Lab VIEW example code, available for download

Sensor recommendations

**DIRECT DIGITAL CONTROL SYSTEM**

Direct Digital Control (DDC) is the automated control of a condition or process by a digital device.

DDC takes a centralized network-oriented approach. All instrumentation is gathered by various analog and digital converters which use the network to transport these signals to the central controller.

The centralized computer then follows all of its production rules (which may incorporate sense points anywhere in the structure) and causes actions to be sent via the same network to valves, actuators, and other HVAC components that can be adjusted.

A microprocessor operating at sufficient clock speed is able to execute more than one PID control algorithm for a process loop, by "time-sharing" its calculating power: devoting slices of time to the evaluation of each PID equation in rapid succession.

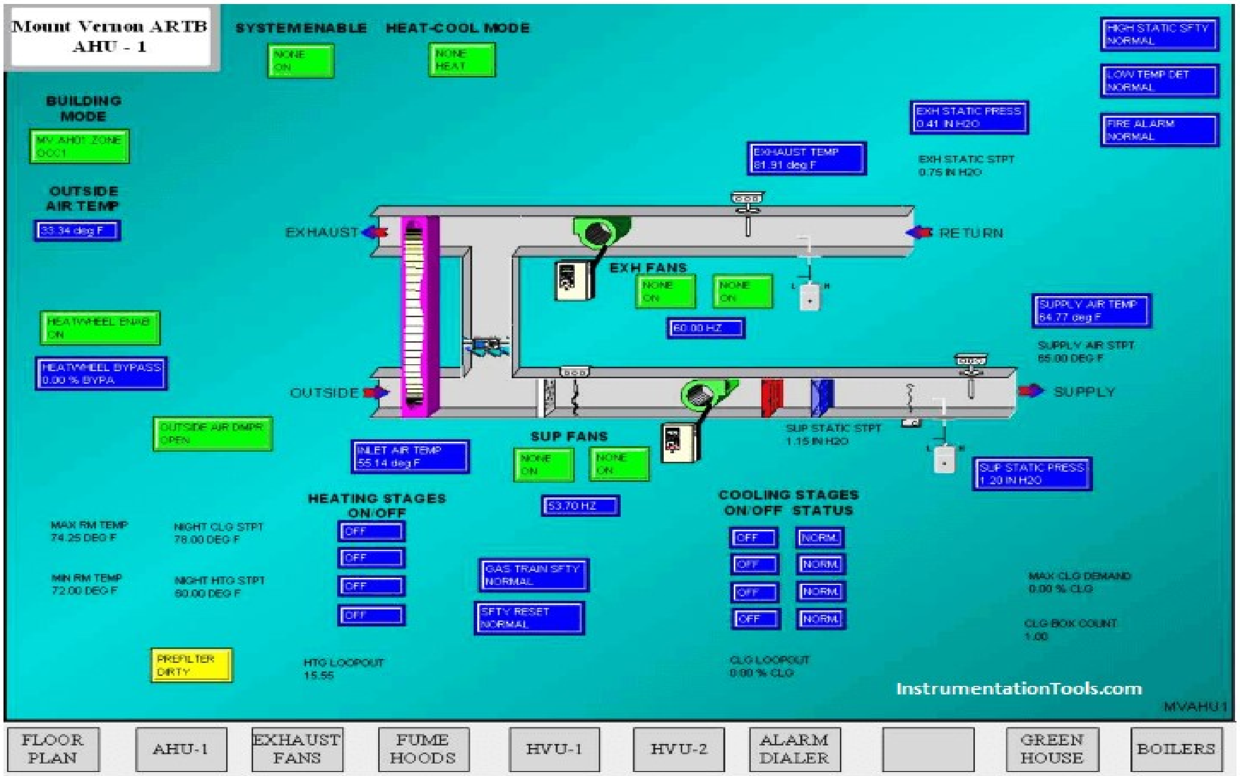
This not only makes multiple-loop digital control possible for a single microprocessor, but also makes it very attractive given the microprocessor's natural ability to manage data archival, transfer, and networking.

A single computer is able to execute PID control for multiple loops, and also make that loop control data accessible between loops (for purposes of cascade, ratio, feed forward, and other control strategies) and accessible on networks for human operators and technicians to easily access.

Such direct digital control (DDC) has been applied with great success to the problem of building automation, where temperature and humidity controls for large structures benefit from large-scale data integration.

Operators, engineers, and technicians alike must use software running on a networked personal computer to access data in this control system.

An example of the HMI (Human-Machine Interface) software one might see used in conjunction with a DDC controller is shown here, also from a Siemens APOGEE building control system:




This particular screenshot shows monitored and controlled variables for a heat exchanger ("heat wheel") used to exchange heat between outgoing and incoming air for the building.