1.1 Study of MOSFET

- MOSFET is metal oxide semiconductor field effect transistor.
- MOSFET is a three terminal device. The three terminals are gate (G), drain (D) andsource (S)
- MOSFET is a unipolar device as its operation depends on flow of majority charge carriersonly.
- It is a voltage controlled device requiring a small input gate voltage.
- It has high input impedance.
- MOSFET is operated in two states viz., ON STATE and OFF STATE.

A power MOSFET is a special type of metal oxide semiconductor field effect transistor. Itis specially designed to handle high-level powers. The power MOSFET's are constructed ina V configuration. Therefore, it is also called as V-MOSFET, VFET

Power MOSFETs are of two types

1. n- channel Enhancement MOSFETs
2. p- channel Enhancement MOSFETs

n-channel enhancement MOSFET is commonly used due to the higher mobility of electrons.

MOSFET CONSTRUCTION

Power MOSFETs are based on vertical structure, the doping and the thickness of the epitaxial layer decide the voltage rating while the channel width decides its current rating. This is the reason because of which they can sustain high blocking voltage and high current, making them suitable for low power switching applications.

The figure shows the planar diffused MOSFET structure for n-channel.

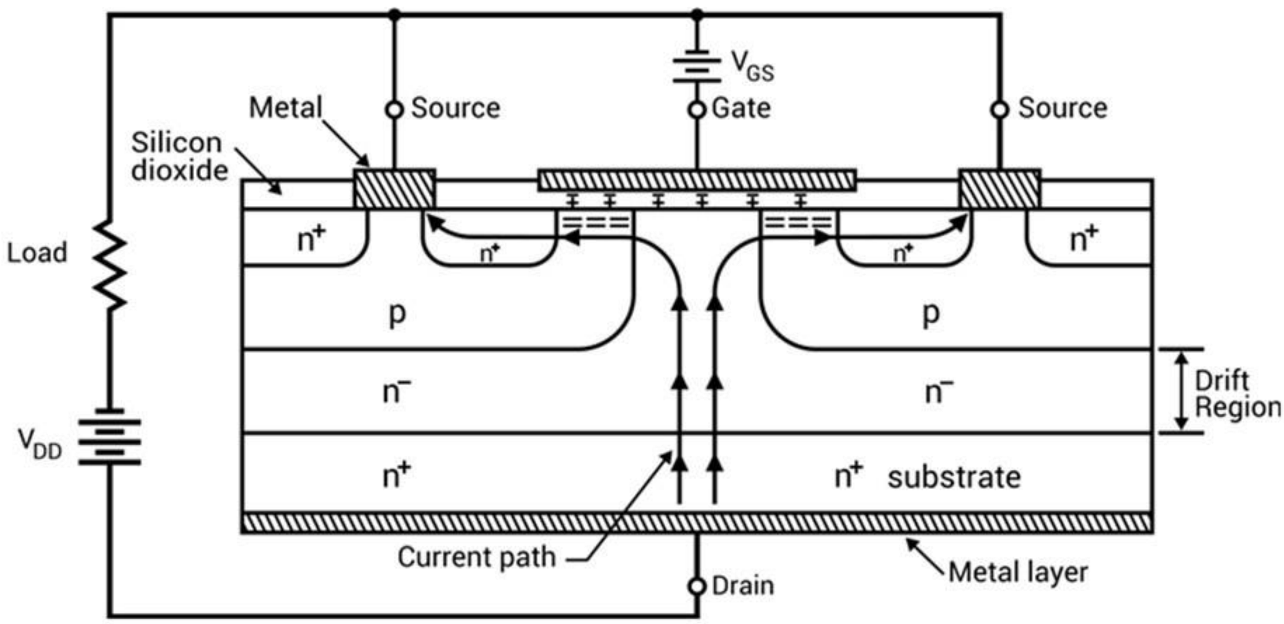

Fig 1.1.1 Structure of MOSFET

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 21]

On n+ substrate, high resistivity n- layer is epitaxial grown. The thickness of n- layer decides the voltage blocking capability of the power Mosfets. The lightly doped n-type semiconductor forms the main body of the device. Two heavily doped p-type regions are there in the body separated by a certain distance L. Now there is a thin layer of silicon dioxide (SiO_2) on the top of the substrate which behaves as a dielectric. There is an aluminum plate fitted on the top of this SiO_2 dielectric layer.

Most importantly, here, the Source (S) terminal is placed over the Drain (D) terminal forming a vertical structure. As a result, in VDMOS the current flows beneath the gate area vertically between the source and the drain terminals through numerous n+ sources conducting in-parallel. As a result, the resistance offered by the device during its ON state RDS(ON) is much lower than that in the case of normal MOSFETs which enablethem to handle high currents.

OPERATION OF MOSFET

When gate circuit voltage is zero, and VDD is present, n- -p- junction is 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 an n channel. With gate voltage increased, drain current also increases.The length of n channel can be controlled.

If we apply a positive voltage at gate (G). This will create positive static potential at the aluminum plate of the capacitor. Due to capacitive action, electrons gets accumulated just below the dielectric layer Now if we further increase the positive voltage at thegate terminal, after a certain voltage called threshold voltage, due to the electrostatic force, covalent bonds of the crystal just below the SiO2 layer start breaking. Consequently, electron-hole pairs get generated there. By applying the positive voltage at gate, we can control the drain current.

VI CHARACTERISTICS OF MOSFET

MOSFET can be in any of the in three operating regions viz.,

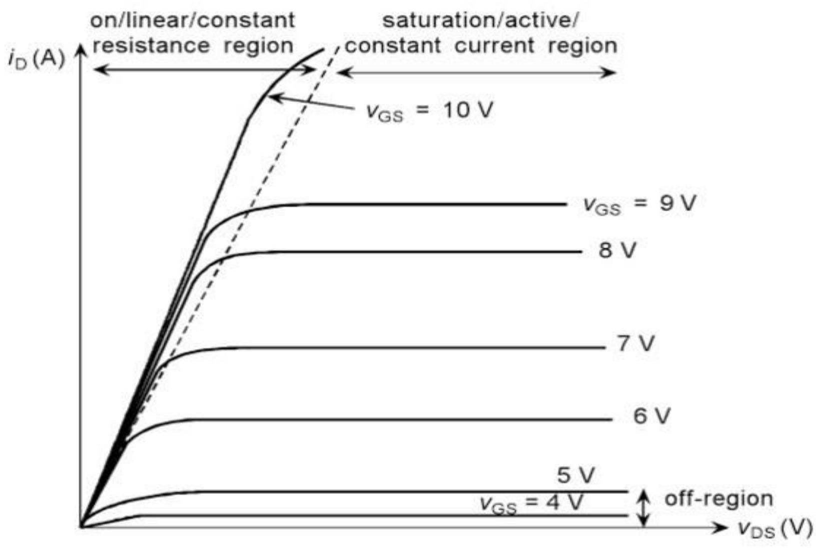

Fig 1.1.2 Characteristics of MOSFET

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 23]

Cut-Off Region

Cut-off region is a region in which the MOSFET will be OFF as there will be no current flow through it. In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.

Ohmic or Linear Region

Ohmic or linear region is a region where in the current IDS increases with an increase in the value of VDS. When MOSFETs are made to operate in this region, theycan be used as amplifiers.

Saturation Region

In saturation region, the MOSFETs have their IDS constant inspite of an increase in VDS and occurs once VDS exceeds the value of pinch-off voltage VP. Under this condition, the device will act like a closed switch through which a saturated value of IDS flows. As a result, this operating region is chosen whenever MOSFETs are required to perform switching operations.

From the transfer characteristics (drain-to-source current IDS versus gate-to-source voltage VGS), itis evident that the current through the device will be zero until the VGS exceeds the value of threshold voltage VT. This is because under this state, the device will be void of channel which will be connecting the drain and the source terminals. Under this condition, even an increase in VDS will result in no current flow as indicated by the corresponding output characteristics (IDS versus VDS). As a result this state represents nothing but the cut-off region of MOSFET's operation.

Next, once VGS crosses VT, the current through the device increases with an increase in IDS initially (Ohmic region) and then saturates to a value as determined by the VGS (saturation region of operation) i.e. as VGS increases, even the saturation current flowing through the device also increases. This is evident by Figure 1b where IDSS2 is greater than IDSS1 as VGS2> VGS1, IDSS3 is greater than IDSS2 as VGS3 >VGS2, so on and so forth. Further, Figure 1b also shows the locus of pinch-off voltage (black discontinuous curve), from which VP is seen to increase with an increase in VGS.

SWITCHING CHARACTERISTICS OF POWER MOSFET

The switching characteristics or the turn-on & turn-off times of the MOSFET are decidedby its internal capacitance and the internal impedance of the gate drive circuit. Turn on time is defined as the sum of turn on delay time and rise time of the device. Turn off time is the sum of turn off delay time and fall time

Turn ON Process:

A positive voltage is applied to the gate of MOSFET to turn e it on. When the gate voltage is applied, the gate to source capacitance CGS starts charging. When the voltage across CGS reached certain voltage level called Threshold voltage(VGST), the drain current ID starts rising.The time required to charge CGS to the threshold voltage level is known as turn ondelay time (td).The time required for charging CGS from threshold voltage to full gate voltage (VGSP). is called rise time (tr).During this period, the drain current rises to its full value, ie ID.Thus the MOSFET is fully turned ON.

The total turn-on time of MOSFET is

TON = tdon+ tr

The turn-on time can be reduced by using low-impedance gate drive source.

Turn OFF Process:

- To turn off the MOSFET, the gate voltage is made negative or zero.
- Due to this, the gate to source voltage then reduces from VI to VGSP.
- As MOSFET is a majority carrier device, turn-off process is initiated soon after removal of gate voltage at time t1.
- That is, CGS discharges from gate voltage V1 to VGSP. The time required for thisdischarge is called turn-off delay time (td(off))
- During this period, the drain current also starts reducing.
- The CGS keeps on discharging and its voltage becomes equal to threshold voltage(VGST).

- The time required to discharge CGS from VGSP to VGST is called fall time (tf). The drain current becomes zero when VGS < VGST. The MOSFET is then said to be have turned-off.
- Thus the total turn-off time of MOSFET is $T_{OFF} = t_{(d(off))} + t_f$
-

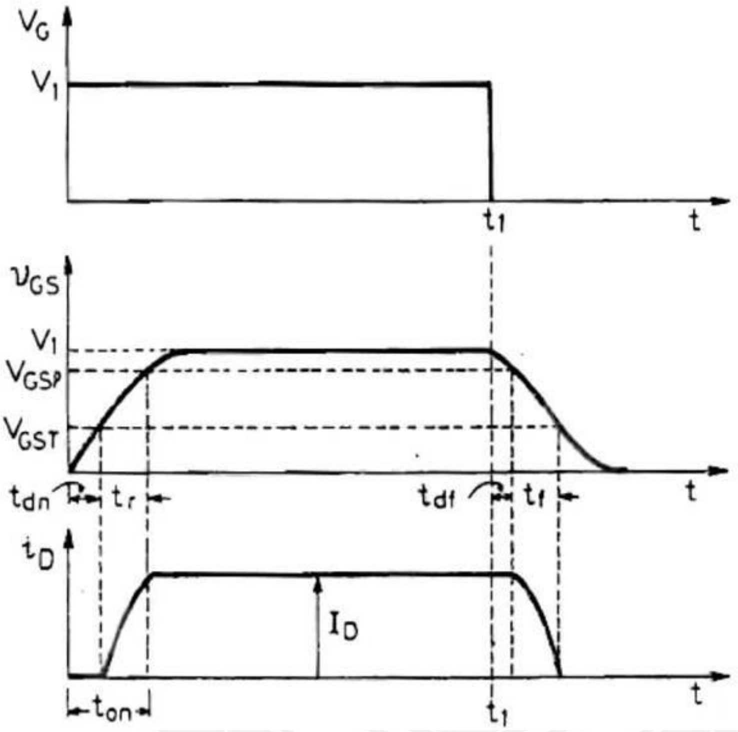

Fig.1.1.3 turn on and off characteristics of MOSFET

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 23]

Applications of POWER MOSFET

Power MOSEFET technology is applicable to many types of circuit.

1. Linear power supplies
2. Switching power supplies
3. DC-DC converters
4. Low voltage motor control

1.2 Introduction to Snubber and Driver Circuits

A snubber circuit limits or stops (snubs) switching voltage amplitude and its rate of rise, therefore reducing power dissipation. In its simplest form, a snubber circuit basically consists of a resistor and capacitor connected across the thyristor.

MOSFET DRIVE CIRCUIT

A driver circuit need to turn on the semiconducting devices. A MOSFET usually needs a gate driver to do the on/off operation at the desired frequency. For high frequencies, MOSFETs require a gate drive circuit to translate the on/off signals from an analog or digital controller into the power signals necessary to control the MOSFET. Since the MOSFET is a voltage-driven device, no DC current flows into the gate.In order to turn on a MOSFET, a voltage higher than the rated gate threshold voltage Vth must be applied to the gate. While in a steady on or off state, the MOSFET gate drive basically consumes no power. The gate-source capacitance of a MOSFET seenby the driver output varies with its internal state.MOSFETs are often used asswitching devices at frequencies ranging from several kHz to more than several hundreds of kHz. The low power consumption needed for gate drive is an advantage of a MOSFET as a switching device. MOSFETs designed for low-voltage drive are alsoavailable.

The basic requirements for a MOSFET drive circuit include an ability to apply a voltage sufficiently higher than Vth to the gate and a drive capability to sufficiently charge the input capacitance. This section describes an example of a drive circuit for an N-channel MOSFET.

The below figure shows a basic MOSFET drive circuit. In practice, the capacitance of a MOSFET to be driven and its usage conditions must be considered in designing a drive circuit.

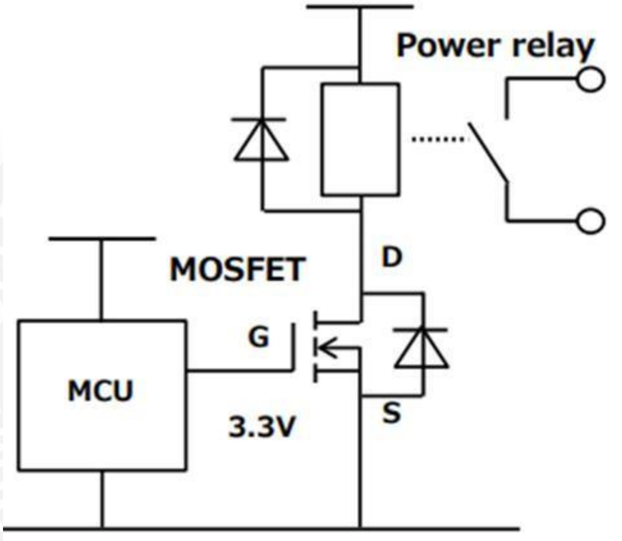

Figure 1.2.1 MOSFET drive circuit

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 23]*

There is a growing need for MOSFETs for switching applications (load switches) to provide a conducting path in a circuit only when it is operated, and thereby reduce the power consumption of electronic devices. At present, MOSFETs are directly driven by a logic circuit or a microcontroller in many applications. Figure 2.2 shows an example of acircuit for turning on and off a power relay. Since turn-on and turn-off times may be as slow as a few seconds for load switches, the MOSFET gate can be driven with a small current.There are other ways of triggering MOSFET are using a high-voltage device and a bootstrap circuit, Pulse transformer drive (insulated switching)

,using a photo coupler and a floating power supply.

1.3 Switched Mode Regulators - BUCK REGULATOR

Switched Mode Regulators provide much greater power efficiency in DC-to-DC conversion than linear regulators, which are simpler circuits that lower voltages by dissipating power as heat, but do not step up output current. Switched mode regulators consists of energy storage elements along with dc-dc chopper circuits.To reduce voltage ripple, filters made of capacitors (or capacitors in combination with inductors) are normally added to such a converter's output (load-side filter)and input (supply-side filter.

Switched Mode Regulators are classified into Buck,Boost ,Buck-Boost Regulators.

BUCK REGULATOR

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage while stepping up current from its input (supply) to its output (load).

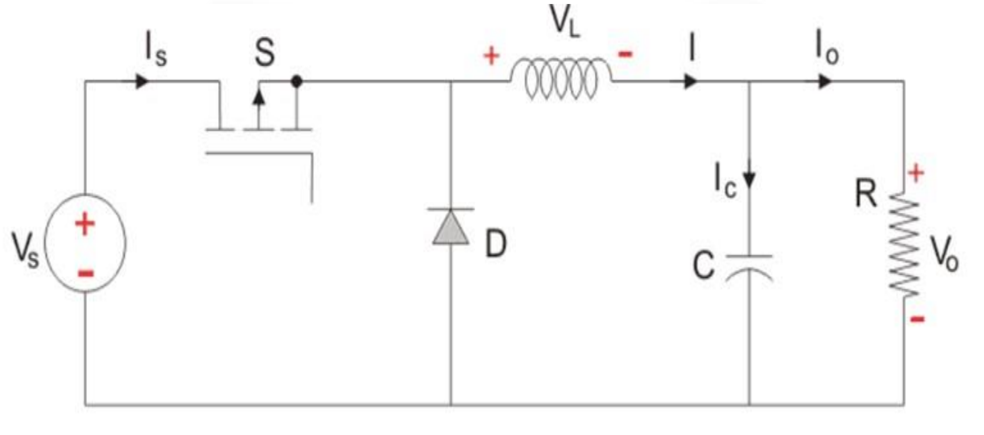

Figure 1.3.1 BUCK REGULATOR

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 492]*

MODE I: SWITCH IS ON, DIODE IS OFF

The voltage across the capacitance in steady state is equal to the output voltage. The switch is on for a time T_{ON} and is off for a time T_{OFF}. We define the time period, T, as T=Ton+Toff, and the switching frequency,

f= 1/T = chopping frequency

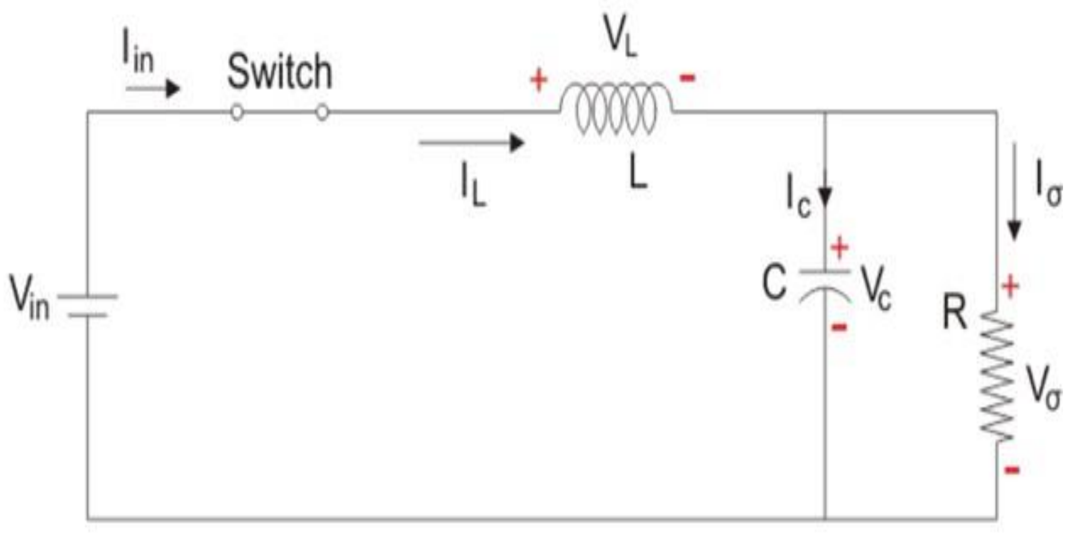

Figure 1.3.2 Buck converter- Mode II circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 492]*

MODE II: SWITCH IS OFF, DIODE IS ON

Here, the energy stored in the inductor is released and is ultimately dissipated inthe load resistance, and this helps to maintain the flow of current through the load. But for analysis we keep the original conventions to analyse the circuit using KVL.

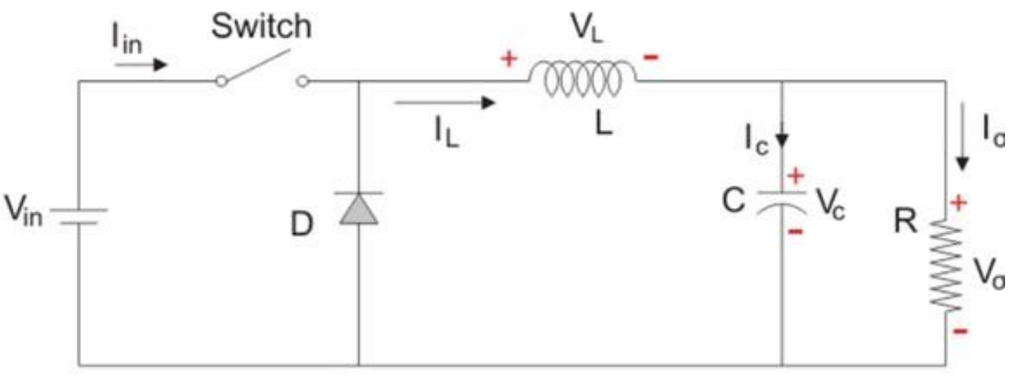

Figure 1.3.3 Buck converter- Mode II circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 493]*

Average load Voltage is given by

- $V_0 = T_{on} / (T_{on} + T_{off}) * Vs = (T_{on}/T) V = D V_s$
- T_{on} : on -time T_{off} : off- time
- Thus the load voltage can be controlled by varying the duty cycle D

$V0 = f. T_{on} .V_s$

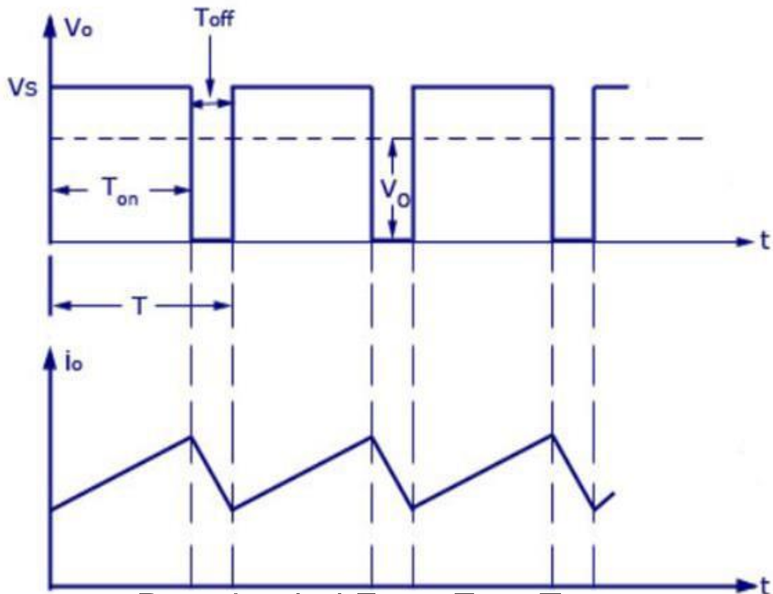

Figure 1.3.4 Buck converter Output Voltage and Current Waveforms

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 493]*

1.4 BOOST CONVERTER

- Boost converter which increases the input DC voltage to a specified DC output voltage. A typical Boost converter is shown below.
- Step-up chopper works as a step-up transformer on DC current.
- The working principle of a step up chopper can be explained from the above diagram. In the circuit, a large inductor L is connected in series to the supply voltage. Capacitor maintains the continuous output voltage to the load. The diode prevents the flow of current from load to source.

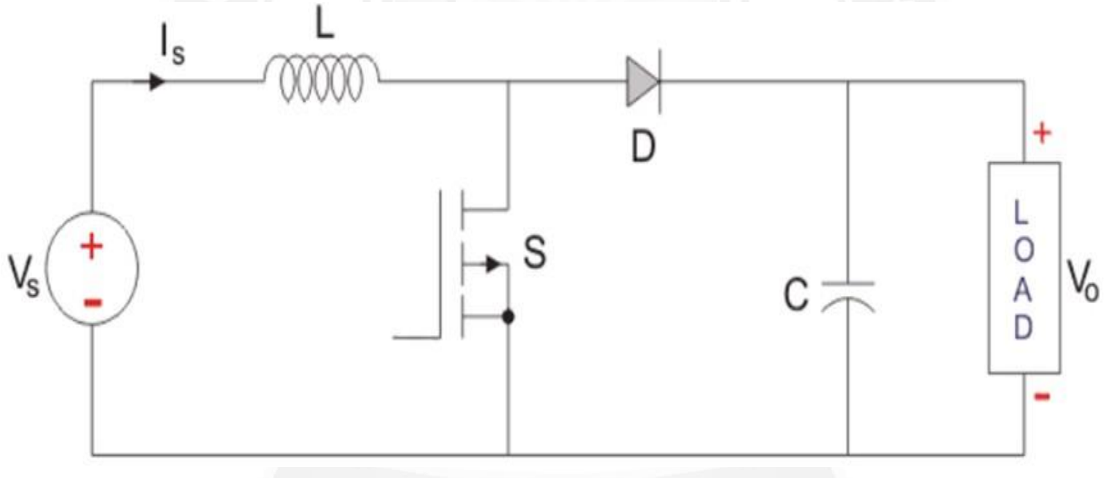

Figure 1.4.1 Block diagram of Boost converter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 279]*

- The input voltage source is connected to an inductor. The solid-state device which operates as a switch is connected across the source. The second switch used is a diode. The diode is connected to a capacitor, and the load and the two are connected in parallel as shown in the figure above.

- The inductor connected to input source leads to a constant input current, and thus the Boost converter is seen as the constant current input source. And the load can be seen as a constant voltage source. The controlled switch is turned on and off by using Pulse Width Modulation(PWM). PWM can be time-based or frequency based. Frequency-based modulation has disadvantages like a wide range of frequencies to achieve the desired control of the switch which in turn will give the desired output voltage. Time-based Modulation is mostly used for DC-DC converters. It is simple to construct and use. The frequency remains constant in this type of PWM modulation.

The Boost converter has two modes of operation.

The first mode is when the switch is on and conducting.

MODE I : SWITCH IS ON, DIODE IS OFF

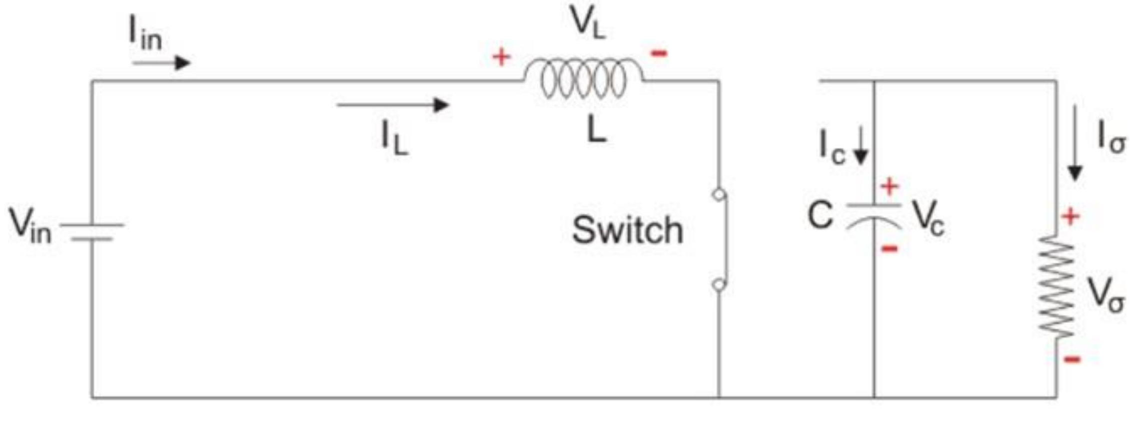

Figure 1.4.2 Boost converter- Mode I circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 280]*

- The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and back to the DC input source. Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF}. We define the time period, T, as T=Ton + Toff.
- When the chopper is turned ON the current through the inductance L will increase from I_1 to I_2. As the chopper is on the source voltage is applied to L that is $v_L = V_S$.

MODE II : SWITCH IS OFF, DIODE IS ON

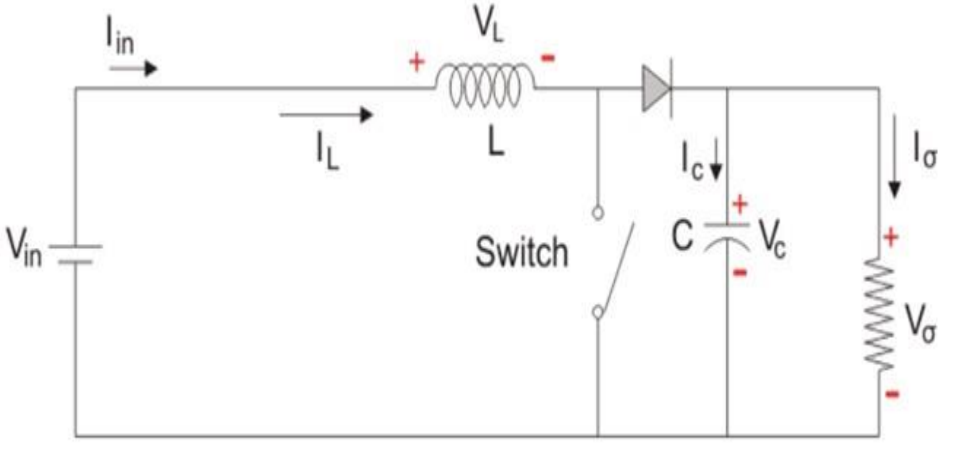

Figure 1.4.3 Boost converter- Mode II circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 280]*

When the chopper is OFF, the KVL can be written as $v_L - V_0 + V_s = 0$ or $v_L = V_0 - V_s$

where v_L is the voltage across L. Variation of source voltage v_S, source current I_S, load voltage v_0 and load current i_O is sketched in the fig .

Let us assume that the variation of output current is linear, the energy input to inductor from the source, during the time period T_{on}, is

$$W_{in}= V_s (I_1+I_2/2)\, T_{on}$$

During the time T_{off} the chopper is off, so the energy released by the inductor to the load is

$$W_{off} = (V_0-V_s)(I_1+I_2/2).T_{off}$$

Let us assume that the system is lossless, then the two energies say W_{in} and W_{off} are equal.

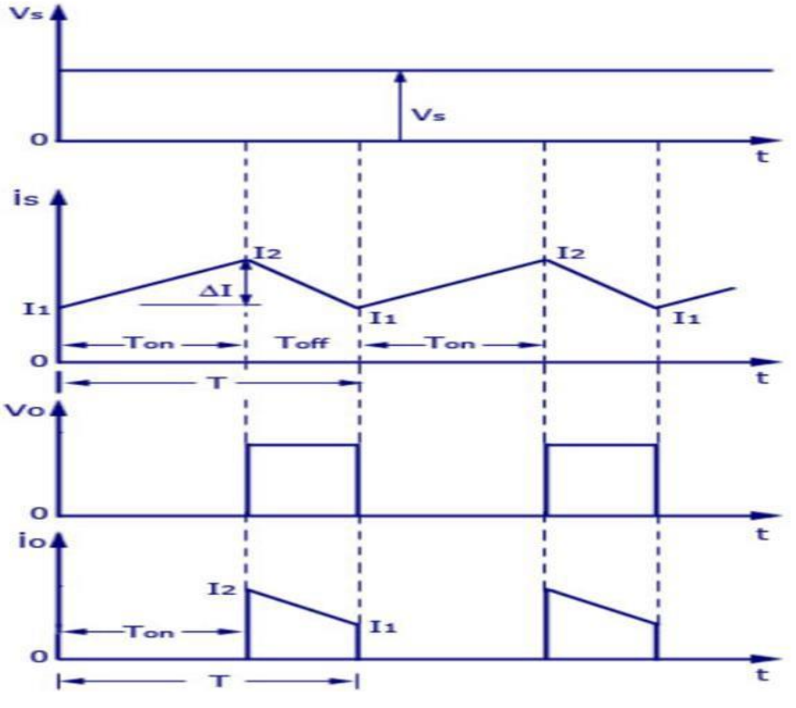

Figure 1.4.4 Boost converter Waveforms

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 281]*

Boost converter Output Voltage

So equating these two we will get

$V_S (I_1+I_2/2) T_{on} = (V_0-V_S)(I_1+I_2/2).T_{off}$

$V_S T_{on} = (V_0-V_S) T_{off}$

$V_0T_{off} = V_S (T_{off} + T_{on}) = V_S .T$

$V_0 = V_S (T/T_{off}) = V_S (T/T-T_{on}) =V_S (1/(1-D)$

From the above equation , we can see that the average voltage across the load can be stepped up by varying the duty cycle.

We know that D varies between 0 and 1. But as we can see from the equation above that if D = 1 then the ratio of output voltage to input voltage at steady state goes to infinity.

1.5 BUCK - BOOST CONVERTER

- **Buck Boost converter** which can operate as a DC-DC Step-Down converter or a DC-DC Step-Up converter depending upon the duty cycle.

A typical Buck-Boost converter is shown below

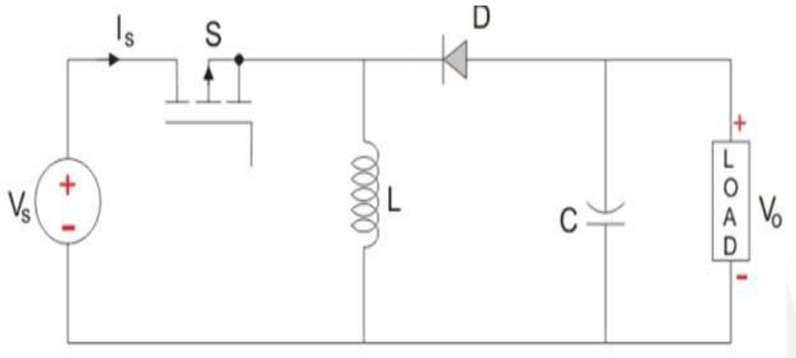

Figure 1.5.1 Buck- Boost converter circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 282]*

- The input voltage source is connected to a solid state device. The second switch used is a diode. The diode is connected, in reverse to the direction of power flow from source, to a capacitor and the load and the two are connected in parallel as shown in the figure above.

- The controlled switch is turned on and off by using Pulse Width Modulation (PWM). PWM can be time based or frequency based. Frequency based modulation has disadvantages like a wide range of frequencies to achieve the desired control of the switch which in turn will give the desired output voltage. Time based Modulation is mostly used for DC-DC converters. It is simple to construct and use. The frequency remains constant in this type of PWM modulation.

The Buck Boost converter has two modes of operation.

MODE I : SWITCH IS ON, DIODE IS OFF

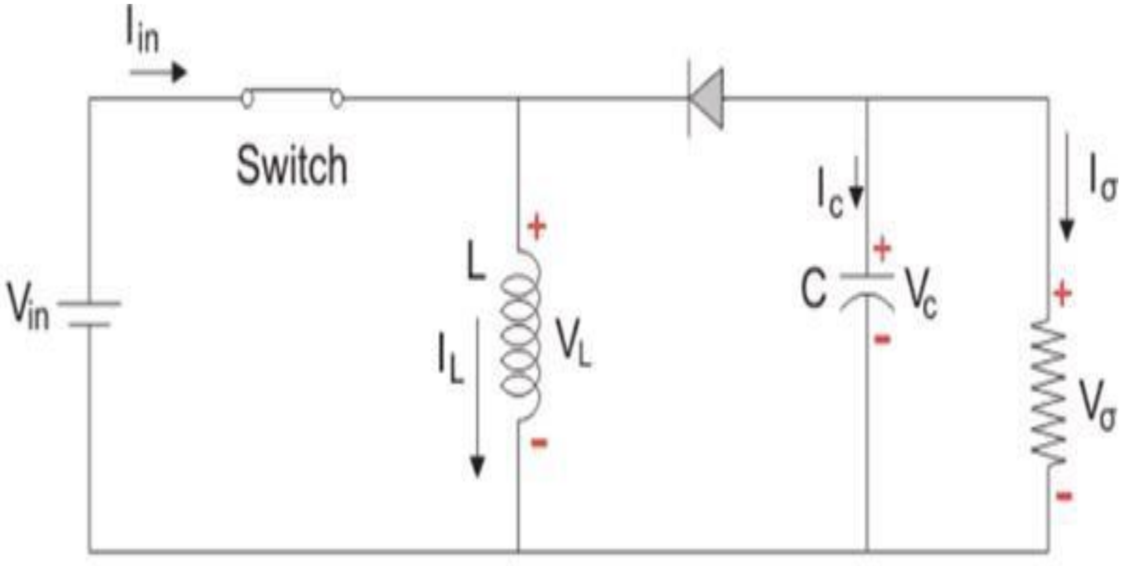

Figure 1.5.2 Buck- Boost converter- Mode I circuit

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 283]*

- The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and the inductor and back to the DC input source. The inductor stores charge during the time the switch is ON and when the solid state switch is OFF the polarity of the Inductor reverses so that current flows through the load and through the diode and back to the inductor.
- So the direction of current through the inductor remains the same.

MODE II : SWITCH IS OFF, DIODE IS ON

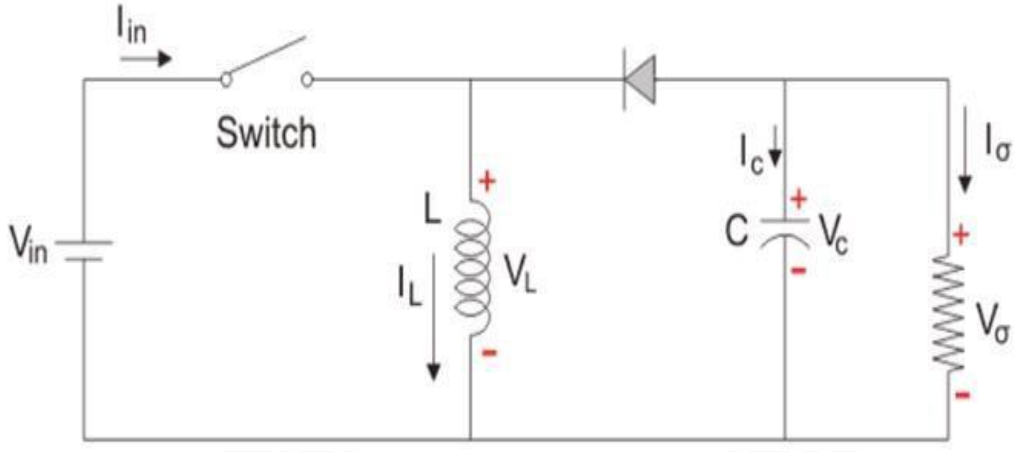

Figure 1.5.3 Buck- Boost converter- Mode II circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 283]*

In this mode the polarity of the inductor is reversed and the energy stored in the inductor is released and is ultimately dissipated in the load resistance and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source.

2.1 Single Phase Inverter

The inverter is a power electronic converter that converts direct power to alternating power.

- ❖ By using this inverter device, we can convert fixed dc into variable ac power which as a variable frequency and voltage.
- ❖ Secondly from this inverter, we can vary the frequency i.e we will be able to generate the 40HZ, 50HZ, 60HZ frequencies as of our requirement.
- ❖ If the dc input is a voltage source then the inverter is known asVSI (Voltage Source Inverter).
- ❖ The bridge inverters are of two types they are **half-bridge inverter and full-bridge inverter.**
- ❖ The full bridge inverters need four switching devices whereas half-bridge inverter needs two switching devices.

SINGLE PHASE HALF BRIDGE INVERTER WITH R,RL and RLC LOAD

The circuit diagram of a single-phase half-bridge inverter with resistive load is shown in the below figure.

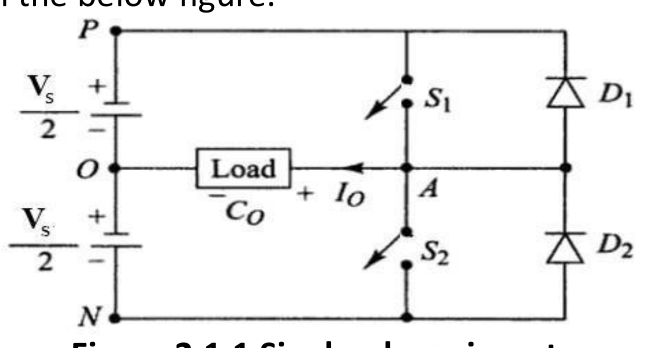

Figure 2.1.1 Single-phase inverter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 310]*

❖ Vs/2 is the voltage source, S1 and S2 are the two switches, i0 is the current. Where each switch is connected to diodes D1 and D2 parallelly.

❖ In the above figure 4, the switches S1 and S2 are the self-commutating switches.The switch S1 will conduct when the voltage is positive and current is negative, switch S2 will conduct when the voltage is negative, and the current is negative. The diode D1 will conduct when the voltage is positive and current is negative, diode D2 will conduct when the voltage is negative, and the current is positive.

Case 1 (when switch S1 is ON and S2 is OFF):

- When switch S1 is ON from a time period of 0 to T/2, the diode D1 and D2 are in reverse bias condition and S2 switch is OFF.
- Where output voltage V0= Vs/2
- Where output current i0 = V0/R= Vs/2R
- In case of supply current or switch current, the current iS1 = i0 = Vs/2R, iS2 = 0 and the diode current iD1 = iD2 = 0.
- **Case 2 (when switch S2 is ON and S1 is OFF):**
- When switch S2 is ON from a time period of T/2 to T, the diode D1 and D2 are in reverse bias condition and S1 switch is OFF.
- Applying KVL (Kirchhoff's Voltage Law)Vs/2+V0=0
- Where output voltage V0= -Vs/2
- Where output current i0 = V0/R= -Vs/2R

- In case of supply current or switch current, the current iS1 = 0, iS2 = i0 = -Vs/2R and the diode current iD1 = iD2 = 0.
- The single-phase half-bridge inverter output voltage waveform is shown in the below figure.

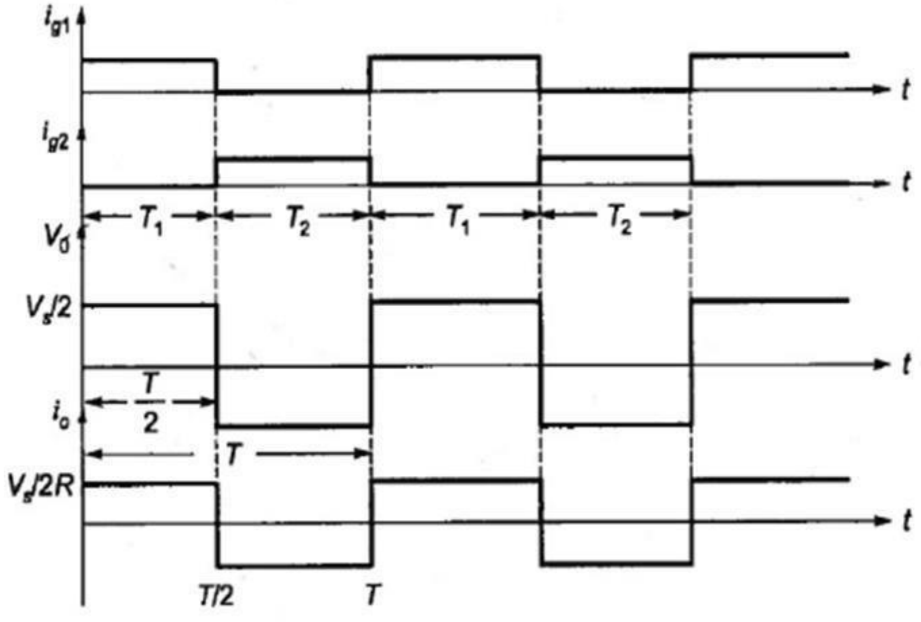

Figure 2.1.2 Single-phase inverter Waveform

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 310]*

2.2 VOLTAGE CONTROL OF INVERTERS

- The various methods for the control of output voltage of inverters can be classified as:

  (a) External control of ac output voltage

  (b) External control of dc input voltage

  (c) Internal control of the inverter.

External Control of ac Output Voltage

In this type of control as shown in Figure, an ac voltage controller is used to control the output of inverter . Through the firing angle control of ac voltage controller the voltage input to the ac load is regulated.

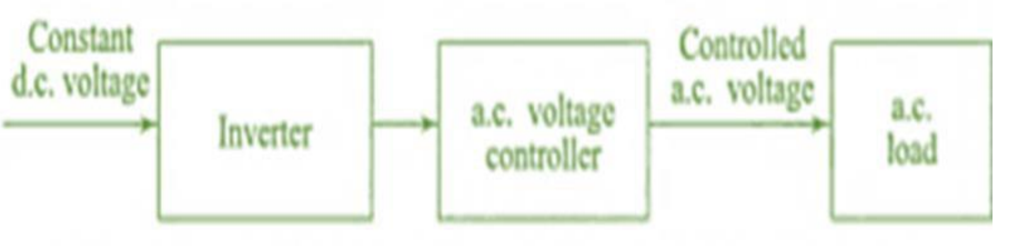

Fig 2.2.1. External Control of Output Voltage

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 347]*

External Control of dc Input Voltage

- When the available voltage souecr is ac then the dc voltage input to the inverter can be controlled through fully controlled rectifier, uncontrolled rectifier and chopper, ac voltage controller and uncontrolled rectifier as shown in Figure .

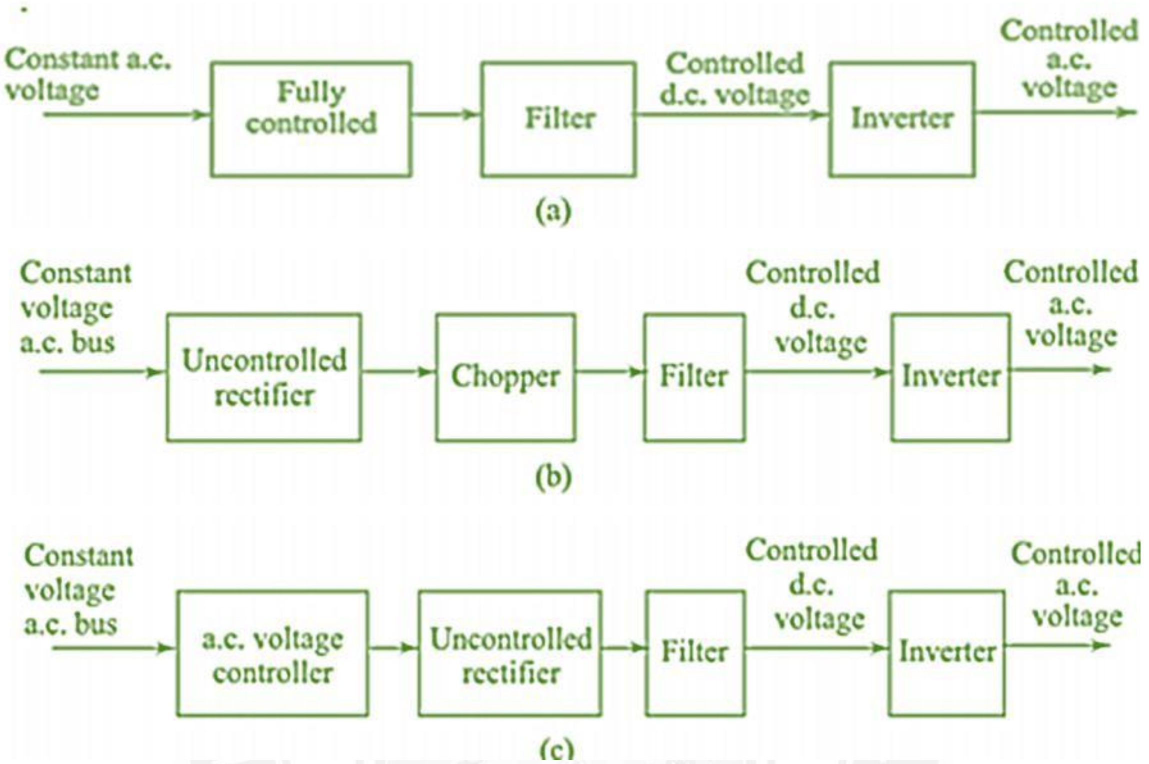

Fig 2.2.2. External Control of Input Voltage

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 348]*

Internal Control of Inverter

- The first method require the use of peripheral components whereas the second method requires no external components.
- Output voltage from an inverter can also be adjusted by exercising a control within the inverter itself. The most efficient method of doing is by pulse- width modulation control used within an inverter. This method is called the internal voltage control of the inverter.

2.3 PWM CONTROL: Multiple pulse width modulation (MPWM)

Pulse width modulation is the most commonly used technique to control the output voltage of inverter. In pulse Width Modulation method, a fixed dc input voltage is given to the inverters and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. PWM is a technique that is used to reduce the overall harmonic distortion THD in a load current. It uses a pulse wave in square form that results in a variable average waveform value, after its pulse width has been modulated.

DIFFERENT TYPES OF PWM CONTROL TECHNIQUE

1. Single pulse width modulation (Single PWM)
2. Multiple pulse width modulation (MPWM)
3. Sinusoidal pulse width modulation (SPWM)
4. Modified Sinusoidal pulse width modulation (MSPWM)
5. Phase displacement control

Multiple Pulse Width Modulation (MPWM)

- The main drawback of single PWM technique is high harmonic content. In order to reduce the harmonic content, the multiple PWM technique is used, in which several pulses are given in each half cycle of output voltage. The generation of gating signal is achieved by comparing the reference signal of the amplitude (Ar) with a triangular carrier wave (Ac) as shown Figure below.

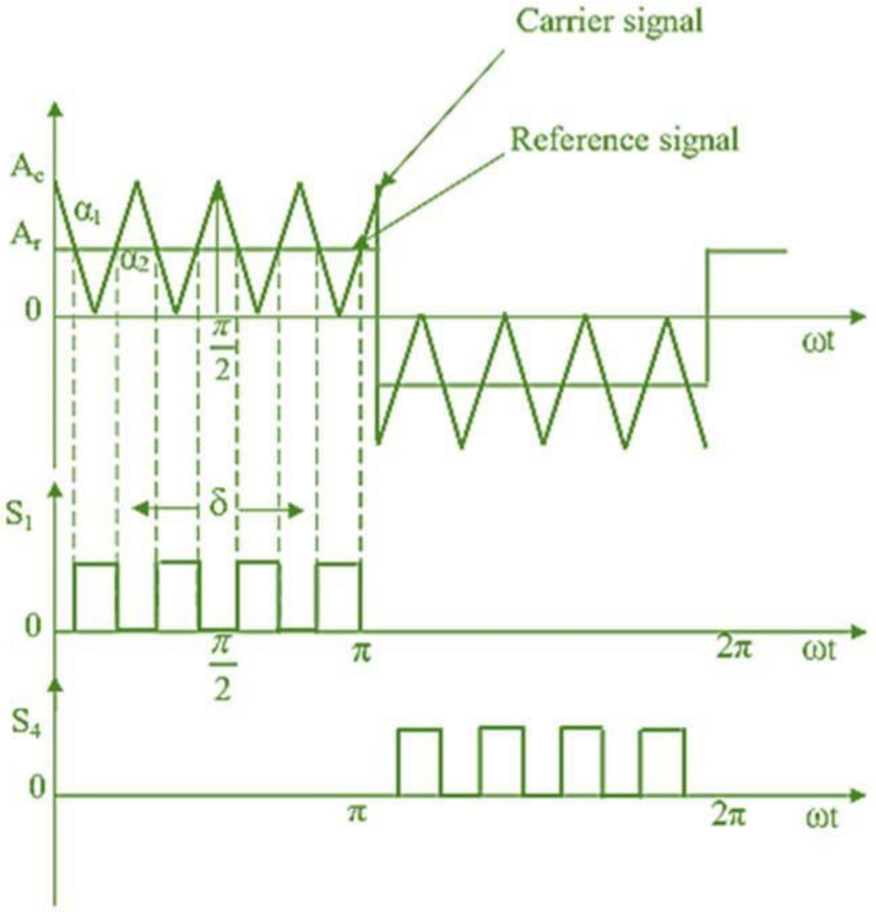

Figure 2.3.1 Multiple pulse width modulation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 352]*

- The output frequency (fo) is determined by the frequency of the reference signal.The output voltage can be controlled by modulation index.

2.4 PWM CONTROL: Sinusoidal pulse width modulation (SPWM)

In Sinusoidal Pulse Width Modulation triangular carrier signal is compared with sine wave. Figure below explains the generation of a sinusoidal PWM signal, which finds more applications in industries. The gating signal can be generated by comparing a sinusoidal reference signal with a triangular carrier wave and the width of each pulse varied proportionally to the amplitude of a sine wave evaluated at the center of the same pulse. The output frequency (fo) of the inverter can be found by using the frequency of the reference signal (fr). The rms output voltage (vo) can be controlled by modulation index M and in turn modulation index is controlled by peak amplitude (Ar). The voltage can be calculated by VO =Vs (S1- S4) . The number of pulses per half cycle depends on the carrier frequency. The gating signal can be produced by using the unidirectional triangular carrier wave.

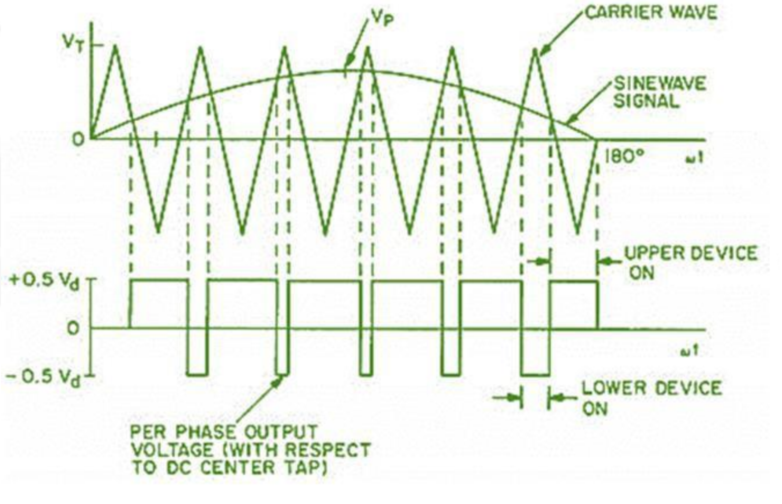

Figure 2.4.1. Multiple pulse width modulation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 352]*

The frequency of control signal or the modulating signal sets the inverter output frequency (fo) and the peak magnitude of control signal controls the modulation index ma which in turn controls the rms output voltage. The area of each pulse corresponds approximately to the area under the sine wave between the adjacent midpoints of off periods on the gating signals. If ton is the width of nth pulse, the rms output voltage can be determined by:

$$V_o = V_s \left(\sum_{n=1}^{2p} \frac{2t_{on}}{T} \right)^{1/2}$$

Pulse width modulation is the most commonly used technique to control the output voltage of inverter. In pulse Width Modulation method, a fixed dc input voltage is given to the inverters and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components.

PWM is a technique that is used to reduce the overall harmonic distortion THD in a load current. It uses a pulse wave in square form that results in a variable average waveform value, after its pulse width has been modulated.

2.5 SINGLE-PHASE CURRENT SOURCE INVERTER

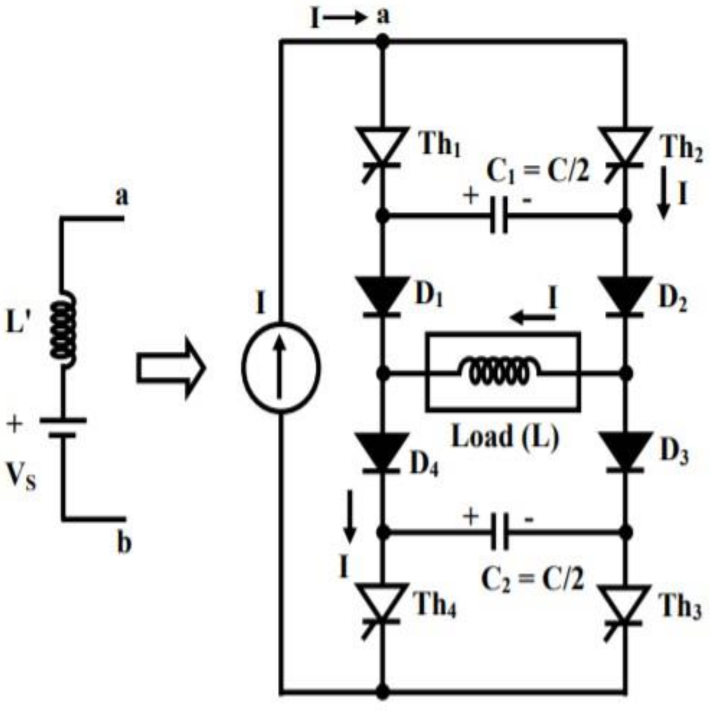

Figure 2.5.1 Single phase current source inverter (CSI)

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 364]*

The circuit of a Single-phase Current Source Inverter (CSI) is shown in Fig. The type of operation is termed as Auto-Sequential Commutated Inverter (ASCI). A constant current source is assumed here, which may be realized by using an inductance of suitable value, which must be high, in series with the current limited dc voltage source. The thyristor pairs, Th1 & Th3, and Th2 & Th4, are alternatively turned ON to obtain a nearly square wave current waveform. Two commutating capacitors − C1 in the upper half, and C2 in the lower half, are used. Four diodes, D1–D4 are connected in series with each thyristor to prevent the commutating capacitors from discharging into the load. The output frequency of the inverter is controlled in the usual way, i.e., by varying the half time period, (T/2), at which the thyristors in pair are triggered by pulses being fed to the respective gates by the control circuit, to turn them ON, as can be observed from the waveforms. The inductance (L) is taken as the load in this case, the reason(s) for which need not be stated, being well known. The operation is explained by two modes.

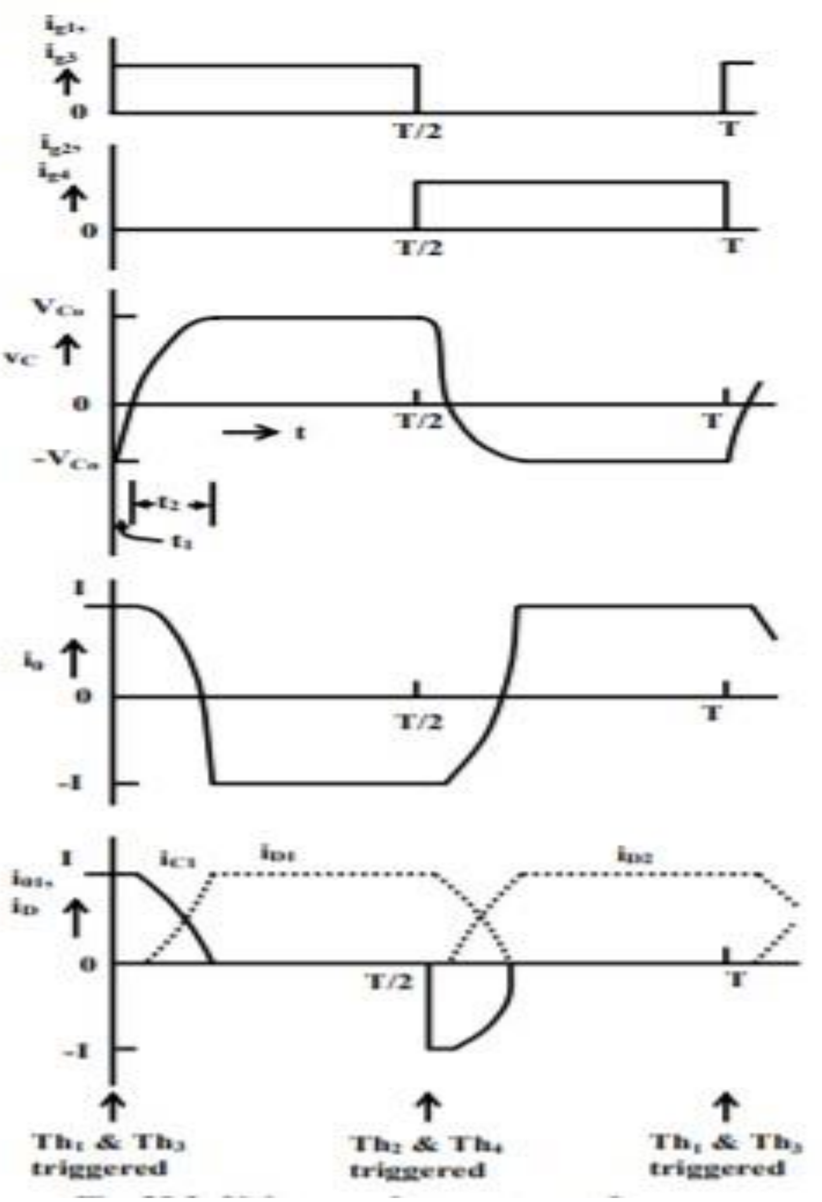

Figure 2.5.2 wave forms of Single phase current source inverter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 365]*

Mode I: The circuit for this mode is shown in Fig. The following are the assumptions. Starting from the instant ,t= 0 , the thyristor pair, Th 2 & Th4, is conducting (ON), and the current (I) flows through the path, Th2, D2, load (L), D4, Th4, and source, I. The commutating capacitors are initially charged equally with the polarity as given, i.e., . This mans that both capacitors have right hand plate positive and left hand plate negative. If two capacitors are not charged initially, they have to pre-charged.

At time, t = 0, thyristor pair, Th1 & Th3, is triggered by pulses at the gates. The conducting thyristor pair, Th2 & Th4, is turned OFF by application of reverse capacitor voltages. Now, thyristor pair, Th1 & Th3, conducts current (I). The current path is through Th1, C1, D2, L, D4,C2, Th3, and source, I. Both capacitors will now begin charging linearly from –Vco by the constant current, I. The diodes, D2& D4, remain reverse biased initially. As the capacitor gets charged, the voltage vD1 across D1, increases linearly. At some time, say t1, the reverse bias across D1 becomes zero (0), the diode, D1.starts conducting. This means that the voltages across C1 & C2, varies linearly from –Vco to zero in time, t1. Mode I ends, whent=t1, and vc= 0 . Note that t1 is the circuit turn-off time for the thyristors.

Mode II: The circuit for this mode is shown in Fig. 39.4a. Diodes, D2 & D4, are already conducting, but at t = t1 , diodes, D1 & D3, get forward biased, and start conducting. Thus, at the end of time t1, all four diodes, D1–D4 conduct. As a result, the commutating capacitors now get connected in parallel with the load (L).At the end of the process, constant current flows in the path, Th1, D1, load (L), D3, Th3, and source, I. This continues till the next commutation process is initiated by the triggering of the thyristor pair, Th2 & Th4.

3.1 SEMICONDUCTOR

A semiconductor is a material which has electrical conductivity to a degree between that of a metal (such as copper) and that of an insulator (such as glass). Semiconductors are the foundation of modern electronics, including transistors, solar cells, light -emitting diodes (LEDs), quantum dots and digital and analog integrated circuits.

DIODE

Diode – Di + ode

Di means two and ode means electrode. So physical contact of two electrodes is known asdiode and its important function is alternative current to direct current.

REVIEW OF INTRINSIC AND EXTRINSIC SEMICONDUCTORSINTRINSIC SEMICONDUCTOR

An intrinsic semiconductor is one, which is pure enough that impurities do not appreciably affect its electrical behaviour. In this case, all carriers are created due to thermally or optically excited electrons from the full valence band into the empty conduction band. Thus equal numbers of electrons and holes are present in an intrinsic semiconductor. Electrons and holes flow in opposite directions in an electric field, though they contribute to current in the same direction since they are oppositely charged. Whole current and electron current are not necessarily equal in an intrinsic semiconductor, however, because electrons and holes have different effective masses (crystalline analogues to free inertial masses).

The concentration of carriers is strongly dependent on the temperature. At low temperatures, the valence band is completely full making the material an insulator. Increasing the temperature leads to an increase in the number of carriers and a corresponding increase in conductivity.

Both silicon and germanium are tetravalent, i.e. each has four electrons (valence electrons) in their outermost shell. Both elements crystallize with a diamond- like structure, i.e. in such a way that each atom in the crystal is inside a tetrahedron formed by the four atoms which are closest to it. Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds.

EXTRINSIC SEMICONDUCTOR

An extrinsic semiconductor is one that has been doped with impurities to modifythe number and type of free charge carriers. An extrinsic semiconductor is a semiconductor that has been doped, that is, into which a doping agent has been introduced, giving it different electrical properties than the intrinsic (pure) semiconductor.

Doping involves adding doping atoms to an intrinsic semiconductor, which changes the electron and hole carrier concentrations of the semiconductor at thermal equilibrium. Dominant carrier concentrations in an extrinsic semiconductor classify it as either an n-type or p-type semiconductor.

A pure or intrinsic conductor has thermally generated holes and electrons. However these are relatively few in number. An enormous increase in the number of charge carriers can be achieved by introducing impurities into the semiconductor ina controlled manner. The result is the formation of an extrinsic semiconductor. This process is referred to as doping. There are basically two types of impurities: donor impurities and acceptor impurities. Donor impurities are made up of atoms (arsenic for example) which have five valence electrons. Acceptor impurities are made up of atoms (gallium for example) which have three valence electrons.

The two types of extrinsic semiconductor are

N-TYPE SEMICONDUCTORS

Extrinsic semiconductors with a larger electron concentration than hole concentration are known as n-type semiconductors. The phrase 'n-type' comes from the negative charge of the electron. In n-type semiconductors, electrons are the majority carriers and holes are the minority carriers.

N-type semiconductors are created by doping an intrinsic semiconductor with donor impurities.In an n-type semiconductor, the Fermi energy level is greater than that of the intrinsic semiconductor and lies closer to the conduction band than the valence band. Arsenic has 5 valence electrons, however, only 4 of them form part of covalent bonds.The 5th electron is then free to take part in conduction. The electrons are said to be themajority carriers and the holes are said to be the minority carriers.

P-TYPE SEMICONDUCTORS

As opposed to n-type semiconductors, p-type semiconductors have a larger hole concentration than electron concentration. The phrase 'p-type' refers to the positive charge of the hole. In p-type semiconductors, holes are the majority carriers and electrons are the minority carriers. P-type semiconductors are created by doping an intrinsic semiconductor with acceptor impurities. P-type semiconductors have Fermi energy levels below the intrinsic Fermi energy level.

The Fermi energy level lies closer to the valence band than the conduction band in a p- type semiconductor. Gallium has 3 valence electrons, however, there are 4 covalent bonds to fill. The 4th bond therefore remains vacant producing a hole. The holes are said to be the majority carriers and the electrons are said to be the minority carriers.

PN JUNCTION DIODE

When the N and P-type semiconductor materials are first joined together a very large density gradient exists between both sides of the junction so some of the free electrons from the donor impurity atoms begin to migrate across this newly formed junction to fill up the holes in the P- type material producing negative ions.

FORWARD BIAS CONDITION

When positive terminal of the battery is connected to the P-type and negative terminal to N-type of the PN junction diode that is known as forward bias condition.

Operation

The applied potential in external battery acts in opposition to the internal potential barrier which disturbs the equilibrium.

As soon as equilibrium is disturbed by the application of an external voltage, the Fermi level is no longer continuous across the junction. Under the forward bias condition the applied positive potential repels the holes in P type region so that the holesmove towards the junction and the applied positive potential repels the electrons in N type region so that the electrons move towards the junction.

When the applied potential is more than the internal barrier potential the depletion region and internal potential barrier disappear.

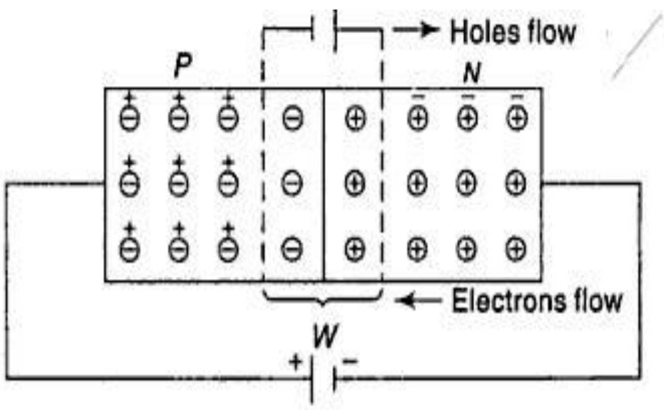

Figure: 1.1.1 PN Junctions under forward bias

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 110]

V-I Characteristics

As the forward voltage increased for $V_F < V_o$, the forward current I_F almost zero because the potential barrier prevents the holes from P region and electrons from N region to flow across the depletion region in opposite direction.

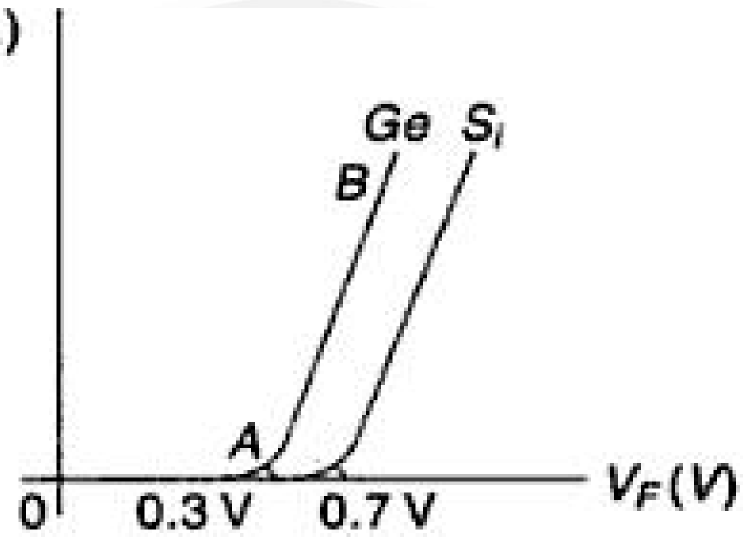

Figure: 1.1.2 V-I characteristics of a diode under forward bias

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 111]

For $V_F > V_o$, the potential barrier at the junction completely disappears and hence, the holes cross the junction from P to N type and electrons cross the junction to opposite direction, resulting large current flow in external circuit.

A feature noted here is the cut in voltage or threshold voltage V_F below which the current is very small. At this voltage the potential barrier is overcome andthe current through the junction starts to increase rapidly.

- Cut in voltage is 0.3V for germanium and 0.7 for silicon.

UNDER REVERSE BIAS CONDITION

When the negative terminal of the battery is connected to the P-type and positiveterminal to N-type of the PN junction diode that is known as forward bias condition.

Operation

The holes from the majority carriers of the P side move towards the negative terminal of the battery and electrons which from the majority carrier of the N side are attracted towards the positive terminal of the battery.

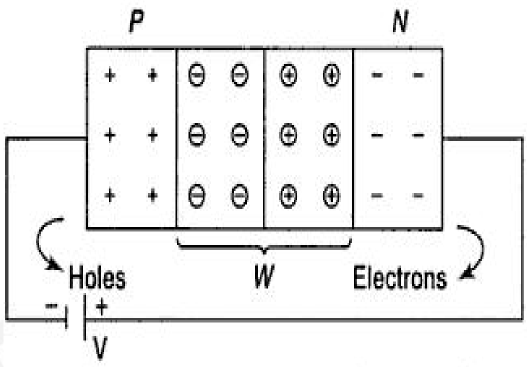

Figure: 1.1.3 PN junctions under reverse bias

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 111]

Hence, the width of the depletion region which is depleted of mobile charge carriers increases. Thus, the electric field produced by applied reverse bias, is in the same direction as the electric field of the potential barrier. Hence the resultant potential barrier is increased which prevents the flow of majority carriers in both directions. Thedepletion width W is proportional to under reverse bias.

V-I characteristics

Theoretically no current flow in the external circuit. But in practice a very small amount of current of the order of few microamperes flows under reverse bias.

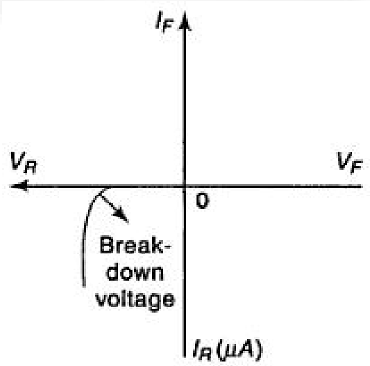

Figure: 1.1.4 V-I characteristics under reverse bias

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 112]

Electrons forming covalent bonds of semiconductor atoms in the P and N type regions may absorb sufficient energy from heat and light to cause breaking covalent bonds. So electron hole pairs continuously produced.

Consequently the minority carriers electrons in the P region and holes in the N region, wander over to the junction and flow towards their majority carrier side giving rise a small reverse current. This current is known as reverse saturation current Io.

The magnitude of this current is depends on the temperature because minority carrier is thermally broken covalent bonds.

3.2 RECTIFIERS

Rectifiers are classified according to the period of conduction. They are

- Half Wave Rectifier
- Full Wave Rectifier

Half Wave Rectifier:

The half wave rectifier is a type of rectifier that rectifies only half cycle of the waveform. This describes the half wave rectifier circuit working. The half rectifier consist a step down transformer, a diode connected to the transformer and a load resistance connected to the cathode end of the diode. The circuit diagram of half wave transformer is shown below:

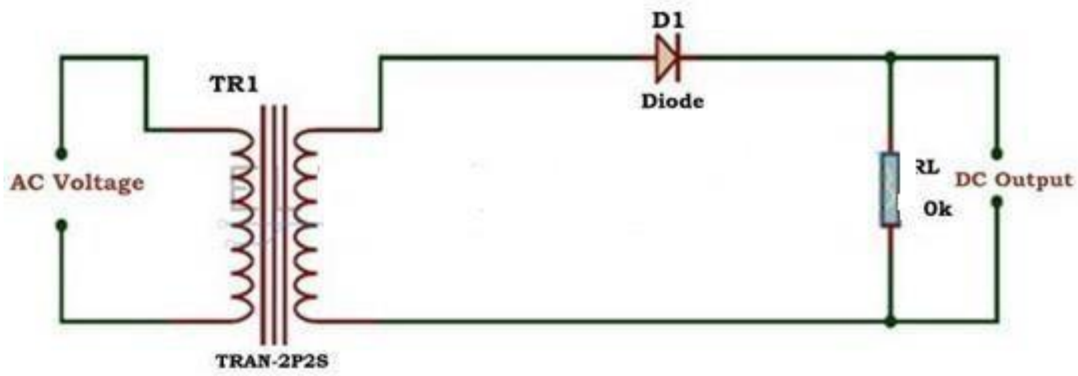

Figure: 1.3.1 Half wave Rectifier

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 252]

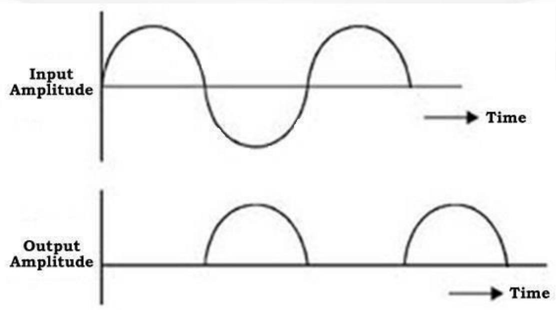

Figure: 1.3.2 Half wave Rectifier Wave Form

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 253]

The main supply voltage is given to the transformer which will increase or decrease the voltage and give to the diode. In most of the cases we will decrease the supply voltage by using the step down transformer here also the output of the step down transformer will be in AC. This decreased AC voltage is given to the diode which is connected serial to the secondary winding of the transformer, diode is electronic component which will allow only the forward bias current and will not allow the reverse bias current. From the diode we will get the pulsating DC and give to the load resistance RL.

Working of Half Wave Rectifier:

The input given to the rectifier will have both positive and negative cycles. The half rectifier will allow only the positive half cycles and omit the negative half cycles. So first we will see how half wave rectifier works in the positive half cycles.

Positive Half Cycle:

- In the positive half cycles when the input AC power is given to the primary winding of the step down transformer, we will get the decreased voltage at thesecondary winding which is given to the diode.
- The diode will allow current flowing in clock wise direction from anode to cathode in the forward bias (diode conduction will take place in forward bias)which will generate only the positive half cycle of the AC.
- The diode will eliminate the variations in the supply and give the pulsating DCvoltage to the load resistance RL. We can get the pulsating DC at the Load resistance.

Negative Half Cycle:

- In the negative half cycle the current will flow in the anti-clockwise directionand the diode will go in to the reverse bias. In the reverse bias the diode will not conduct so, no current in flown from anode to cathode, and we cannot getany power at the load resistance.
- Only small amount of reverse current is flown from the diode but this current is almost negligible.

Characteristics of Half Wave Rectifier:

There are some characteristics to the half wave rectifier they are

- **Efficiency:** The efficiency is defined as the ratio of input AC to the output DC.Efficiency, η = P dc / Pac
- DC power delivered to the load, $P_{dc} = I^2_{dc} R_L = (I_{max/pi})^2 R_L$

AC power input to the transformer, P_{ac} = Power dissipated in junction of diode + Power

Dissipated in load resistance RL= $I^2_{rms} R_F + I^2_{rms} R_L = \{I^2_{MAX}/4\} [R_F + R_L]$

Rectification Efficiency, $\eta = P_{dc} / P_{ac} = \{4/ ^2\} [RL/ (R_F + R_L)] = 0.406/\{1+ R_{F/RL} \}$

If RF is neglected, the efficiency of half wave rectifier is 40.6%.

- **Ripple factor:** It is defined as the amount of AC content in the output DC. It nothingbut amount of AC noise in the output DC. Less the ripple factor, performance of the rectifier is more. The ripple factor of half wave rectifier is about 1.21 (full wave rectifier has about0.48). It can be calculated as follows:
- The effective value of the load current I is given as sum of the rms values of harmonic currents I1, I2, I3, I4 and DC current Idc.
- $I^2 = I^2dc + I^2 1 + I^2 2 + I^2 4 = I^2 dc + I^2 ac$
- Ripple factor, is given as $\gamma = I_{ac} / I_{dc} = (I^2 - I^2_{dc}) / I_{dc} = \{(I_{rm}dcs /I^2)- 1\} = K_f^2 - 1)$ Where Kf is the form factor of the input voltage. Form factor is given as

  $K_f = I_{rms} / I_{avg} = (I_{max}/_2)/ (I_{max}/pi) = pi/2 = 1.57$

  So, ripple factor, $\gamma = (1.57^2 - 1) = 1.21$

- **Peak Inverse Voltage:** It is defined as the maximum voltage that a diode can with standin reverse bias. During the reverse bias as the diode do not conduct total voltage drops across the diode. Thus peak inverse voltage is equal to the input voltage Vs.

- **Transformer Utilization Factor (TUF):** The TUF is defined as the ratioof DC poweris delivered to the load and the AC rating of the transformer secondary. Half wave rectifier has around 0.287 and full wave rectifier has around 0.693.
- Half wave rectifier is mainly used in the low power circuits. It has very low performance when it is compared with the other rectifiers.

3.3.FULL WAVE RECTIFIER

Full wave rectifier rectifies the full cycle in the waveform i.e. it rectifies both the positive and negative cycles in the waveform. We have already seen the characteristics and working of Half Wave Rectifier. This Full wave rectifier has an advantage over the half wave i.e. it has average output higher than that of half wave rectifier. The number of AC components in the output is less than that of the input.

The full wave rectifier can be further divided mainly into following types.

- Center Tapped Full Wave Rectifier
- Full Wave Bridge Rectifier

Centre-Tap Full Wave Rectifier

We have already discussed the Full Wave Bridge Rectifier, which uses four diodes, arranged as a bridge, to convert the input alternating current (AC) in both half cycles to direct current (DC).

In the case of centre-tap full wave rectifier, only two diodes are used, and are connected to the opposite ends of a centre-tapped secondary transformer as shown in the figure below. The centre-tap is usually considered as the ground point or the zero voltage reference point.

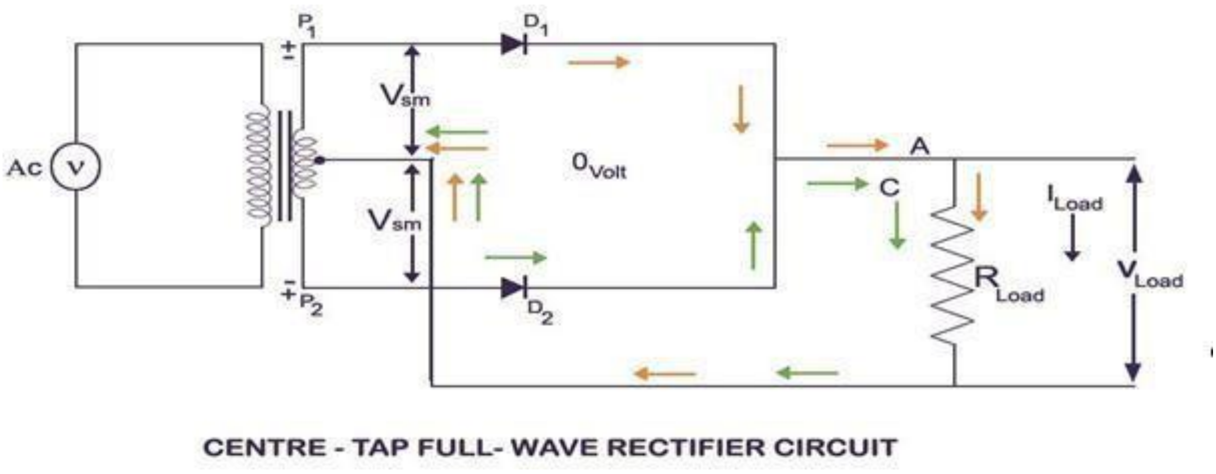

Figure: 1.4.1 Centre Tap Full Wave Rectifier Circuit

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 268]

Working of Centre-Tap Full Wave Rectifier

As shown in the figure, an ac input is applied to the primary coils of the transformer. This input makes the secondary ends P1 and P2 become positive and negative alternately.

For the positive half of the ac signal, the secondary point D1 is positive, GND point will have zero volt and P2 will be negative.

At this instant diode D1 will be forward biased and diode D2 will be reverse biased.

As explained in the Theory behind P-N Junction and Characteristics of P-N JunctionDiode, the diode D1 will conduct and D2 will not conduct during the positive half cycle. Thus the current flow will be in the direction P1-D1-C-A-B-GND. Thus, the positive half cycle appears across the load resistance RLOAD.

During the negative half cycle, the secondary ends P1 becomes negative and P2 becomes positive. At this instant, the diode D1 will be negative and D2 will be positive with the zero reference point being the ground, GND. Thus, the diode D2 will be forward biased and D1 will be reverse biased. The diode D2 will conduct and D1 will not conduct during the negative half cycle. The current flow will be in the directionP2-D2-C-A-B-GND.

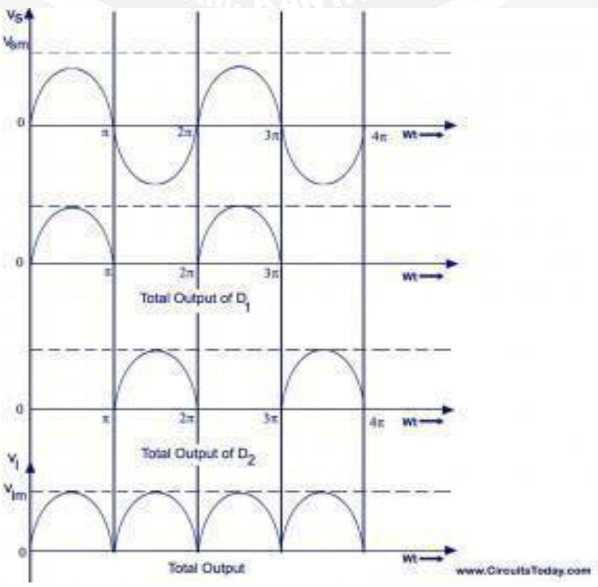

Figure: 1.4.2 Centre-tap Full-wave Rectifier-Waveform

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 268]

When comparing the current flow in the positive and negative half cycles, we can conclude that the direction of the current flow is the same (through load resistance RLOAD). When compared to the Half-Wave Rectifier, both the half cycles are used to produce the corresponding output.

The frequency of the rectified output voltage is twice the input frequency. The output that is rectified, consists of a dc component and a lot of ac components of minute amplitudes.

Peak Inverse Voltage (PIV) of Centre-Tap Full Wave Rectifier

PIV is the maximum possible voltage across a diode during its reverse biased period. Let us analyze the PIV of the Centre-tapped rectifier from the circuit diagram. During the first half or the positive half of the input ac supply, the diode D1 is positive and thus conducts and provided no resistance at all. Thus, the whole of voltage Vs developed in the upper-half of the ac supply is provided to the load resistance RLOAD.

- **Peak Current**

The instantaneous value of the voltage applied to the rectifier can be written as

$$V_s = V_{sm} \sin wt$$

Assuming that the diode has a forward resistance of RFWD ohms and a reverse resistance equal to infinity, the current flowing through the load resistance RLOAD isgiven as

$$I_m = V_{sm} / (R_F + R_{Load})$$

- **Output Current**

Since the current is the same through the load resistance RL in the two halves of the ac cycle, magnitude of dc current Idc, which is equal to the average value of ac current, can be obtained by integrating the current i1 between 0 and pi or current i2 between pi

$$Idc = 1/ \int_0^{\pi} i1\, d(wt) = 1/\pi \int_0^{\pi} Imax \ \sin wt\, d(wt) = 2Im/ \ \pi$$

Output current of Centre Tap rectifier

- **DC Output Voltage**

Average or dc value of voltage across the load is given as

$$Idc = 1/ \int_0 i1\, d(wt) = 1/ \int_0 Imax\, wt\, d(wt) = 2Im/$$

DC Output Voltage of center Tap Rectifier

- **Root Mean Square (RMS) Value of Current**

RMS or effective value of current flowing through the load resistance R_L is givenas

$$I^2rms = 1/ \int_0 i\, d(wt) = I^2\, m/2 \text{ or } I_{rms} = I_m/\sqrt{2}$$

3.4 FULL WAVE BRIDGE RECTIFIER.

A Full wave rectifier is a circuit arrangement which makes use of both half cycles of input alternating current (AC) and convert them to direct current (DC). In our tutorial on **half wave rectifiers**, we have seen that a half wave rectifier makes use of only one half cycle of the input alternating current. Thus a full wave rectifier is much more efficient (double+) than a half wave rectifier. This process of converting both half cycles of the input supply (alternating current) to direct current (DC) is termed full wave rectification. Full wave rectifier can be constructed in 2 ways. The first method makes use of a center tapped transformer and 2 diodes. This arrangement is known as **Center Tapped Full Wave Rectifier**. The second method uses a normal transformer with 4 diodes arranged as abridge. This arrangement is known as a Bridge Rectifier.

Full Wave Rectifier Theory

To understand full wave bridge rectifier theory perfectly, you need to learn half wave rectifier first. In the tutorial of half wave rectifier we have clearly explained the basic working of a rectifier. In addition we have also explained the theory behind a p n junction and the characteristics of a p n junction diode.

Full Wave Rectifier Working & Operation

The working & operation of a full wave bridge rectifier is pretty simple. The circuit diagrams and wave forms we have given below will help you understand the operation of a bridge rectifier perfectly. In the circuit diagram, 4 diodes are arranged in the form of a bridge. The transformer secondary is connected to two diametrically opposite points of the bridge at points A & C. The load resistance R_L is connected to bridge through points B and D.

During the first half cycle

During first half cycle of the input voltage, the upper end of the transformer secondary winding is positive with respect to the lower end. Thus during the first half cycle diodes D1 and D3 are forward biased and current flows through arm AB, enters the load resistance RL, and returns back flowing through arm DC.

During this half of each input cycle, the diodes D2 and D4 are reverse biased and current is not allowed to flow in arms AD and BC. The flow of current is indicated by solid arrows in the figure above. We have developed another diagram below to help you understand the current flow quickly. See the diagram below – the green arrows indicate beginning of current flow from source (transformer secondary) to the load resistance. The red arrows indicate return path of current from load resistance to the source, thus completing the circuit.

Full Wave Bridge Rectifier – Circuit Diagram with Input and Output Wave Forms

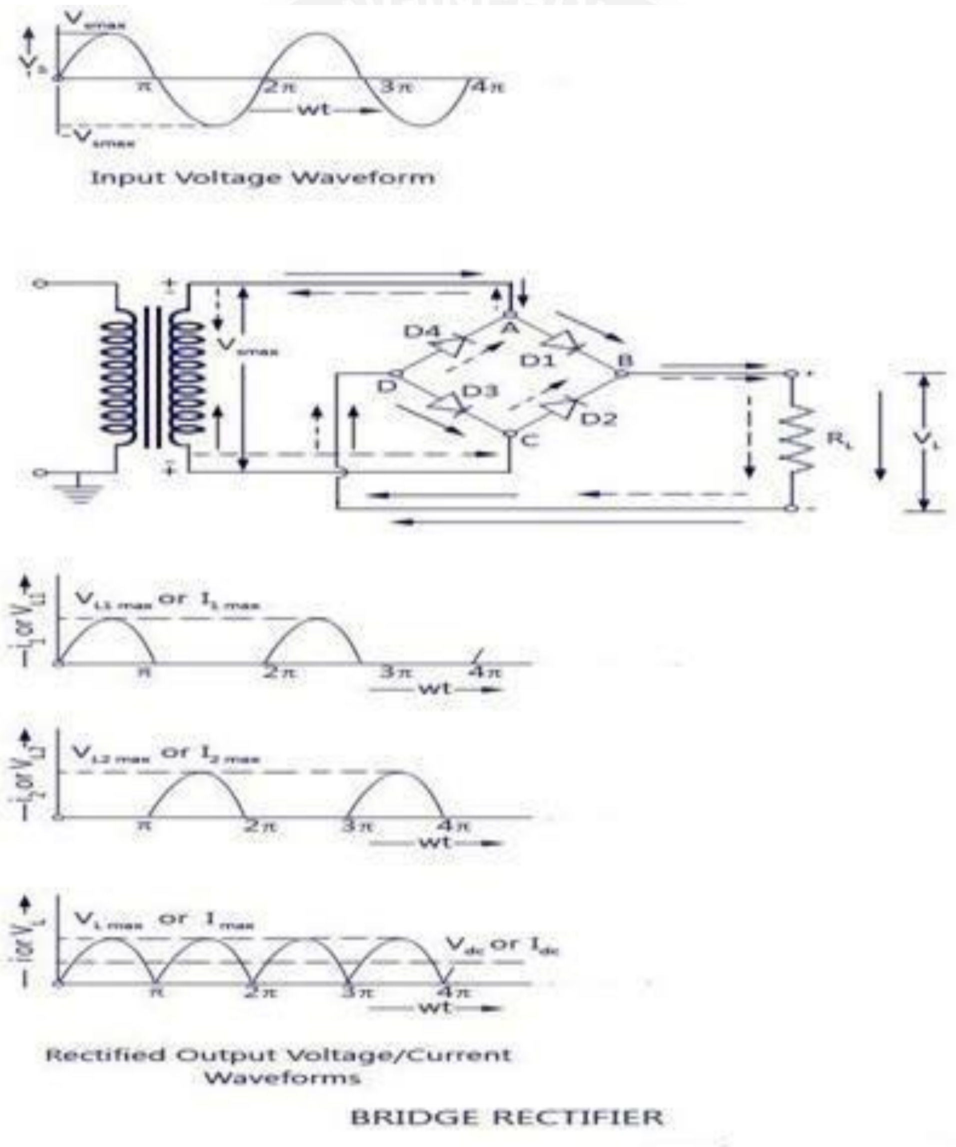

Figure: 3.4.1 Flow of current in Bridge Rectifier

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 271]

During the second half cycle:

During second half cycle of the input voltage, the lower end of the transformer secondary winding is positive with respect to the upper end. Thus diodes D_2 and D_4 become forward biased and current flows through arm CB, enters the load resistance R_L, and returns back to the source flowing through arm DA. Flow of current has been shown by dotted arrows in the figure. Thus the direction of flow of current through the load resistance R_L remains the same during both half cycles of the input supply voltage. See the diagram below – the green arrows indicate beginning of current flow from source (transformer secondary) to the load resistance. The red arrows indicate return path of current from load resistance to the source, thus completing the circuit.

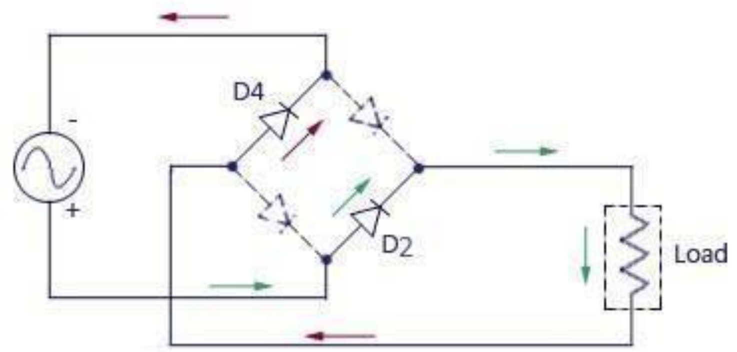

Figure: 3.4.2 Full Wave Bridge Rectifier

[Source: "Electronic devices and circuits" by "Balbir Kumar, Shail.B.Jain, and Page: 271]

3.5 ACTIVE FILTERS

An electric filter is often a frequency selective circuit that passes a specified band of frequencies and blocks or alternates signal and frequencies outside this band. Filters may be classified as

- Analog or digital.
- Active or passive
- Audio (AF) or Radio Frequency (RF)

1. Analog or digital filters:

Analog filters are designed to process analog signals, while digital filters process analog signals using digital technique.

2. Active or Passive:

Depending on the type of elements used in their construction, filter may beclassified as passive or Active elements used in passive filters are Resistors, capacitors, inductors. Elements used in active filters are transistor, or op-amp.

ACTIVE FILTERS OFFER THE FOLLOWING ADVANTAGES OVERPASSIVE FILTERS

1. Gain and Frequency adjustment flexibility:

Since the op-amp is capable of providing gain, the i/p signal is not attenuated as it is in a passive filter. [Active filter is easier to tune or adjust].

2. No loading problem:

Because of the high input resistance and low o/p resistance of the op-amp,the active filter does not cause loading of the source or load.

3. Cost:

Active filters are more economical than passive filter. This is because of the variety of cheaper op-amps and the absence of inductors.

The most commonly used filters are these:

1. Low pass Filters
2. High pass Filters
3. Band pass filters

4. Band –reject filters

Frequency response of the active filters:

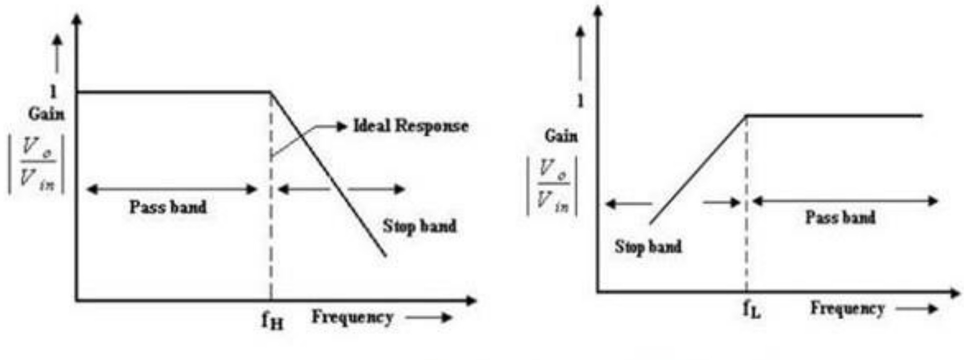

Figure 2.9.1 a).Frequency response of LPF and HPF

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

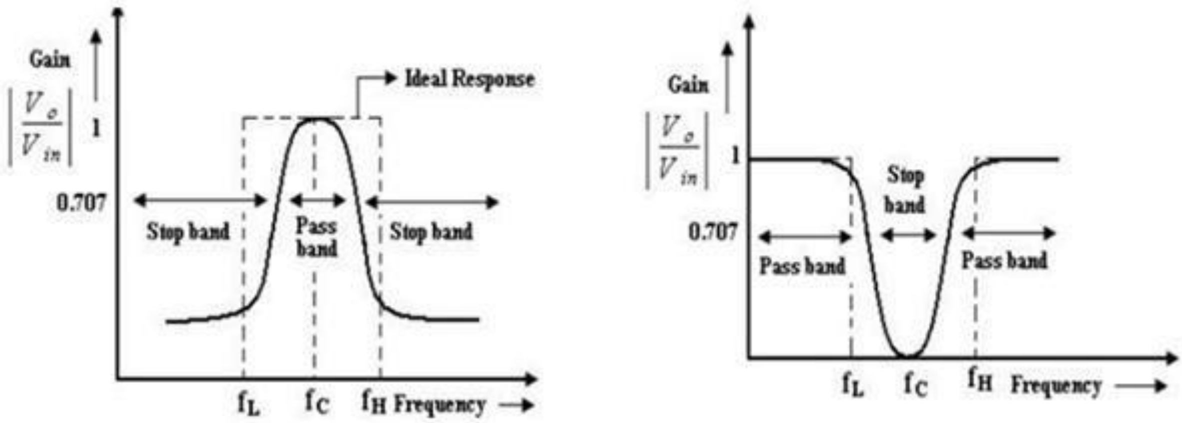

Figure 2.9.1 b) Frequency response of BPF and Band reject filter

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

LOW PASS FILTERS

- It has a constant gain from 0 Hz to a high cutoff frequency f_1.
- At f_H the gain in down by 3db.
- The frequency between 0 Hz and f_H are known as the pass band frequencies

where as the range of frequencies those beyond f_H, that are attenuated includes the stop band frequencies.

HIGH PASS FILTER

High pass filter with a stop band $0 < f < f_L$ and a pass band $f > f_L$

f_L -> low cut off frequencyf

-> operating frequency.

BAND PASS FILTER

It has a pass band between 2 cut off frequencies f_H and f_L where $f_H > f_L$ and two, stop bands: $0 < f < f_L$ and $f > f_H$ between the band pass filter (equal to $f_H - f_L$). Band –reject filter: (Band stop or Band elimination). It performs exactly opposite to the band pass.It has a band stop between 2 cut-off frequency f_L and f_H and 2 pass bands: $0 < f < f_L$ and $f > f_H$ f_C -> center frequency.

FIRST ORDER LPF BUTTERWORTH FILTER

First order LPF that uses an RC for filtering op-amp shown in figure 2.9.2a)is used in the non-inverting configuration. Figure 2.9.2 b) shows the frequency response of first order LPF. Resistor R_1 & R_f determine the gain of the filter. According to the voltage –divider rule, the voltage at the non-inverting terminal (across capacitor) C is,

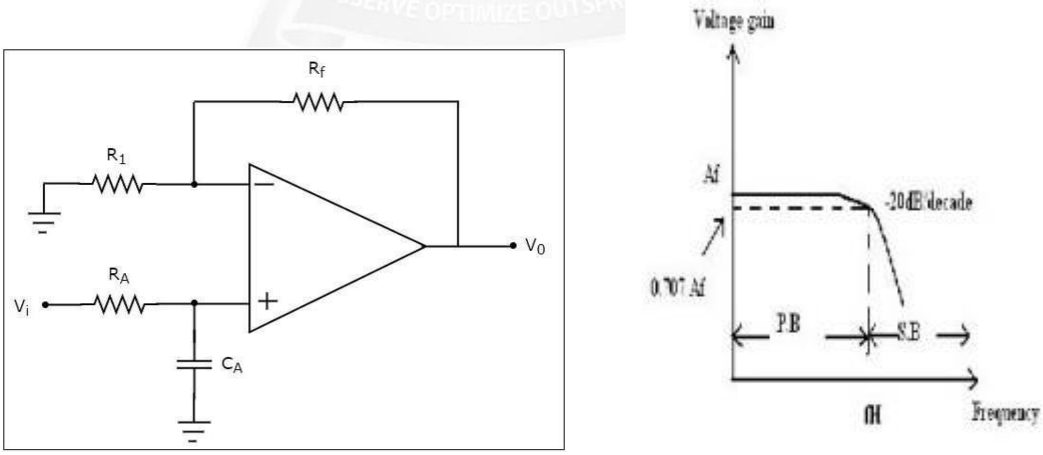

Figure 2.9.2 a) First order low pass filter figure 2.9.2 b)frequency response

[source:https://www.tutorialspoint.com/linear_integrated_circuits_applications /linear_integr ated_circuits_applications_active_filters.htm]

Gain $A = (1+R_f/R_1)$

Voltage across capacitor $V_1 = V_i / (1+j2\pi fRC)$

Output voltage V_0 for non inverting amplifier =A V_1

$$= (1+R_f/R_1)\ Vi/(1+j2\pi fRC)$$

Overall gain $V_0/V_i = (1+R_f/R_1)\ Vi/(1+j2\pi fRC)$ Transfer

function $H(s) = A/(jf/f_h+1)$

if $f_h = 1/2\pi RC$

$H (j\omega) = A/(j\omega RC+1) = A/(j\omega RC+1)$.

The gain magnitude and phase angle of the equation of the LPF can be obtainedby converting eqn. (1) b into its equivalent polar form as follows.

1. At very lowω)|frequency, $f < f_H$

$$|H (j\omega) = A$$

2. At $f = f_H$

$$|H (j\omega)| = A/\sqrt{2} = 0.707A$$

3. At $f > f_H$

$$|H (j\omega)| << A \cong 0$$

When the frequency increases by tenfold (one decade), the volt gain is divided by 10. The gain falls by 20 dB (=20log10) each time the frequency is reduces by 10. Hence the rate at which the gain rolls off f_H = 20 dB or 6dB/octave (twofold R_{in} frequency). The frequency $f = f_H$ is called the cut off frequency because the gain of the filter at this frequency is down by 3 dB (=20 log 0.707).

SECOND ORDER LP BUTTERWORTH FILTER

A second order LPF having a gain 40dB/decade in stop band. A First order LPF can be converted into a II order type simply by using an additional RC network shown in figure 2.9.3

- An improved filter response can be obtained by using a second order active filter.
- A second order active filter consists of two RC pairs & has roll off rate of -40db/decade.
- The op-amp is connected as non-inverting amplifier hence

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_B = A_o V_B$$

$$where, A_o = \left(1 + \frac{R_f}{R_1}\right)$$

$$and\ V_B \rightarrow voltage\ at\ node\ B$$

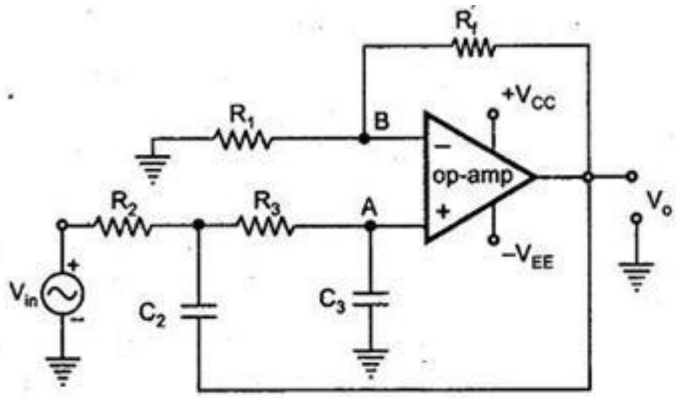

Figure 2.9.3.Second order low pass butterworth filter

[source: https://www.eeeguide.com/second-order-low-pass-butterworth-filter/]

Let us consider the General prototype second order filter circuit as in figure 2.9.4.

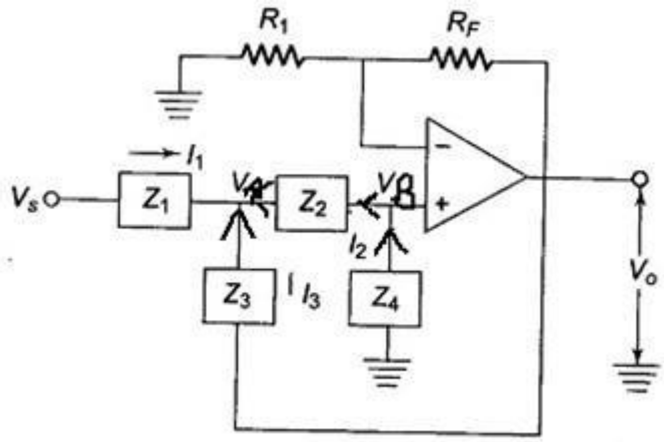

Figure 2.9.4 General prototype second order filter circuit

[source: https://www.eeeguide.com/second-order-low-pass-butterworth-

filter/]

KCL at node A,

$$(V_i - V_A)Z_1 + (V_0 - V_A)Z_3 + (V_B - V_A)Z_2 = 0$$

$$V_iZ_1 + V_oZ_3 + V_BZ_2 - V_A(Z_1 + Z_2 + Z_3) = 0$$

$$V_iZ_1 = V_A(Z_1 + Z_2 + Z_3) - V_BZ_2 - V_oZ_3$$

$$A_o = \frac{V_o}{V_B}$$

$$V_B = \frac{V_o}{A_o}$$

$$V_i Z_1 = V_A(Z_1 + Z_2 + Z_3) - V_B Z_2 - \frac{V_O}{A_O} Z_3 \text{------}(1)$$

KCL at node B ,

$$(V_B - V_A)Z_2 + V_B Z_4 = 0$$

$$V_A Z_2 = V_B(Z_4 + Z_2)$$

$$V_A Z_2 = \frac{V_O}{A_O}(Z_4 + Z_2)\text{------}(2)$$

$$V_A = \frac{V_o}{A_O}\frac{(Z_2 + Z_4)}{Z_2}$$

Sub V_A (2) *in* (1)

$$V_i Z_1 = \frac{V_o}{A_o}\frac{(Z_2 + Z_4)}{Z_2}(Z_1 + Z_2 + Z_3) - V_B Z_2 - \frac{V_O}{A_O} Z_3$$

$$V_i Z_1 = V_o\left(\frac{(Z_2 + Z_4)(Z_1 + Z_2 + Z_3) - Z_3(A_o Z_2) - Z^2{}_2}{A_o Z_2}\right)$$

$$\frac{V_o}{V_i} = \frac{A_o Z_1 Z_2}{Z_1 Z_2 + Z^2{}_2 + Z_2 Z_3 + Z_1 Z_4 + Z_2 Z_4 + Z_3 Z_4 - A_o Z_2 Z_3 - Z^2{}_2}$$

$$\frac{V_O}{V_i} = \frac{A_O Z_1 Z_2}{Z_1 Z_2 + Z_4(Z_1 + Z_2 + Z_3) + Z_2 Z_3(1 - A_0)} \quad --(3)$$

To make a low pass filter , choose $Z_1 = Z_2 = \frac{1}{R}$ And $Z_3 = Z_4 =$

SC from first fig.

From (3), *we get the transfer function* $H(s)$ *of a low pass filter as*

$$\frac{A_o}{\quad}$$

$$H(S) = \frac{R^2}{\left(\frac{1}{R^2} + SC\left(\frac{1}{R} + \frac{1}{R} + SC\right) + \frac{SC}{R}(1 - A_o)\right)}$$

$$After\ simplifying,\ we\ get$$

$$H(S) = \frac{A_o}{S^2C^2R^2 + SCR(3 - A_o) + 1} \quad \text{-----(4)}$$

From (4),

$$H(s) = A_o, \; for \; S = 0$$

$$H(s) = \infty, \; for \; S = \infty$$

The transfer function of the low pass second order system can be written as

$$H(s) = \frac{A_o \omega_n^2}{S^2 + \alpha\omega_n S + \omega_n^2} \quad \text{-------(5)}$$

Where, $A_o \rightarrow$ *the gain*

$\omega_n \rightarrow$ *upper cutoff frequency in rad/*sec

$\alpha \rightarrow$ *sampling coefficient*

comparing equ (4)&(5)

$$\omega_n = \frac{1}{RC} \quad , \alpha = (3 - A_o)$$

The value of the damping coefficient α *for low pass active RC filter can be determined by the value of* A_o *chosen*

Sub $S = j\omega$ *in* (5)

$$H(j\omega) = \frac{A_o \omega_n^2}{(j\omega)^2 + \alpha\omega_n j\omega + \omega_n^2}$$

$$H(j\omega) = \frac{A_o}{\left(\frac{j\omega}{\omega_n}\right)^2 + j\alpha\frac{\omega}{\omega_n} + 1}$$

The normalised expression for lowpass filter is

$$H(j\omega) = \frac{A_o}{S_n^2 + \alpha S_n + 1}$$

Where, normalised frequency $S_n = j\left(\frac{\omega}{\omega_n}\right)$

The expression of magnitude in db of the transfer function is

$$20\,log|H(j\omega)| = 20\,log\left(\frac{Ao}{1+j\alpha\left(\frac{\omega}{\omega n}\right)+\left(\frac{j\omega}{\omega n}\right)^2}\right)$$

$$= 20\,log\left(\frac{Ao}{\left(1-\frac{\omega^2}{\omega n^2}\right)^2+\left(\alpha\frac{\omega}{\omega n}\right)^2}\right)$$

FIRST ORDER HP BUTTERWORTH FILTER

High pass filters are often formed simply by interchanging frequency-determining resistors and capacitors in low-pass filters. (i.e) I order HPF is formed from a I order LPF by interchanging components R & C as shown in figure 2.9.5. Similarly, II order HPF is formed from a II order LPF by interchanging R & C.

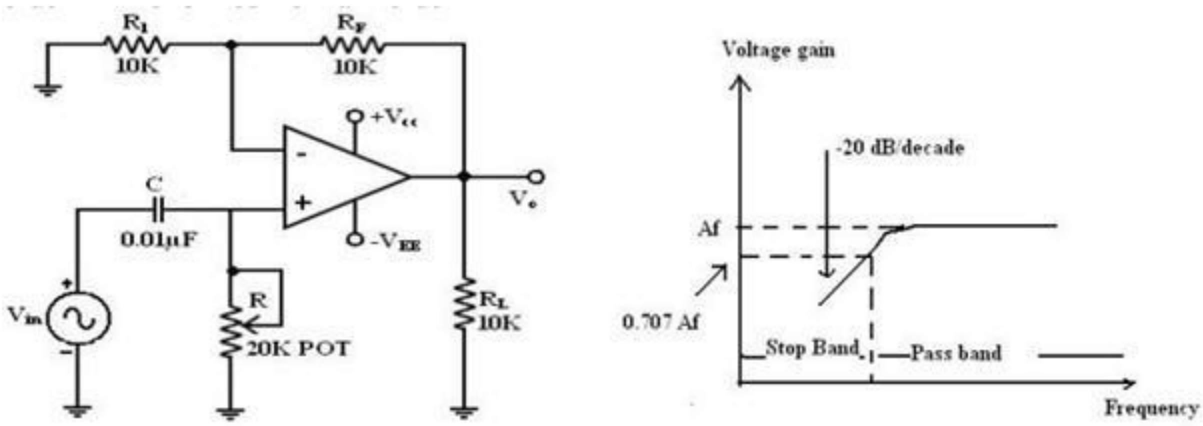

Figure 2.9.5.first order high pass filter and its frequency response

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

Here I order HPF with a low cut off frequency of f_L. This is the frequency at which the magnitude of the gain is 0.707 times its passband value.

Here all the frequencies higher than f_L are passband frequencies.The output voltage V_0 of the first order active high pass filter is

$$V_o = \left(1 + \frac{R_f}{R_i}\right) \frac{j2\pi fRC}{1 + j2\pi fRC} V_i$$

The gain of the filter:

$$\frac{V_o}{V_i} = A\left(\frac{j\left(\frac{f}{f_L}\right)}{1 + j\left(\frac{f}{f_L}\right)}\right)$$

Frequency response of the filter

$$|H(jf)| = \left|\frac{V_o}{V_i}\right| = \frac{A\left(\frac{f}{f_L}\right)}{\sqrt{1+\left(\frac{f}{f_L}\right)^2}} = \frac{A}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}}$$ is

- At high frequencies $f > f_L$ gain = A.

- At f= f_L gain = 0.707 A.
- At f < f_L the gain decreases at a rate of -20 db /decade. The frequency belowcutoff
  frequency is stop band.

SECOND – ORDER HIGH PASS BUTTERWORTH FILTER

I order Filter, II order HPF can be formed from a II order LPF by interchanging the frequency

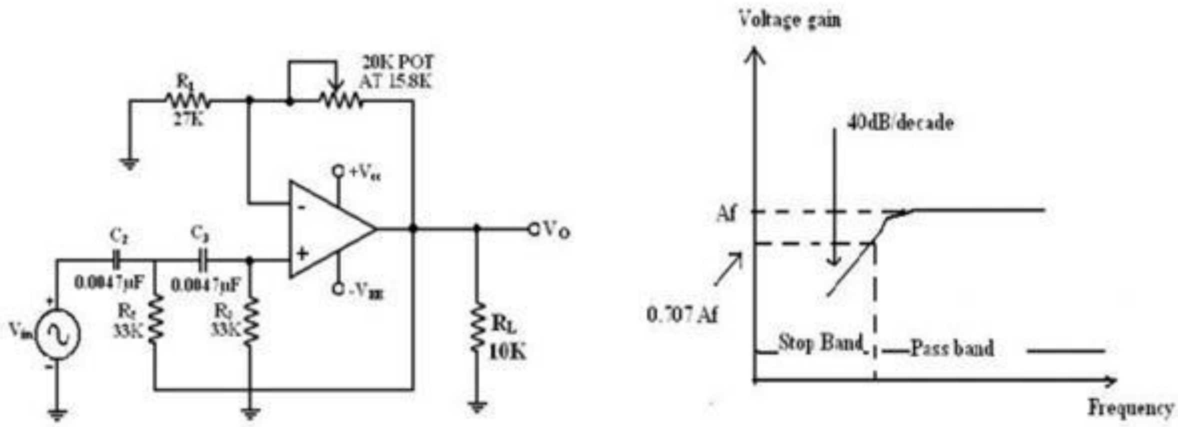

Figure 2.9.6 second order high pass filter and its frequency response

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

BAND PASS FILTERS

- Filters that pass band of frequencies and attenuates others. Its high cutoff frequency and low cutoff frequency are related as $f_H > f_L$ and maximum gain at resonant frequency

$$f_r = \sqrt{f_H f_L}$$

- Figure of merit Q= $f_r / (f_H - f_L) = f_r / B$ where B= bandwidth.
- 2 types of filters are Narrow band pass and wide band pass filters

WIDE BAND PASS FILTER

It is connection of a low pass filter and a high pass filter in cascade as in figure 2.9.7.The f_H of low pass filter and f_L of high pass filter are related as $f_H > f_L$

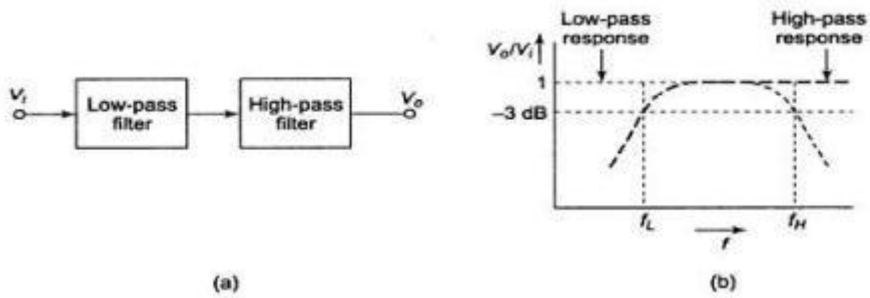

Figure 2.9.7 a)wide band pass filter b) its frequency response

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

4.1 Two Transistor Analogy of SCR

The two transistor analogy or two transistor model of SCR expresses the easiest way to understand the working of SCR by visualizing it as a combination of two transistors. The collector of each transistor is connected to the base of the other transistor.

The two transistor analogy or two transistor model of SCR expresses the easiest way to understand the working of SCR by visualizing it as a combination of two transistors as shown in figure. The collector of each transistor is connected to the base of the other transistor.

Assume that load resistance is connected between the anode and cathode terminals and a small voltage is applied at the gate and cathode terminals. When there is no gate voltage, the transistor 2 is in cut-off mode due to zero base current. Therefore, no current flows through the collector and hence the base of transistor T1. Hence, both transistors are open circuited and thereby no current flows through the load.And hence the base current at the transistor T1 drives the transistor into saturation mode.

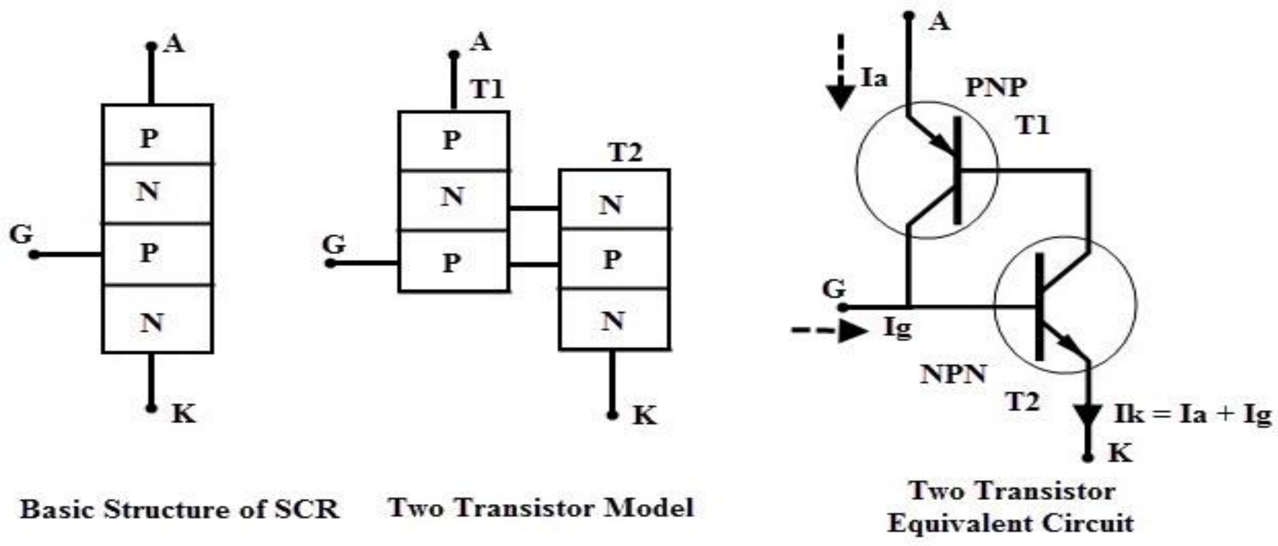

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Figure 4.1.1 Two Transistor Model

[Source: "Power Electronics Circuits, Devices and Applications" by M.H. Rashid, Page: 12]

From the above figure the base current of transistor T2 becomes the collector current of transistor T1 and vice-versa.

Hence

$I_{b2} = I_{c1}$ and $I_{c2} = I_{b1}$

Also current through the cathode terminal, $I_k = I_g + I_a$ ……(1)

For a transistor,

$I_{b1} = I_{e1} – I_{c1}$ ……(2)

and $I_{c1} = \alpha_1 I_{e1} + I_{co1}$……(3)

Where I_{co1} is the leakage current.

Substituting equation 3 in equation 2 we get

$I_{b1} = I_{e1} (1 – \alpha_1) – I_{co1}$ …….(4)

From the figure anode current is the emitter current of transistor T1,

$I_a = I_{e1}$

Then $I_{b1} = I_a (1 – \alpha_1) – I_{co1}$

And also for transistor T2

$I_{c2} = \alpha_2 I_{e2} + I_{co2}$

But $I_k = I_{e2}$

Therefore $I_{c2} = \alpha_2 I_k + I_{co2}$

$I_{c2} = \alpha_2 (I_g + I_a) + I_{co2}$ …..(5)

But $I_{b1} = I_{c2}$ …..(6)

Substituting the equations 4 and 5 in equation 6 we get

$I_a (1 - \alpha_1) - I_{co1} = \alpha_2 (I_g + I_a) + I_{co2}$

$I_a = [\alpha_2 I_g + I_{co1} + I_{co2}] / [1 - (\alpha_1 + \alpha_2)]$

By assuming the leakage currents are negligible in both transistors we get

$I_a = [\alpha_2 I_g] / [1 - (\alpha_1 + \alpha_2)]$

where α_1 and α_2 are the respective gains of the two transistors.

4.2 Two Pulse Converter

FULLY CONTROLLED BRIDGE CONVERTER

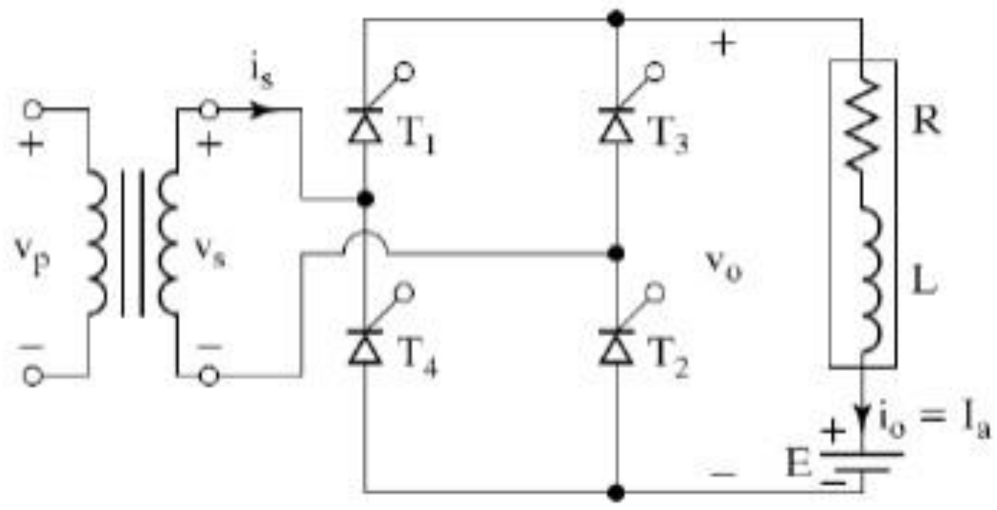


Figure 4.2.1 SINGLE PHASE FULL CONVERTER

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 191]*

CONSTRUCTION

The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a highly inductive load and a dc source in the load circuit so that the load current is continuous and ripple free (constant load current operation). The fully controlled bridge converter consists of four thyristors T1, T2,T3 and T4 connected in the form of full wave bridge configuration as shown in the figure. Each thyristor is controlled and turned on by its gating signal and naturally turns off when a reverse voltage appears across it.

During the positive half cycle when the upper line of the transformer secondary winding is at a positive potential with respect to the lower end the thyristors T1and T2are forward biased during the time interval ωt = 0 to π. The thyristors T1and T2are triggered simultaneously ωt =α; (0 ≤α≤π) , the load is connected to the input supply through the conducting thyristors T1and T2.. Due to the inductive load T1 and T2will continue to conduct beyond ωt =π, even though the input voltage becomes negative. T1 and T2 conduct together during the time period α to (π+α) , for a time duration of π radians (conduction angle of each thyristor = 180^0).

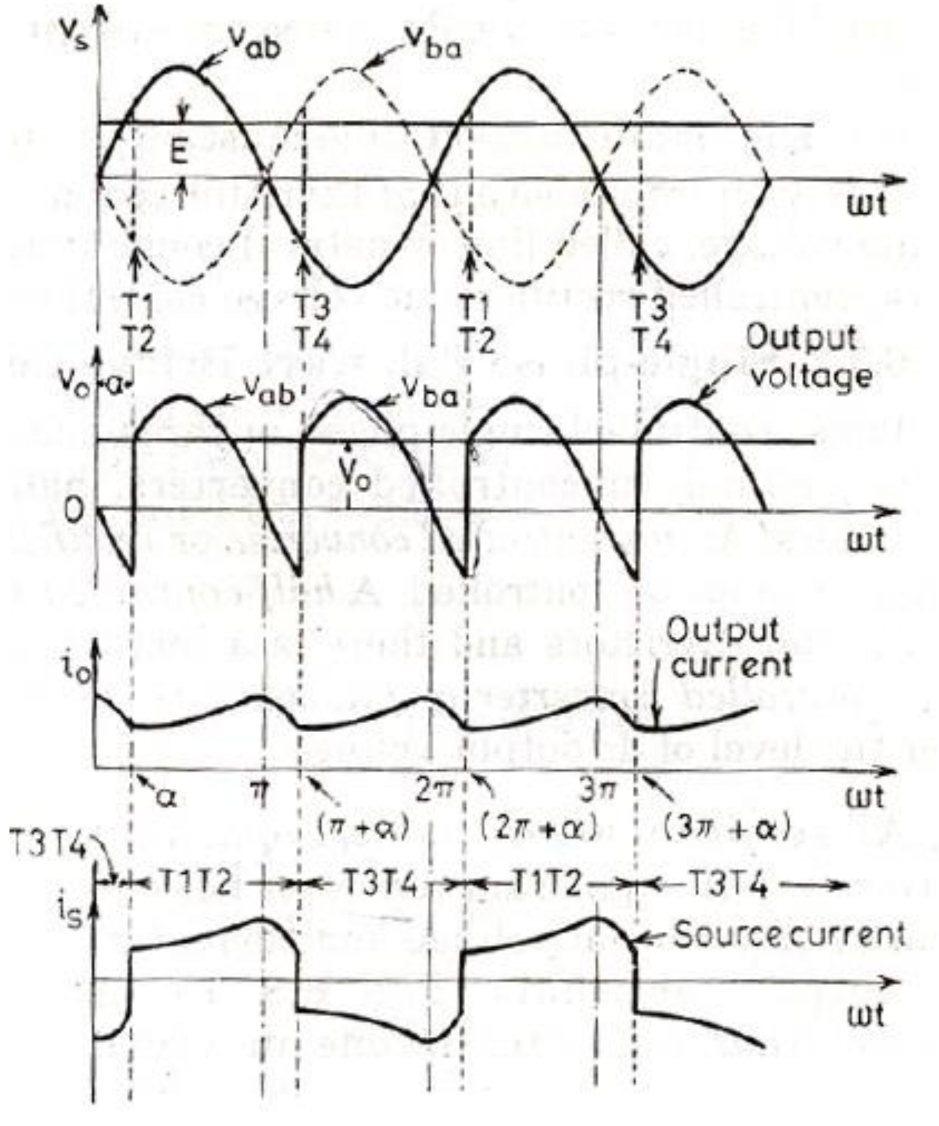


Figure 4.2.2 FULL CONVERTER WAVEFORM

During the negative half cycle of input supply voltage for ωt =π to 2π the thyristors T3and T4are forward biased. T3 and T4are triggered at ωt = (π+α) . As soon as the thyristors 3 T and 4 T are triggered a reverse voltage appears across the thyristors T1and T2and they naturally turn-off and the load current is transferred from T1and T2to the thyristors T3and T4. In the next positive half cycle when T1and T2 are triggered, T3and T4are reverse biased and they turn-off. The figure shows the waveforms of the input supply voltage, the output load voltage, the constant load current with negligible ripple and the input supply current.

During the time period ωt =α to π, the input supply voltage V_S and the input supply current is both positive and the power flows from the supply to the load. The converter operates in the rectification mode during ωt =α to π.

During the time period ωt =π to (π+α) , the input supply voltage Vs is negative and the input supply current is positive and there will be reverse power flow from the load circuit to the input supply. The converter operates in the inversion mode during the time period ωt =π to (π+α) and the load energy is fed back to the input source.

The single phase full converter is extensively used in industrial applications up to about 15kW of output power. Depending on the value of trigger angle α, the average output voltage may be either positive or negative and two quadrant operation is possible.

4.3 Three Pulse Converter

INTRODUCTION TO 3-PHASE CONTROLLED RECTIFIERS

Three phase converters are 3-phase controlled rectifiers which are used to convert ac input power supply into dc output power across the load.

FEATURES OF 3-PHASE CONTROLLED RECTIFIERS ARE

- Operate from 3 phase ac supply voltage.
- They provide higher dc output voltage and higher dc output power.
- Higher output voltage ripple frequency.
- Filtering requirements are simplified for smoothing out load voltage and load current.Three phase controlled rectifiers are extensively used in high power variable speed industrial dc drives.

3-PHASE HALF WAVE CONVERTER WITH R LOAD (Three Pulse Converter)

Three single phase half-wave converters are connected together to form a three phase half-wave converter as shown in the figure.

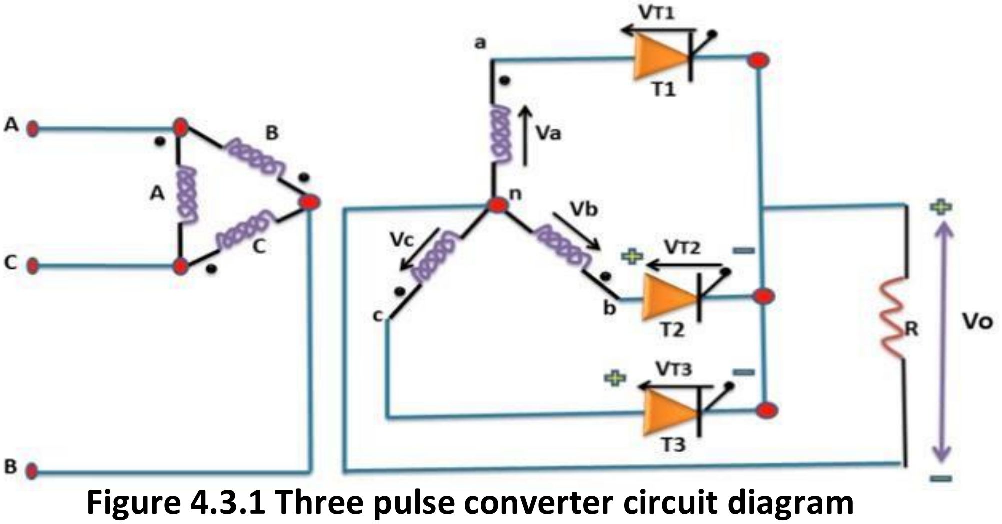


Figure 4.3.1 Three pulse converter circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 214]*

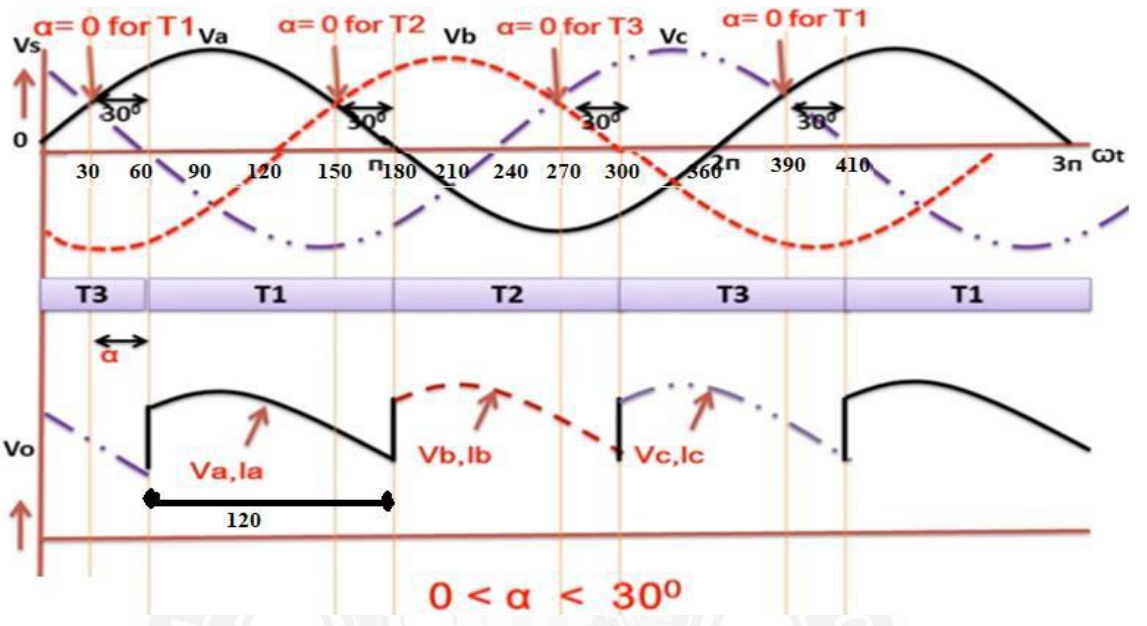


Figure 4.3.2 Three pulse converter Waveforms

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 11]*

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor T1 in series with one of the supply phase windings ' a - n ' acts as one half wave controlled rectifier. The second thyristor T2 in series with the supply phase winding,'b - n ' acts as the second half wave controlled rectifier. The third thyristor T3 rectifier in series with the supply phase winding ' c - n ' acts as the third half wave controlled.

The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.When the thyristor T 1 is triggered the load current flows through the supply phase winding 'a - n ' and through thyristor T1 as long as T1 conducts.

When thyristor T 2 is conducts the phase voltage Vbn appears across the load until the thyristor T3 is triggered . When the thyristor T3 is triggered the phase voltage Vcn appears across the load.

For a purely resistive load where the load inductance 'L = 0' and the current appears as discontinuous.

The frequency of output ripple frequency for a 3-phase half wave converter is 3fs , where fs is the input supply frequency.

The 3-phase half wave converter is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components.

4.4 Six Pulse Converter

THREE PHASE FULL CONVERTER

Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

FEATURES OF 3-PHASE CONTROLLED RECTIFIERS ARE

- They provide higher dc output voltage and higher dc output power.
- Higher output voltage ripple frequency.
- Three phase controlled rectifiers are extensively used in high power variable speed industrial dc drives.

Three phase fully controlled bridge converter

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable out put dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf. for commutation and are referred to as the "Load commutated inverter".

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig.

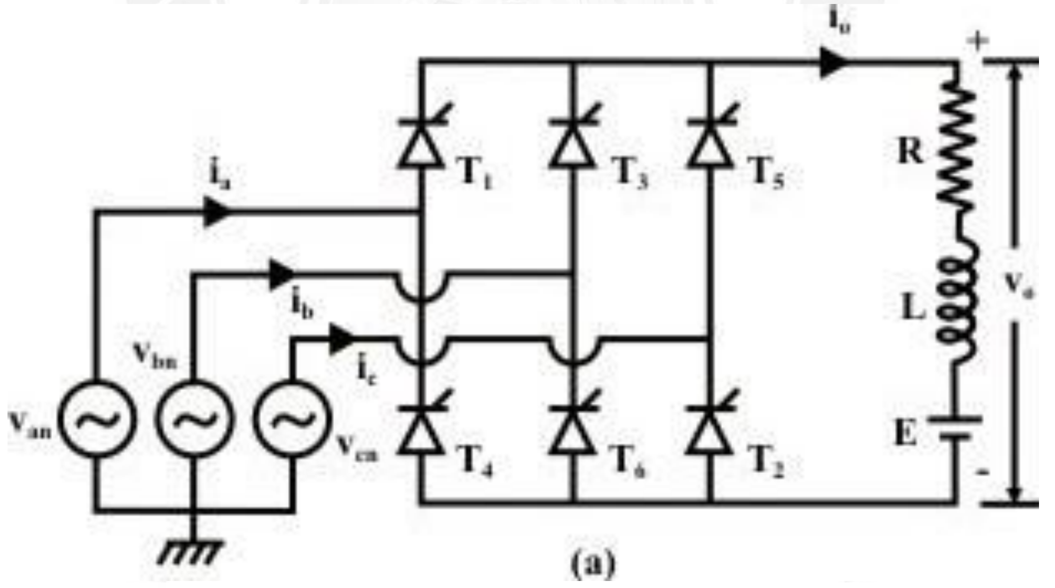


Figure 4.4.1 Six pulse converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 210]*

- The three thyristors (T1 ,T3 andT5) will not work together at the same time or two of them also will not work together at the same time.

➢ The three thyristors (T2 ,T4 andT6) will not work together at the same time or two of them also will not work together at the same time.

➢ (T1 and T4), (T3 and T6) or (T5 and T2) will not work together at the same time.

➢ Each thyristor is triggered at an interval of 2pi / 3.

➢ Each thyristors pair ((T6&T1), (T1&T2), (T2&T3), (T3&T4), (T4&T5), (T5&T6)) is triggered at an interval of pi / 3.

➢ The frequency of output ripple voltage is 6fS.

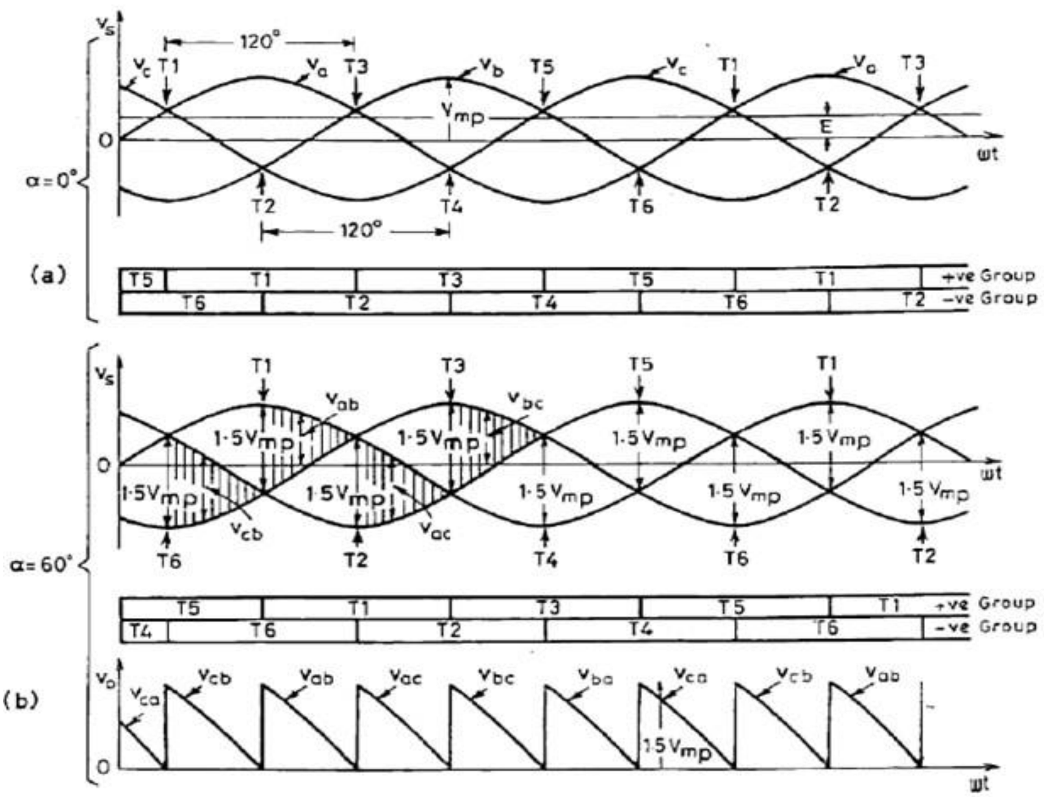


Figure 4.4.2 Six pulse converter Waveforms

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 211]*

- If T1 is triggered at (30 + α), T3 will be triggered at (30 + α+120) and T5 will be triggered at (30 +α+240). T4 will be triggered at (30 + α+180), T6 will be triggered at (30 + α+120+180) and T2 will be triggered at (30 +α +240+180).

Firing Angle	T1	T2	T3	T4	T5	T6
0˚	30˚	90˚	150˚	210˚	270˚	330˚
30˚	60˚	120˚	180˚	240˚	300˚	360˚
60˚	90˚	150˚	210˚	270˚	330˚	390˚
90˚	120˚	180˚	240˚	300˚	360˚	420˚

Three phase full converter – triggering angles of thyristor

At ωt = 30˚+α, thyristor T6 is already conducting when the thyristor T 1is turned on by applying the gating signal to the gate of T 1. During the time period to ωt =30+α to 90˚+α thyristors T 1and T 6 conduct together and the line to line supply voltage Vab appears across the load. At ωt = 90 ˚+α , the thyristor T2 is triggered and T6 is reverse biased immediately and T6 turns off due to natural commutation. During the time period ωt = 90˚+α to 150˚+α , thyristor T1 and T2 conduct together and the line to line supply voltage V ac appears across the load. The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered.

4.5 EFFECT OF SOURCE INDUCTANCE

In actual practice, the converter is connected to ac mains through a transformer.

In a converter,because of source inductance, the current in the outgoing thyristor cannot change from full value to zero instantaneously and the current through the incoming thyristor cannot increase from zero to full value instantaneously. Therefore after the triggering gate pulse is applied to a thyristor, the current of the outgoing thyristor decreases from full value to zero over a time $\omega t = \mu$. During this time interval the current through incoming thyristor rises from zero to full value. During this period μ known as commutating period, both the outgoing and incoming thyristors are conducting. μ is also known as overlap angle**.** The overlapping of currents causes a reductionin output voltage. During this commutation period, the output voltage is equal to 0 .

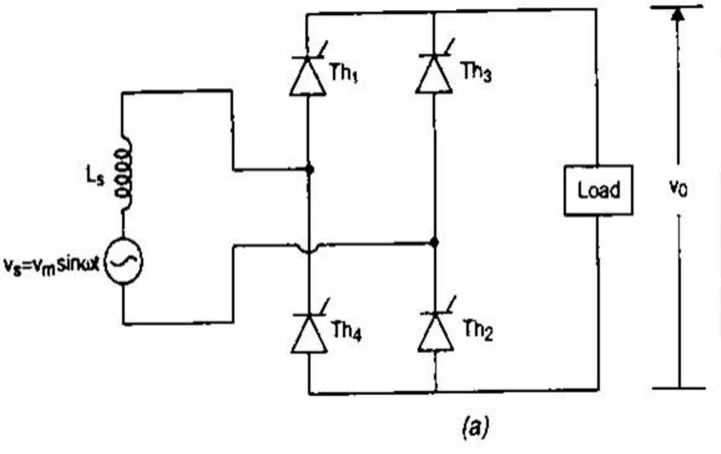


Figure 4.5.1 Single Phase Converter with Source Inductance

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 222]*

Figure shows a single phase fully controlled bridge convereter with source inductance L_S. The load is assumed to be highly inductive so that load current can be assumed to be constant and equal to I_0. Let i_1 and i_2 be the currents through Th_1, Th_2 combination and Th_3, Th_4 combination respectively.

During overlap period μ one of these currents decays to zero and the other builds up from zero to full value. Four thyristors conduct together as shown in Fig

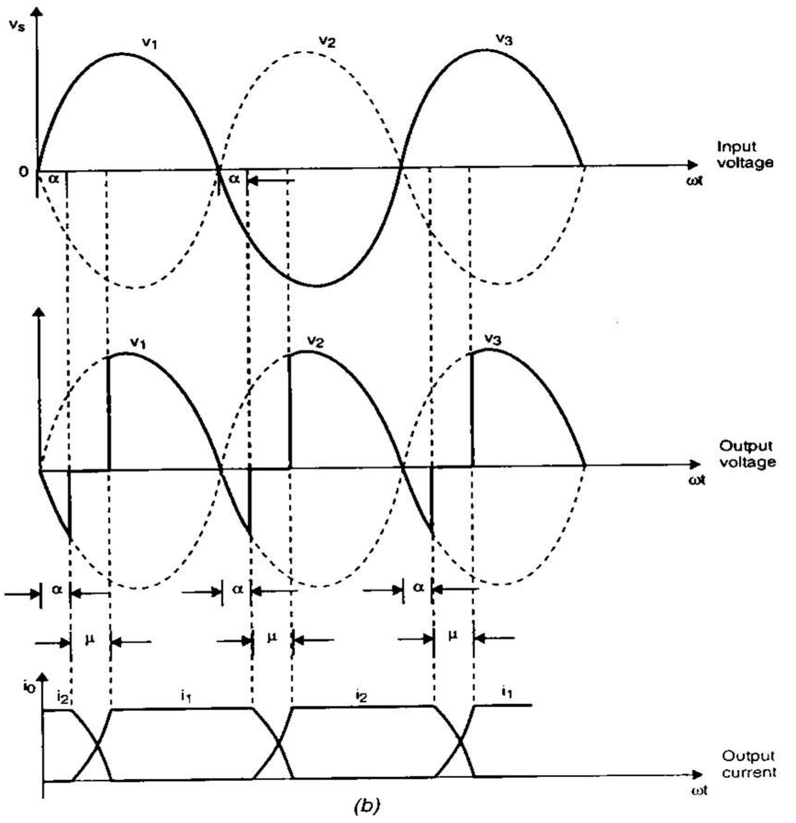


Figure 4.5.2 Effect of Source Inductance

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 223]*

5.1 Introduction - AC voltage controllers

AC voltage controllers are thyristor based devices which convert fixed alternating voltage directly to variable alternating voltage without a change in the frequency. Some of the main applications of ac voltage controllers are for domestic and industrial heating, transformer tap changing, lighting control, speed control of single phase and three phase ac drives and starting of induction motors.

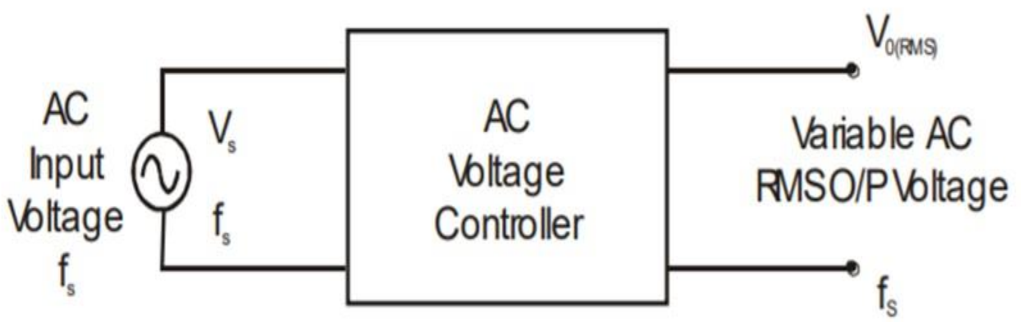


Figure 5.1.1 Block diagram of AC voltage controller

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 392]*

TYPE OF AC VOLTAGE CONTROLLERS

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.

- Single Phase AC Controllers.
- Three Phase AC Controllers.

- Single phase ac controllers operate with single phase ac supply voltage of 230V RMS at 50Hz in our country.
- Three phase ac controllers operate with 3 phase ac supply of 400V RMS at 50Hz supply frequency.

APPLICATIONS OF AC VOLTAGE CONTROLLERS

- Lighting / Illumination control in ac
- power circuits. Induction heating.
- Industrial heating & Domestic heating.
- Transformers tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor control).

5.2 SINGLE-PHASE HALF-WAVE AC VOLTAGE CONTROLLER

- It consists of one thyristor in antiparallel with one diode.
- Then SCR is forward biased during positive half cycle, it is turned on at firing angle α.
- Load voltage at once jumps to Vm sinωt, likewise load current becomes Vm sinα.
- Thyristor get turned off at ωt = ∏ for R load. After ωt = ∏, negative half cycle forward biases diode Dl, therefore Dl conducts from ωt = ∏ to 2∏.
- Only positive half cycle onduction can be controlled, by varying firing angle. negative half cycle cannot be controlled. So single-phase half wave voltage controller is also called single phase unidirectional voltage controller. From the Figure it is understood that positive half cycle is not identical with negative half- cycle for both voltage and current waveforms. As a result, dc component is introduced in the supply and load circuits which is undesirable.

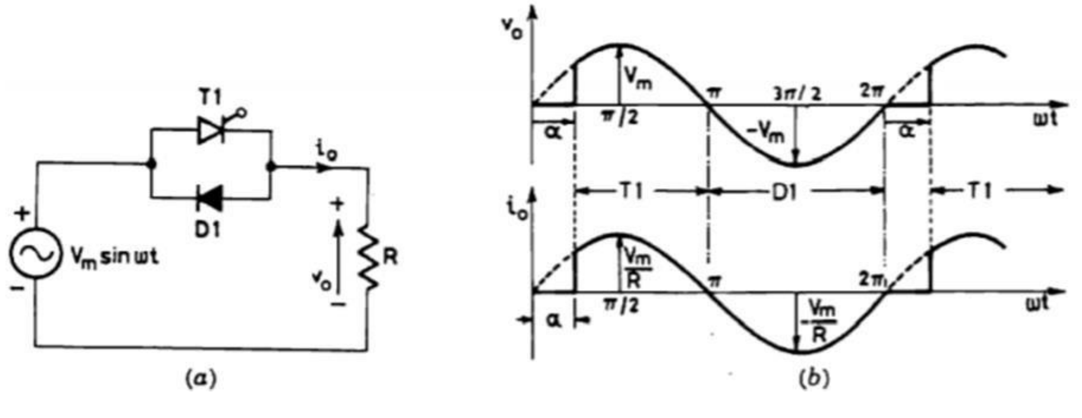


Figure 5.2.1 Single Phase AC voltage controller

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 396]*

RMS VALUE OF OUTPUT VOLTAGE OF SINGLE PHASE UNIDIRECTIONAL VOLTAGE CONTROLLER:

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

$$V_{or}^2 = \frac{V_m^2}{4\pi}\int_{\alpha}^{2\pi}(1-\cos 2\omega t)d(\omega t)$$

$$V_{or}^2 = \frac{V_m^2}{4\pi}\left[(2\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]$$

$$V_{or} = \frac{V_m}{2}\left[\frac{1}{\pi}\left[(2\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]\right]^{\frac{1}{2}}$$

$$I_{or} = \frac{V_{or}}{R}$$

AVERAGE VALUE OF OUTPUT VOLTAGE:

$$V_o = \left[\frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m \sin \omega t d(\omega t)\right]$$

$$V_o = \frac{V_m}{2\pi}(-\cos\omega o)_{\alpha}^{2\pi}$$

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

SINGLE PHASE FULL WAVE AC VOLTAGE CONTROLLER

- It consists of two SCRs connected in antiparallel.
- During positive halfcycle T1 is triggered at firing angle , it conducts from wt = α to ∏ for R load.
- During negative half cycle,T2 is triggered at wt = ∏ + α, it conducts from rot = ∏

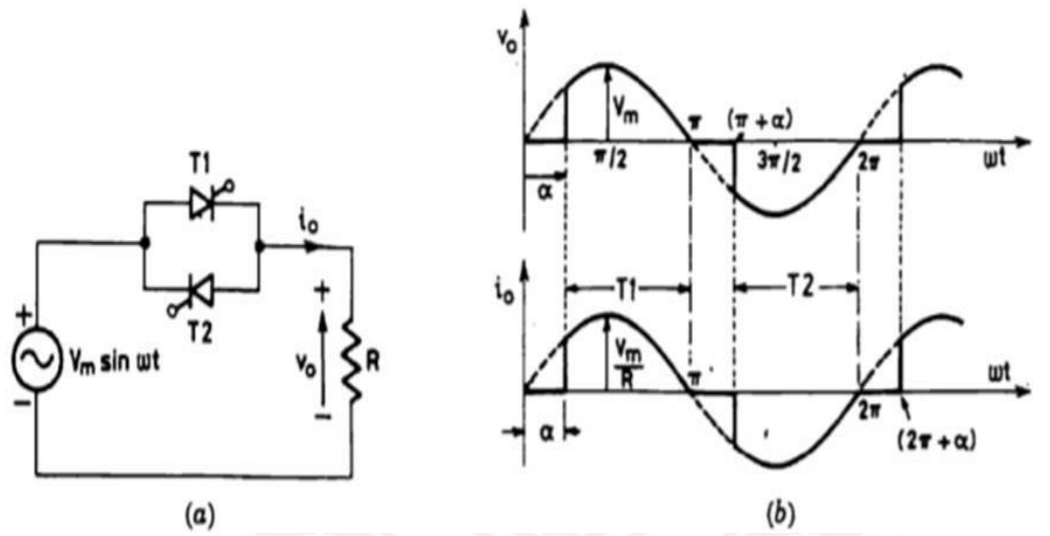


Figure 5.2.2 Single-phase full-wave ac voltage controller

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 397]*

- It has been stated above that ac voltage controllers are phase-controlled converters, the phase relationship between the start of load current and the supply voltage is controlled by varying the firing angle. These are called phase- controlled ac voltage controllers or ac voltage controllers. Single phase full-wave ac voltage controller is also called single phase bidirectional voltage-controller.

5.3 THREE PHASE AC VOLTAGE CONTROLLER

- To control the current and voltage of three phase loads, Three Phase AC Voltage Controller are required. The single phase controller described previously can be introduced singly in each phase or line, to form a three phase controller. There exist a variety of connections for Three Phase AC Voltage Controller.

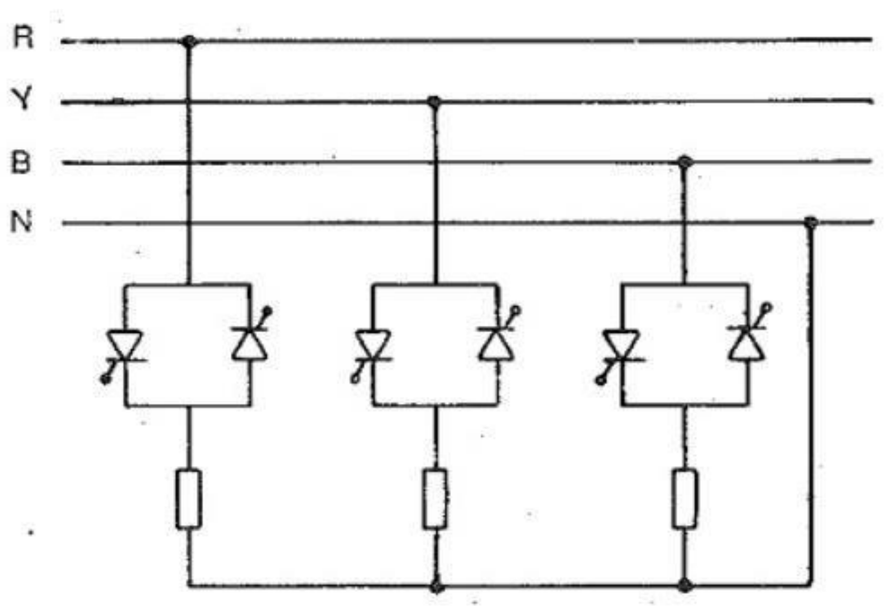


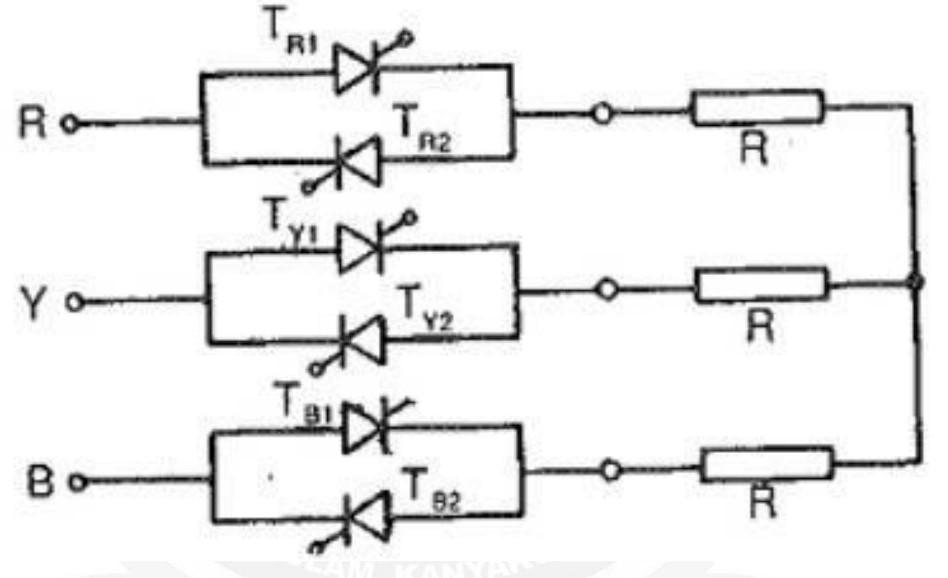
Figure 5.3.1 Block diagram of Three Phase AC voltage controller

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 398]*

- A three phase four wire controller is shown in Fig 5.6. The load neutral and supply neutral are connected together. Each of the three controllers can be independently controlled to feed the load impedance. Each phase has the same relations as a single phase controller. The neutral and line currents contain triplet harmonics along with other odd harmonics.

A Three Phase AC Voltage Controller has symmetrical control if both the back to back connected thyristors have the same firing angle. It has asymmetrical control if the firing angles differ or if one of the thyristors is replaced by a diode, or if the controllers are placed in only two of the three lines.

We now discuss the features of a symmetrically controlled three phase, three wire, star-connected controller for both ohmic and inductive loads.



5.3.2 Three phase ac voltage controller feeding a resistive load

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 399]*

The schematic of a three phase, three wire voltage controller feeding a three phase, star-connected balanced resistance is shown in Fig. 5.10. Phase control of the thyristors is employed. The phase and line voltages of the three phase system are shown in Fig. 5.10. For a controller, the control pulse is of a long duration, equal to the conduction period of the thyristor. This is to make sure that the firing pulse is available at the gate whenever the thyristor is forward biased, so that the thyristor can go into conduction.

It also ensures the firing of the thyristor whenever a forward current is expected. If, because of some circuit condition, the current goes to zero the thyristor turns off. A lengthy pulse can bring it into conduction. Further, slow building up of current in the load circuit when the thyristor is fired (to give maximum load voltage) may cause the thyristor to go to an off state if it is not fully turned on.

For current to flow it is necessary to trigger at least two thyristors at a time. If we define the instantaneous input phase voltages as:

$$v_{an} = V_m \sin \omega t$$

$$v_{bn} = V_m \sin (\omega t - 2\pi / 3)$$

$$v_{cn} = V_m \sin (\omega t - 4\pi / 3)$$

The instantaneous input line voltages are

$$v_{ab} = 3\ v_{an} = 3\ v_m \sin (\omega t + \pi/6)$$

$$v_{bc} = 3\ v_{bn} = 3\ v_m \sin (\omega t - \pi/2)$$

$$v_{ca} = 3\ v_{cn} = 3\ v_m \sin (\omega t - 7\pi/6)$$

5.4 AC VOLTAGE CONTROL STRATEGY

There are two different types of thyristor control used in practice to control the flow ac power

1. Phase control
2. On-Off control

PHASE CONTROL TECHNIQUE

In phase control, the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using thyristors during a part of each input cycle. The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load. By controlling the phase angle or the trigger angle 'α' (delay angle), the output RMS voltage across the load can be controlled.

INTEGRAL CYCLE CONTROL

Integral cycle control consists of switching on the supply to load for an integral number of cycles and then switching off the supply for a further number of integral cycles.

The principle of integral cycle control can be explained by referring to the above Figure for a single phase voltage controller with resistive load. Gate pulses ig1 turn on the thyristors Tl, T2 respectively at zero-voltage crossing of the supply voltage.

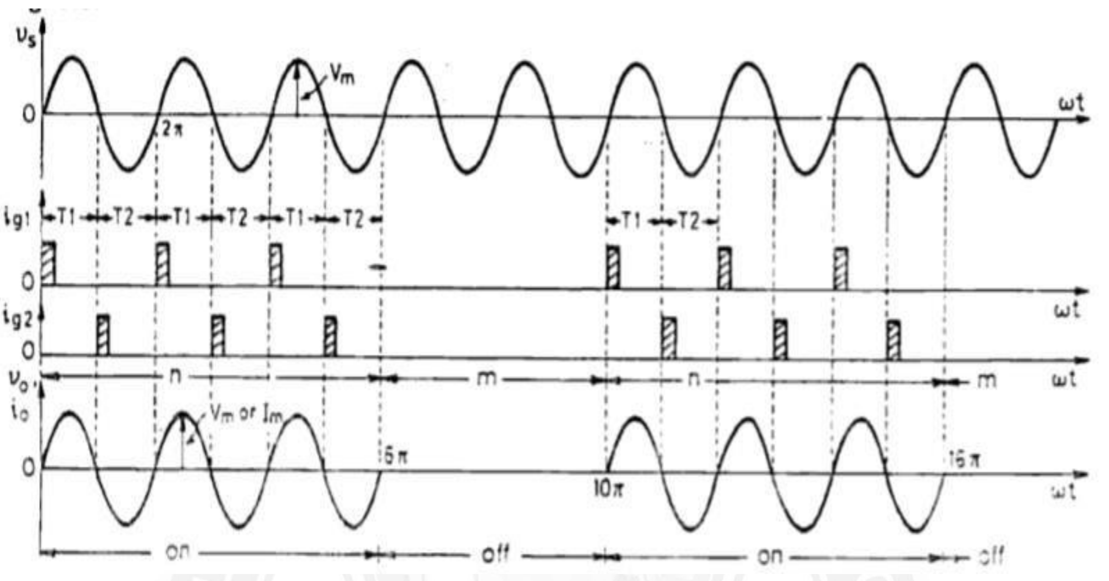


Figure 5.4.1 Integral cycle control

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 393]*

The source energises the load for n (= 3) cycles. When gate pulses are withdrawn, load remains off for m (= 2) cycles. In this manner, process of turn on and turn off is repeated for the control of load power. By varying the number of n and m cycles, power delivered to load can be regulated as desired.

For n = 3 and m = 2. Power is delivered to load for n cycles. No power is delivered to load for m cycles. It is the average power in the load that is controlled.

Integral cycle control is also known as on-off control, burst firing, zero- voltage switching, cycle selection cycle syncopation.

5.5 TRIAC BASED PHASE CONTROLLERS

A TRIAC is a three terminal semiconductor device which can control the flow of the current and thus its name is TRIAC it has a similar operation to two thyristors connected in reverse parallel with a common gate connection. Thus it has the ability to be triggered into conduction.

TRIACS are used in power control to give full wave control and it could control the voltage between zero and full power Many industries face problems like voltage sags and extended under voltage and thus it could cause a negative impact on productivity for this we need to install voltage controllers to control the voltage TRIAC provides a wide range of control in AC circuit without the need for external components.

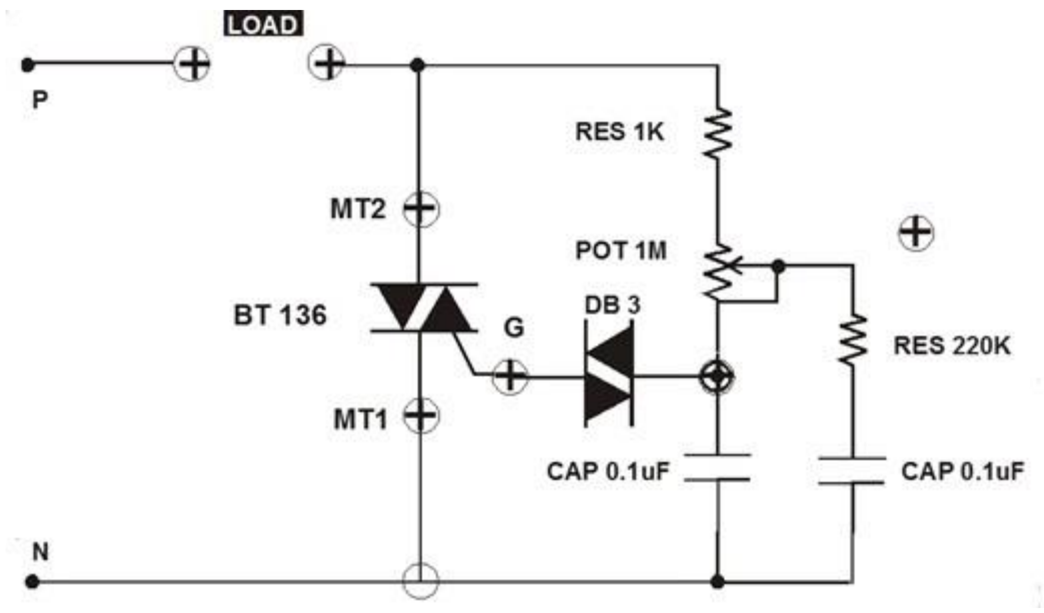


Figure 5.5.1 TRIAC BASED PHASE CONTROLLERS

[Source: "Power Electronics Circuits, Devices and Applications" by M.H. Rashid, Page: 212]

A lamp load is connected with the circuit. By varying the variable resistor see the variation of light. There will be voltage and current reading at different steps of the load lamp or induction load would be there optionally. The wave observes form the

CRO and divide it by 10 and check the gate of TRIAC. Variation of phase angle could be seen while varying the potentiometer

The AC voltage controllers are of two types it is classified according to the type of input supply applied to the circuit

- Single phase AC controllers
- Three phase AC controllers

Single phase controllers operate with single phase supply voltage 230v at 50Hz In the case of three phase, it will be 400v at 50hz DIAC will have a break over voltage at the range of 30 volts and if a voltage less than this is applied to the polarity it would remain in high resistance with a flow of small leakage current

Application of AC voltage controller :

- Illumination control in AC circuits
- Industrial heating, induction heating, and domestic heating
- Tap changing of a transformer
- Induction motor speed control
- Control of AC magnets