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POLLACHI INSTITUTE OF ENGINEERING AND TECHNOLOGY

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Department of Electrical and Electronics Engineering

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EE3591- POWER ELECTRONICS

1.9 Commutation Circuit for SCR

To turn on a Thyristor, there arevarious triggeringmethods inwhich a trigger pulse is applied at its Gate terminal. Similarly, there are various techniques to turn Off a Thyristor, these techniques are called Thyristor Commutation Techniques. It can be done bybringing the Thyristor back into the forward blocking state from the forward conduction state. To bring the Thyristor into forward blocking state, forward current is reduced below the holding current level. For the purpose of power conditioning and power controla conducting Thyristor must be commutated properly.

There are mainly two techniques for Thyristor Commutation:

Natural Commutation- in ac circuits:

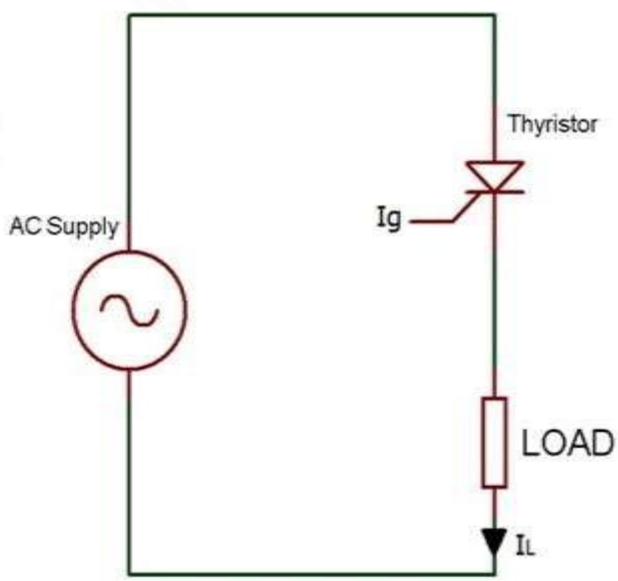


Figure 1.9.1 Natural Commutation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 160]*

Natural Commutation

Natural Commutation occurs only in AC circuits, and it is named so because it occurs naturally and doesn't require any external circuit. When a positive cycle reaches to zero and the anode current is zero, immediately a reverse voltage (negative cycle) is applied across the Thyristor which causes the Thyristor to turn OFF.A Natural Commutation occurs in AC Voltage Controllers, Cycloconverters, and Phase Controlled Rectifiers.

Forced Commutation- in dc circuits

Forced commutation is classified into 5 types based on the commutation voltage generatedas

1. Class A: Self or Load Commutation
2. Class B: Resonant-Pulse Commutation
3. Class C: Complementary Commutation
4. Class D: Impulse Commutation
5. Class E: External Pulse Commutation

Forced Commutation

As we know there is no natural zero current in DC Circuits like as natural commutation. So, Forced Commutation is used in DC circuits and it is also called as DC commutation. It requires commutating elements like inductance and capacitance to forcefully reduce the anode current of the Thyristor below the holding current value, that's why it is called as Forced Commutation. Mainly forced commutation is used in Chopper and Inverters circuits. Forced commutation is divided into six categories, which are explained below:

Class A: Self or Load Commutation

Class A is also called as “Self-Commutation” and it is one of the most used technique among all Thyristor commutation technique. In the below circuit, the inductor, capacitor and resistor form a second order under damp circuit.

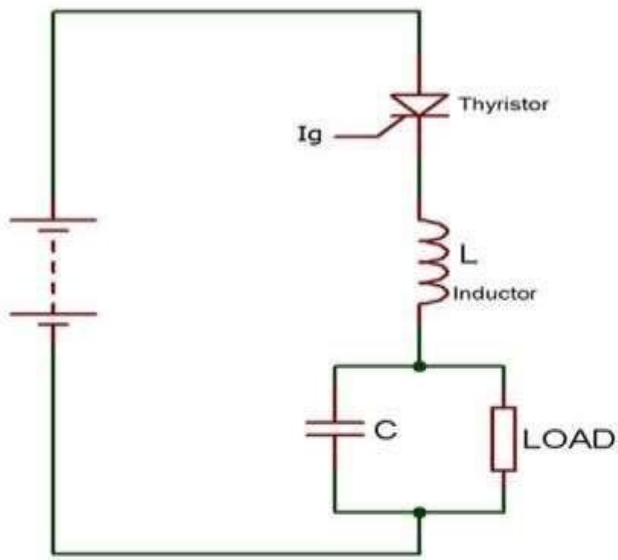


Figure 1.9.2 Class A: Self or Load Commutation

[Source: “Power Electronics” *by* P.S.Bimbra, Khanna Publishers *Page: 161]*

When we start supplying the input voltage to the circuit the Thyristor will not turn ON,as it requires a gate pulse to turn ON. Now when the Thyristor turns ON or forward biased, the current will flow through the inductor and chargesthecapacitor to its peakvalue orequal totheinput voltage. Now, as the capacitor gets fully charged, inductor polarity gets reversed and inductor starts opposing the flow of current. Due to this, the output current starts to decrease and reach to zero. At this moment the current is below the holding current of the Thyristor, so the Thyristor turns OFF.

Class B: Resonant-Pulse Commutation:

Class B commutation is also called as Resonant-Pulse Commutation. There is only a small change between Class B and Class A circuit. In class B LC resonant circuit is connected in parallel while in Class A it's in series.

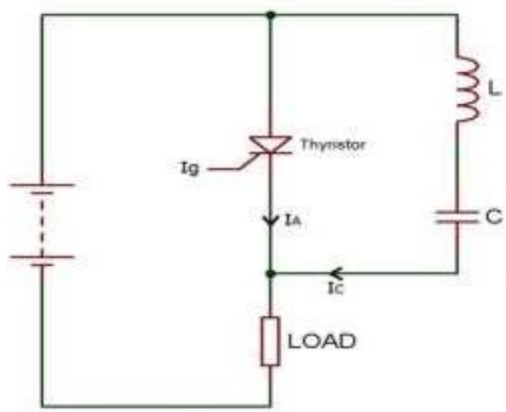


Figure 1.9.3 Class B: Resonant-Pulse Commutation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 162]*

Now, as we apply the input voltage, the capacitor starts charging up to the input voltage (Vs) and Thyristor remains reversed biased until the gate pulse is applied. When we apply the gate pulse, the Thyristor turns ON and now the current start flowing from both the ways. But, then the constant load current flows through the resistance and inductance connected in series, due to its large reactance.

Then a sinusoidal current flow through the LC resonant circuit to charge the capacitor with the reverse polarity. Hence, a reverse voltage appears across the Thyristor, which causes the current Ic (commutating current) to oppose the flow of the anode current IA. Therefore, due to this opposing commutating current, when the anode current is getting lesser than the holding current, Thyristor turns OFF.

1.10 Introduction to Snubber and Driver Circuits

A snubber circuit limits or stops (snubs) switching voltage amplitude anditsrateofrise, thereforereducingpowerdissipation. In itssimplestform, 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 as switching 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.

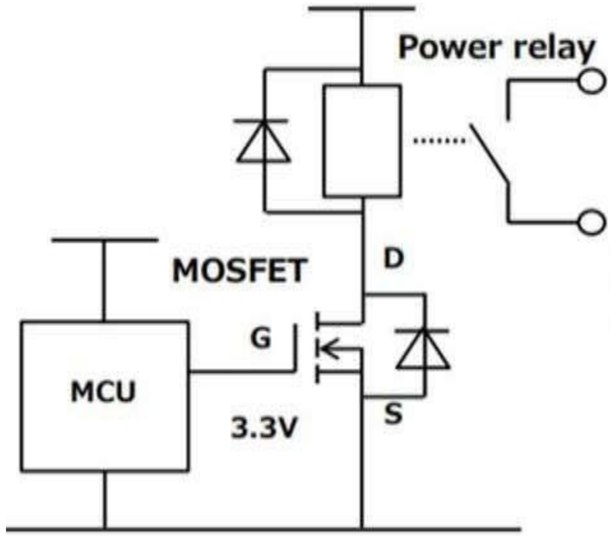


Figure 1.10.1 MOSFET drive circuit

[Source:"Power Electronics" byP.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.

1.5 BIPOLAR JUNCTION TRANSISTOR

BJT is a 3-layer, 2-junction, 3-terminal npn or pnp semiconductor device. Bipolar= 2 polarities of charge carriers constitute the current flow in the device. There are 2 types, NPN and PNP. NPN type is widely used as they are easy to manufacture and cheaper.

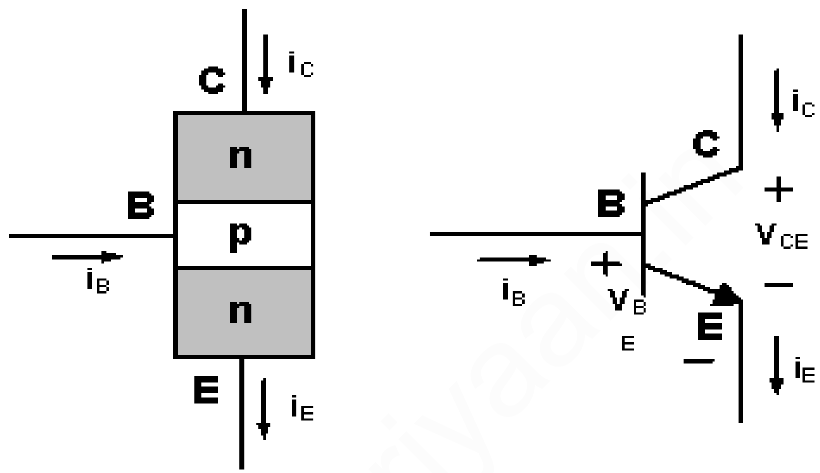


Figure 1.5.1 Symbol

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

CONSTRUCTION

A power transistor is a vertically oriented four-layer structure of alternating p-type and n-type. It helps in maximizing the cross-section area and results in higher current rating of BJT, minimize the on-state resistance, and thus reduce the power losses.

- It has an extra lightly doped (n-) region called as collector drift region in addition toNPN layers
- The n-layer increases the voltage blocking capacity of transistor which is needed isfast switching application in efficient power control
- The characteristics of the device is determined by the doping level in each of the layers and the thickness of the layers.

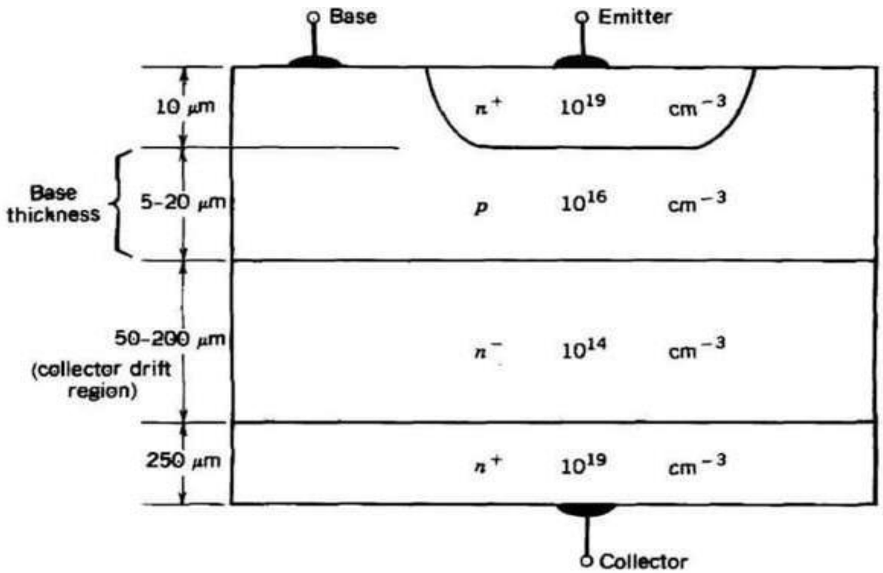


Figure 1.5.2 Structure of BJT

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

The thickness of the drift region determines the breakdown voltage of the Powertransistor. Thebasethickness ismadeas small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised.

POWER BJT – VI CHARACTERISTICS

The VI characteristics of the Power BJT is different from signal level transistor. The major differences are Quasi saturation region & secondary breakdown region. The Quasi saturation region is available only in Power transistor characteristic not in signal transistors. It is because of the lightly doped collector drift region present in Power BJT. The primary breakdown is similar to the signal transistor's avalanche breakdown. Operation of device at primary and secondary breakdown regions should be avoided as it will lead to the catastrophic failure of the device.

Input characteristics

A graph between base current IB and base emitter voltage VBE is called as input characteristics. The base emitter region is a diode and hence the input characteristics resembles the V-I characteristics of a PN junction diode. Base current decreases as collector emitter voltage increases for the same base emittervoltage.

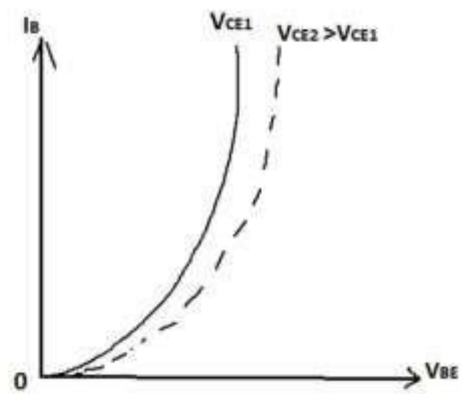


Figure 1.5.3 Input characteristics of BJT

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

Output characteristics

A graph between collector current IC and collector emitter voltage VCE is called as output characteristics, Power BJT operates in four regions

- *Cutoff region-Both BE and CE junction must be reversed biased.*
- Active region-BE junction must be forward biased and CB reverse biased
- *Quasi-saturation region-Both forwardbiased.*
- Hard-saturation region-Both forwardbiased.

Quasi-saturation region

- Quasi saturation region is a new region in Power BJT due to lightly doped (n-) drift region. If the BJT is to be operated in high switching frequency, they operate in this region. It provides low resistance to voltage in on state than active region. Since it does not get into deep saturation we can turn on and off power BJT very quickly.

- In power handling and control purposes power BJT are generally used in cutoff for off state and quasi-saturation for on state to act as a switch.

Cut-off Region

- When the base current (IB) is zero, the collector current (IC) is insignificant and the transistor is driven into the cutoff region. The transistor is now in the OFF state.

- The collector–base and base–emitter junctions are reverse biased in the cutoff regionor OFF state, the transistor behaves as an open switch.

- In this region:IC= 0 and the collector–emitter voltage VCE is equal to the supply voltage VCC

Saturation Region

When the base current is sufficient to drive the transistor into saturation.During saturation, both junctions are forward-biased and the transistor acts like a closed switch.In the quasi saturation and hard saturation, the base drive is applied and transistor issaid to be on.

In this region: I(C)=VCC/RC and VCE=0.

Active Region

In the active region, the collector–base junction is reversed-biased and the base–emitter junction is forward-biased.

The active region of the transistor is mainly used for amplifier applications and shouldbe avoidedforswitching operation.

The power BJT is neveroperatedintheactiveregion(i.e. asan amplifier) it is alwaysoperated between cut-off and saturation.

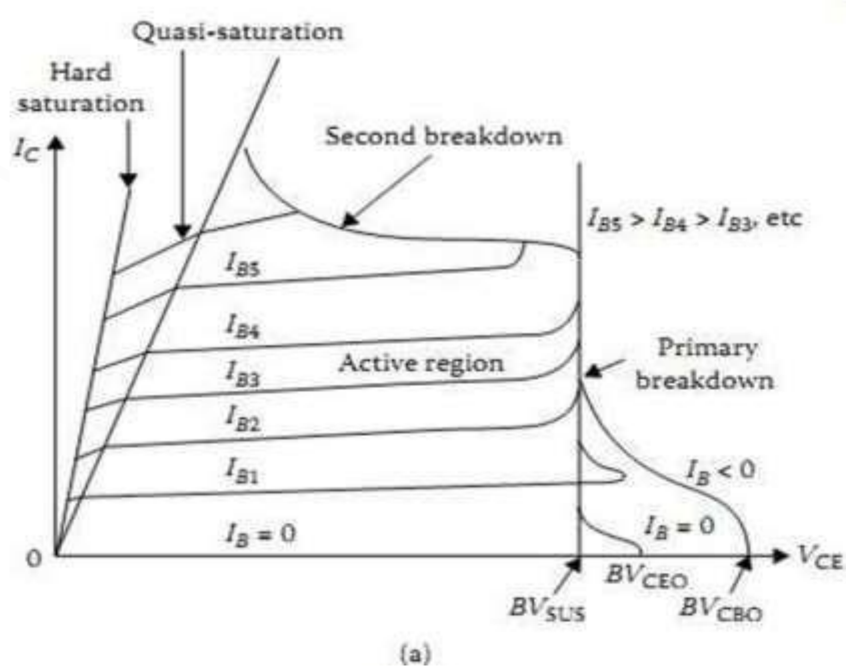


Fig 1.5.4 output characteristics of BJT

SWITCHING CHARACTERISTICS OF POWER BJT

Switching characteristics of power BJT is shown in Fig. As the positive base voltage is applied, base current starts to flow but there is no collector current for some time. This time is known as the delay time (td) required to charge the junction capacitance of the base to emitter to 0.7 V approx. (known as forward-bias voltage). For t > td, collector current starts rising and VCE starts to drop with the magnitude of 90% of its peak value. This time is called rise time, required to turn on the transistor. The transistor remains on so long as the collector current is at least of this value.

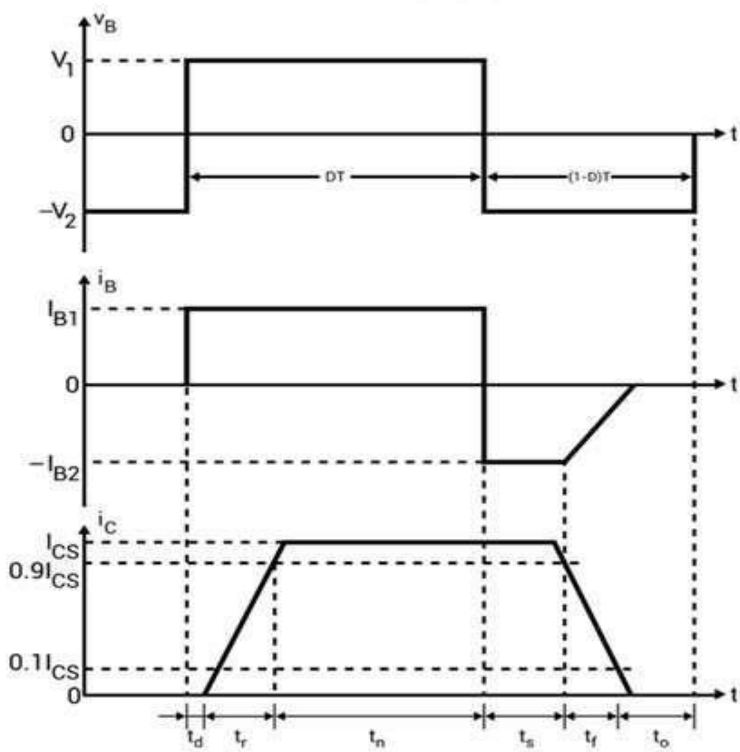


Fig 1.5.5 Switching characteristics of BJT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 15]*

For turning off the BJT, polarity of the base voltage is reversed and thus the base current polarity will also be changed as shown in Fig. The base current required during the steady-state operation is more than that required to saturate the transistor. Thus, excess minority carrier charges are stored in the base region which needs to be removed during the turn-off process. The time required to nullify this charge is the storage time ts. Collector current remains at thesame value for this time. After this, collector current starts decreasing and base-to-emitter junction charges to the negative polarity, base current also get reduced.

APPLICATIONS OF POWER BJT

- SMPS (Switch mode power supply) used in computers.
- Final audio amplifier in stereo systems.
- Power amplifiers.
- DC to ACinverters.
- Relay and display drivers.
- AC motor speedcontrollers.
- control circuits.

1.4 Study of GTO

The Gate turn off thyristor (GTO) is a four layer PNPN power semiconductor switching device that can be turned on by a short pulse of gate current and can be turned off by a reverse gate pulse.

- This reverse gate current amplitude is dependent on the anode current to be turned off.
- There is no need for an external commutation circuit to turn it off. So inverter circuitsbuilt by this device are compact and low-cost.
- The device is turned on by a positive gate current and it is turned off by a negativegate cathode voltage.

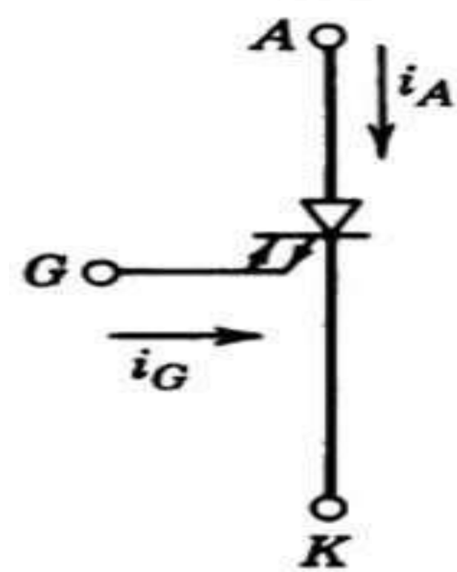


Fig 1.4.1 Symbol of GTO

[Source:“PowerElectronics”byP.S.Bimbra,KhannaPublishersPage:127]

The Symbol has three terminals namely Anode(A), Cathode(K) and Gate(G). The two-way arrow convention on the gate lead distinguishes the GTO from the conventional thyristor.

CONSTRUCTION

Consider the below structure of GTO, which is almost similar to the thyristor. It is alsoa four layer, three junction P-N-P-N device like a standard thyristor. In this, the n+ layer at the cathode end is highly doped to obtain high emitter efficiency. This result the breakdown voltage of the junction J3 is low which is typically in the range of 20 to40 volts.The doping level of the p type gate is highly graded because the doping level should be low to maintain high emitter efficiency, whereas for having a good turn OFF properties, doping of this region should be high. In addition, gate and cathodes should be highly interdigited with various geometric forms to optimize the currentturn off capability.

The junction between the P+ anode and N base is called anode junction. A heavily doped P+ anode region is required to obtain the higher efficiency anode junction so that a good turn ON properties is achieved. However, the turn OFF capabilities are affected with such GTOs. This problem can be solved by introducing heavily doped N+ layers at regular intervals in P+ anode layer as shown in figure. So this N+ layer makes a direct contact with N layer at junction J1. This cause the electrons to travel from base N region directly to anode metal contact without causing hole injection from P+ anode. This is called as a anode shorted GTO structure.Due to these anode shorts, the reverse blocking capacity of the GTO is reduced to thereverse breakdown voltage of junction j3 and hence speeds up the turn OFF mechanism.

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

PRINCIPLE OF OPERATION

The turn ON operation of GTO is similar to a conventional thyristor. When the anode terminal is made positive with respect to cathode by applying a positive gate current, the hole current injection from gate forward bias the cathode p-base junction. This results in the emission of electrons from the cathode towards the anode terminal. This induces the hole injection from the anode terminal into the base region. This injection of holes and electrons continuous till the GTO comes into the conduction state.

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

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

TWO TRANSISTOR MODEL OF GTO OPERATION

The aspects of the Gate turnoff thyristor, GTO are very similar to that of the ordinary thyristor. In GTO, one PNP and one NPN transistor being connected in a regenerative configuration whereby once turned on the system maintains itself in this state.

When a potential is applied across the gate turn-off thyristor between the anode and cathode, no current will flow because neither device is turned on. Current would only flow if the voltage exceeded the breakdown voltage and current would flow as a result of avalanche action, but this mode would not suggested for normal operation. In this non-conducting state the gate turn-off thyristor is said to be in its forward blocking mode.

To turn the device on it is necessary to inject current into gate circuit of the device. When this is done, it turns on TR2 in the Fig. This pulls the collector of this transistor down towards the emitter voltage and in turn this turns on the other transistor TR1.

The fact that TR1 is now switched on ensures current flows into the base of TR2, and thus this feedback process ensures that once the gate turn-off thyristor like any other thyristor is turned on it remains on.The key capability of the gate turn-off thyristor is its ability to be turned off by the use of the gate electrode on the device.

The device turn off is achieved by applying a negative bias to the gate with respect tothecathode. Thisextracts currentfromthebaseregionof TR2. Theresulting voltage drop in the base starts to reverse bias the junction and thereby stopping the current flow in this transistor TR2.Which stops the injection into the base region of TR1 and this prevents current flow in this transistor.

When the overall current flow stops and the depletion layers around the junctions grow- the gate turn-off thyristor enters its forward blocking state again.

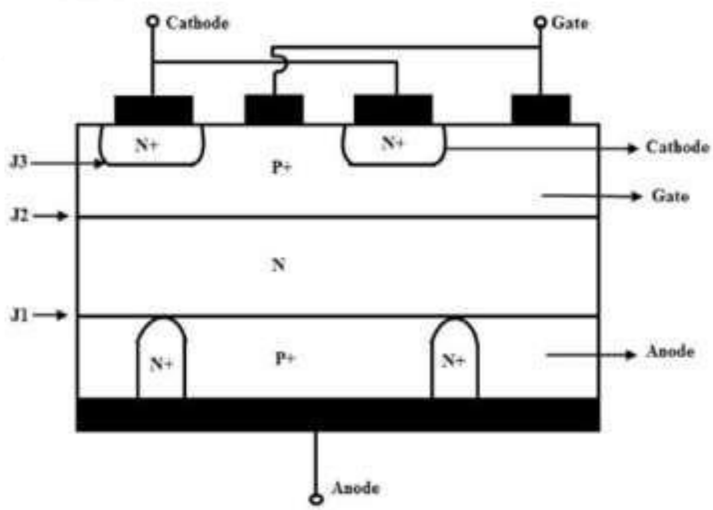


Fig. 1.4.2. Basic structure of GTO

[Source:"PowerElectronics"byP.S.Bimbra,KhannaPublishersPage:127]

Static VI characteristics of GTO

The static I-V characteristics of a GTO is identical with that of a conventional thyristor.If gate current is not able to turn on the GTO,it behaves like a high-voltage, low gain transistor with considerable anode current. This leads to a noticeable power loss under such conditions. In the reverse mode, reverse-voltage blocking capability of GTO is low, typically 20 to 30V, because of (i) anode shorts and (ii) large doping densities on both sides of reverse blocking junction J3

GATE TURN-ON:

The turn-on process in n GTO is similar to that of a conventional thyristor. Gate turn-on time for GTO is made up of delay time, rise time and spread time like a CT. Further, turn- ontimein a GTOcanbedecreased byincreasingits forward gatecurrent as in a thyristor. In Fig. 1.15 (b), a steep-fronted gate pulse is applied to tum-on GTO. Gate drive can be removed once anode current exceeds latching current. However, some manufacturers advise that even after GTO is on, a continuous gate current, called back porch current should be applied during the entire on-period of GTO. The aim of this recommendation is to avoid any possibility of unwanted turn-off of the GTO.

GATE TURN-OFF:

The turn-off characteristics of a GTO are different from those of an SCR. Before the initiation of turn-off process, a GTO carries a steady current Ia. Fig. 15(b). This figure shows a typical dynamic turn-off characteristic for a GTO. The total turn-off 'time tq is subdivided into three different periods; namely the storage period (ts), the fall period (tf) and the tail period (tt).

In other words,

Initiation of turn-off process starts as soon as negative gate current begins to flow after t= 0 at instant A. The rate of rise of this gate current depends upon the gate circuit inductance L and the gate voltage applied. During the storage period, anode current Ia and anode voltage (equal to on-state voltage drop) remain constant. Termination of the storage period is indicated by a fall in If and rise in Va . During ts excess charges, i.e. holes, in p base are removed by negative gate current and the centre junction comes out of saturation. In other words, during storage time the negative gate current rises to a particular value and prepares the GTO for turning-off (or commutation) by flushing outthe stored carriers. After ts anode current begins to fall rapidly and anode voltage starts rising The anode current falls to a certain value and then abruptly changes its rate of fall. This interval during which anode current falls rapidly is the fall time tf Fig. 1.15 (b) and is of the order of 1second. The fall period tf is measured from the instant gate current is maximum negative to the instant anode current falls to its tail current.

At the time t = ts + tf there is a spike in voltage due to abrupt change in anode current. After tf anode current ia and anode voltage Va keep moving towards their turn-off valuesfor a time called tail time tt . After tf anode current reaches zero value and Va undergoes a transient overshoot due to the presence of Rs, Cs and then stabilizes to its off-state value equal to the source voltage applied to the anode circuit. Here Rs and Cs are the snubber circuit parameters. The turn-off process is complete when tail current reaches zero. The over shoot voltage and tail current can be decreased by increasing the size of Cs, but a compromise with snubber loss must be made. The duration off, depends upon the device characteristics.

APPLICATION OF GTO:

- GTOs are used in motor drives, static VAR compensators (SVCs) and AC/DC power supplies with high power ratings.

DISADVANTAGES OF GTO

Compared to a conventional SCR, the GTO has the following disadvantages:

1. Magnitude of latching, holding currents is more. The latching current of the GTO is

   several times more as compared to conventional thyristors of the same rating.
2. On state voltage drop and the associated loss is more.
3. Due to multi cathode structure of GTO, triggering gate current is higher than thatrequired for normal SCR.
4. Gate drive circuit losses are more. Its reverse voltage blocking capability is less thanthe forward voltage blocking capability.

ADVANTAGES OF GTO OVER BJT

Compared to BJT the GTO has the following advantages:

1. High blocking voltage capabilities
2. High over current capabilities
3. exhibits low gatecurrents
4. fast and efficient turn off
5. Better static and dynamic dv/dt capabilities

1.8 Study of IGCT

The Integrated Gate-Commutated Thyristor (IGCT) operates on the principle thatthyristors are ideal conduction devices whereas transistors are ideal turn-off devices. The IGCT therefore converts a thyristor structure to a transistor structure prior to turn- off by fast commutation of the cathode current and keeps it biased off with a 20 V source. This results in a device which dynamically and statically blocks like an IGBT (open-base pnp transistor producing the same turn-off losses) but conducts like a thyristor i.e. with about half the on-state voltage due to the greater plasma density produced by the two emitters. (pnp & npn transistors)

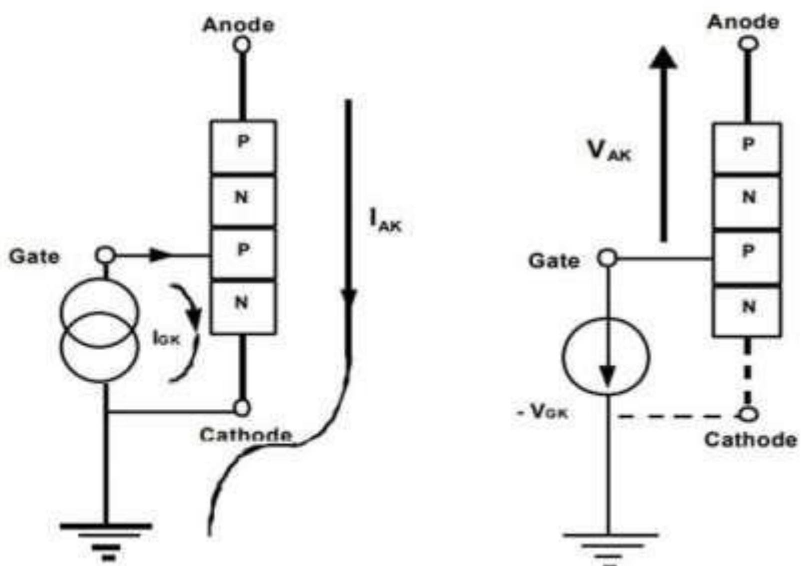


Fig 1.8.1 Symbol of IGCT

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 27]

IGCT is the new member in the power semiconductor family (1997). It was introduced by ABB. It is a special type of GTO thyristor. Similar to GTO, it is a fully controllable power switch. ie, It can be turned-On and turned-Off by applying a gate signal. It has lower conduction losses as compared to GTO thyristors. It withstands higher rates of voltage rise(dv/dt). So snubber circuits are not required for most of the applications.

STATIC AND SWITCHING CHARACTERISTICS OF IGCT

The structure of IGCT is very similar to a GTO thyristor.

In an IGCT, the gate turn-off current is greater than the anode current. This results in shorterturn-off times.The main difference compared with a GTO and thyristor is a reduction in cell size, combined with a much more substantial gate connection, resulting in a much lower inductance in the gate drive circuit and drive circuit connection.The very high gate currents and the fast di/dt rise of the gate current means that regular wires cannot be used to connect the gate drive to the IGCT.

TURN-ON

In the turn-on mode, GCT behaves exactly like a thyristor (or a GTO). This operation principle can be understood by considering the equivalent two-transistor model. The p+n− p and n+ p n− regions represent PNP and NPN transistors respectively. The anode of the GCT is connected to p+ region, which is the emitter of the PNP transistor. The collector of the PNP is connected to the gate of the NPN transistor and vice-versa, because of n− region neighboring the p region. The cathode of the GCT is connected to the n+ region, which is the emitter of the NPN transistor. This two-transistor model has two stable states, ON and OFF, which are determined by the gate control. When a current is supplied to the gate to turn on the GCT, the gate current flows to the cathode.

This turns on the NPN transistor and its collector current will now flow from the anode through the J1junction. The J1junction is the emitter of the PNP transistor; therefore,the collector current of the PNP is then the base current of the NPN.

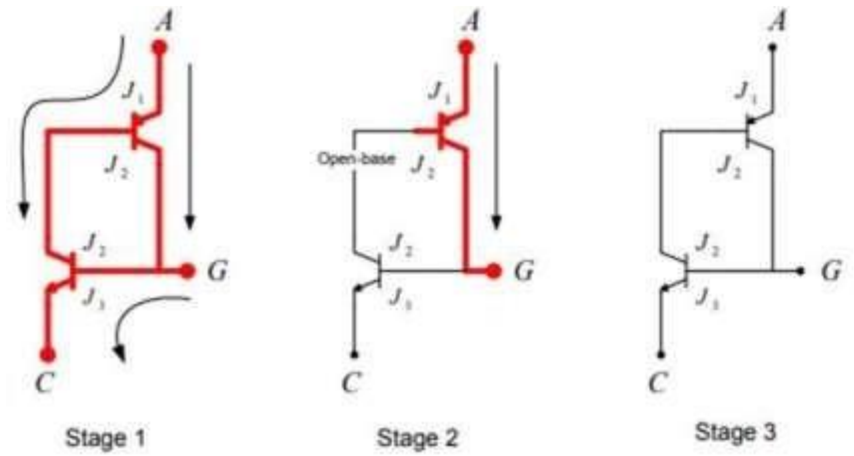


Fig 1.8.2 Turn on stages of IGCT

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 28]

The two transistorsare connected in positive feedback allowing for a self-sustaining state called latch-up. This state is reached because the large current flowing between the anode and cathode is able to inject enough carriers into the base regions to keep the transistors saturated without the need of continuous gate current flow. Typical turn-on time for a GCT is about ≈ 10µs.

TYPES OF IGCT

These devices are available either with or without reverse blocking capability.IGCTs capable of blocking reverse voltage are known as symmetrical IGCTs. The typical application of symmetrical IGCTs is in Current Source Inverters (CSI).IGCTs incapable of blocking reverse voltage are known as asymmetrical IGCTs. They typically have a reverse breakdown rating in tens of volts or less. Such IGCTs are used where either a reverse conducting diode is applied in parallel or where reverse voltage would never occur. Asymmetrical IGCT can be fabricated with a reverse-conducting diode in the same package. These are known as reverse conducting (RC) IGCTs.

APPLICATIONS

The main applications of IGCT are in variable frequency inverters, drivers and traction. Multiple IGCTs can be connected in series or in parallel for higher power applications. The device has been applied in power system inter-tie installations (100MVA) and medium-power (up to 5MW) industrial drives.

1.7 INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

- IGBT is a voltage controlled device.
- It has high input impedance like a MOSFET and low on-state conduction losses like aBJT.
- IGBT has three terminals gate (G), collector (C) and emitter (E).
- Withcollector andgatevoltagepositivewith respectto emitter the device is in forwardblocking mode.
- When gate to emitter voltage becomes greater than the threshold voltage of IGBT, an- channel is formed in the P-region.

Now device is in forward conducting state.

CONSTRUCTION OF IGBT

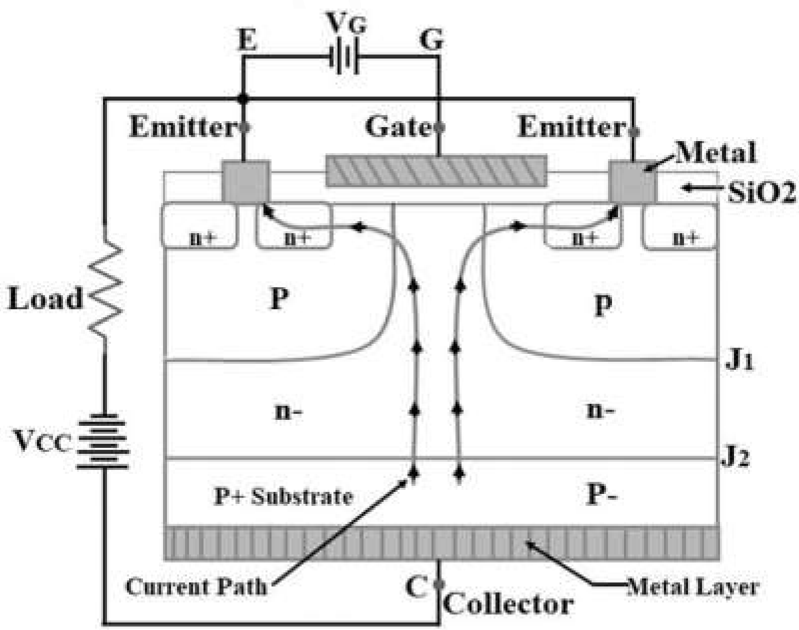


Figure 1.7.1 Structure of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 24]*

The structure of IGBT is very much similar to that of Power MOSFET, except one layer known as injection layer which is p+ unlike n+ substrate in PMOSFET. This p+ injectionlayer is the key to the superior characteristics of IGBT.It injects holes into n- layer. Thickness of n- layer decides the voltage blocking capability. Other layers are called the drift and the body region. The two junctions are labelled J1 and J2.

OPERATION OF IGBT

N-channel IGBT turns ON when the collector is at a positive potential with respect to emitter and gate also at sufficient positive potential (>VGET) with respect to emitter. This condition leads to the formation of an inversion layer just below the gate, leading to a channel formation and a current begins to flow from collector to emitter. This n- channel short circuits the n+ with n- emitter regions. Electrons from emitter n+ region flows to n- drift region throughn-channel.

The collector current Ic in IGBT constitutes of two components- Ie and Ih. Ie is the current due to injected electrons flowing from collector to emitter through injection layer, drift layer and finally the channel formed. Ih is the hole current flowing from collector to emitter through Q1 and body resistance Rb.

Characteristics of IGBT

There are two characteristics

1. An output characteristic is a plot of collector current Ic versus collector to emitter voltage VCE for given values of gate to emitter voltage VGE

2. A plot of collector current Ic versus gate-emitter voltage VGE for a given value of VCE gives the transfer characteristic.

Controlling parameter is the gate-emitter voltage VGE in IGBT. If VGE is less than the threshold voltage VT then IGBT is in OFF state. If VGE is greater than the threshold voltage VT then the IGBT is in ON state.

The graph is similar to that of a BJT except that the parameter which is kept constant for a plot is VGE because IGBT is a voltage controlled device unlike BJT which is a current controlled device. When the device is in OFF mode (VCE is positiveand VGE < VGET) the reverse voltage is blocked by J2 and when it is reverse biased,i.e. VCE is negative, J1 blocks the voltage.

Transfer Characteristics of IGBT

Figure below shows the transfer characteristic of IGBT, which is exactly same as PMOSFET. The IGBT is in ON-state only after VGE is greater than threshold value VGET.

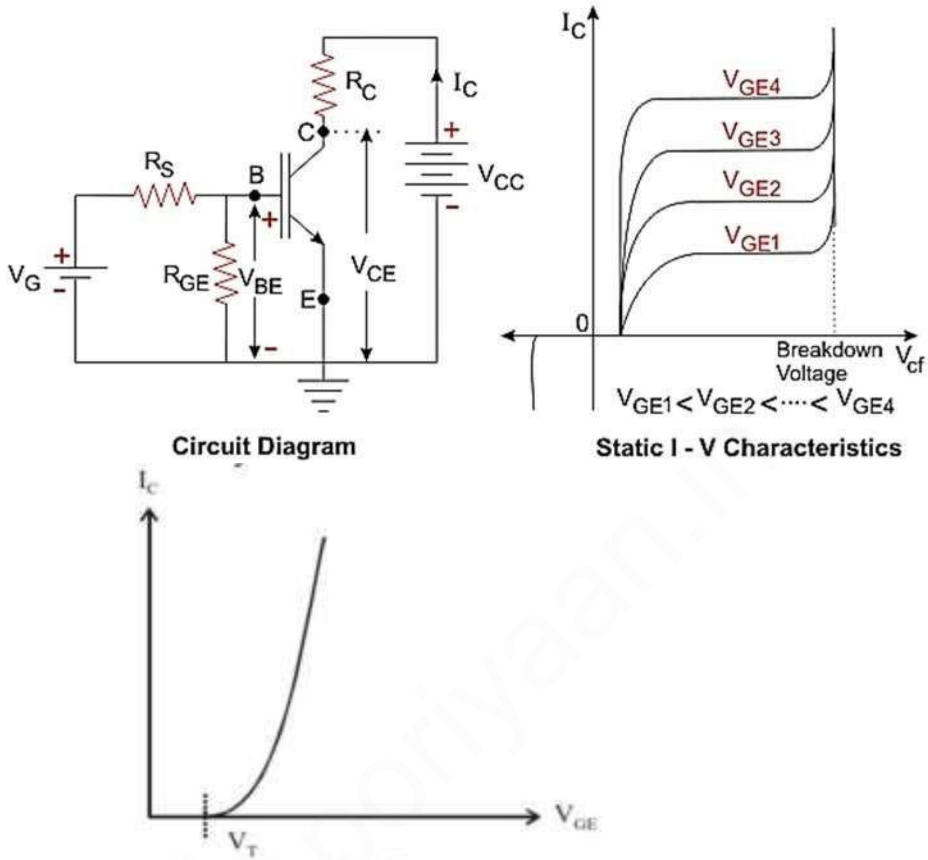


Figure 1.7.2 Characteristics of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 25]*

SWITCHING CHARACTERISTICS OF IGBT

After turn-on collector-emitter voltage VCE will be very small during the steady state conduction of the device.

- The turn off time toff consists of three components, delay time (tdf), initial fall time (tf1) and final fall time (tf2). Delay time is defined as time when collector current falls from IC to 0.9 IC and VGE falls to threshold voltage VGET and VCE begins to rise. Initialfall time is the time during which collector currentfalls from 0.9 IC to 0.2 IC and collector emitter voltagerises

0.1 VCE. The final fall time is defined as time during which collector current falls from 0.2 IC to 0.1 IC. During the turn-off time interval collector-emitter voltage rises to its final value VCE.

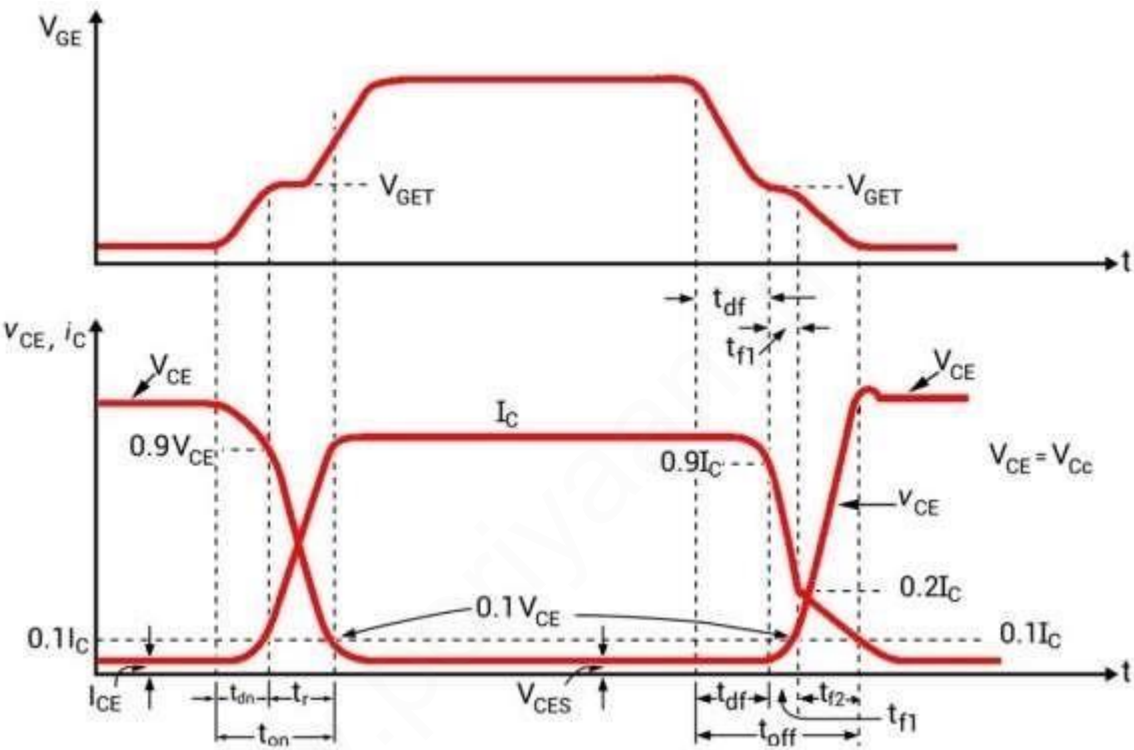


Figure 1.7.3 Switching Characteristics of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 26]*

The gate drive circuit of an IGBT should ensure fast and reliable switching of the device. In particular, it should.

- Apply maximum permissible VgE during ON period.
- Apply a negative voltage during off period.
- Control dic/dt during turn ON and turn off to avoid excessive Electro magneticinterference (EMI).
- Control dvce dt during switching to avoid IGBT latch up.
- Minimize switching loss.
- Provide protection against short circuit fault.

IGBT APPLICATIONS

IGBT finds its use in Medium power applications like

1. DC and AC motor drives,
2. medium power supplies,

3. solid state relays and contractors,
4. general purpose inverters,
5. UPS,
6. welder equipments,
7. servo controls,
8. robotics,
9. cutting tools

1.6 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.

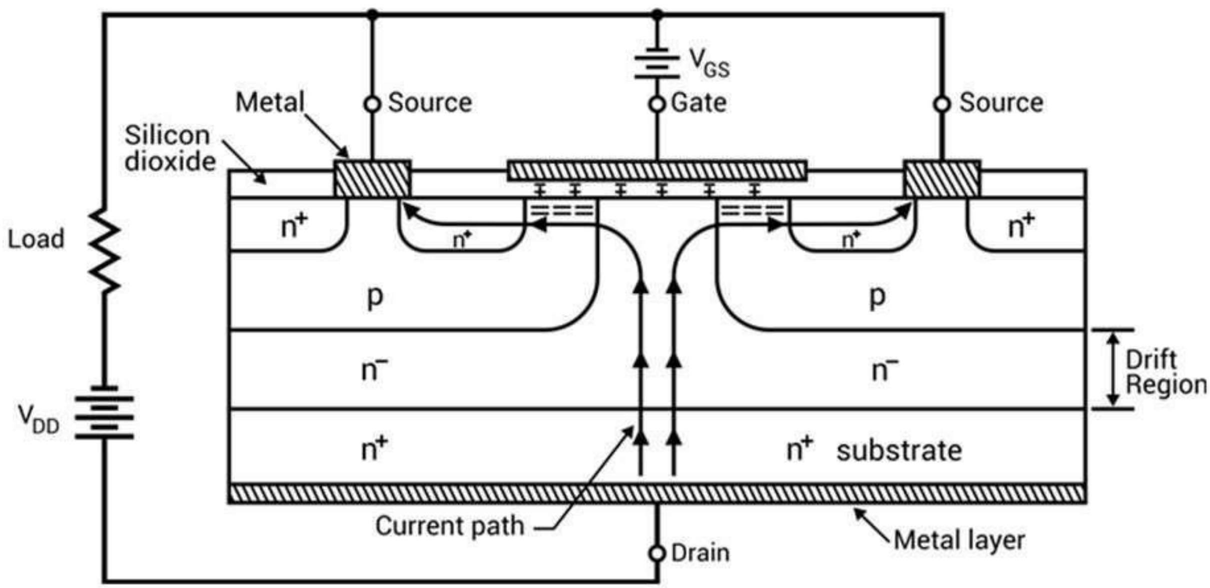


Fig 1.6.1 Structure of MOSFET

[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 silicondioxide(SiO2) on thetopofthesubstrate whichbehavesas adielectric. Thereis an aluminum plate fitted on the top of this SiO2 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 OFMOSFET

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

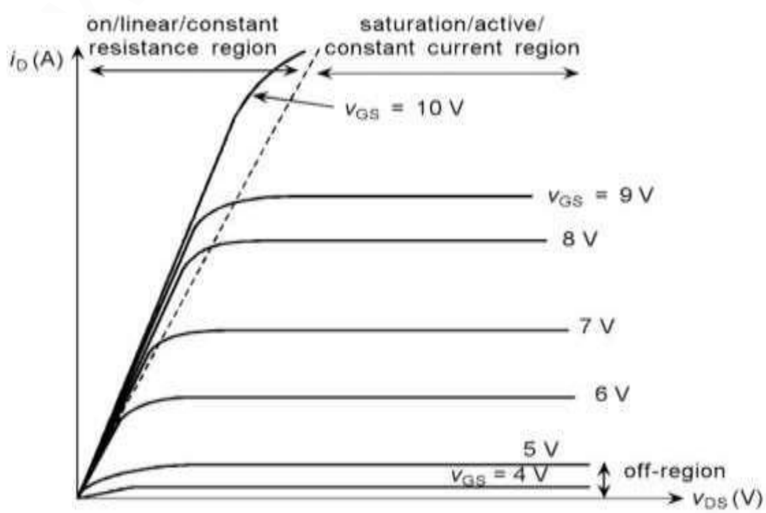


Fig 1.6.2 Characteristics of MOSFET

[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 beno 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 increasein 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, thedraincurrent 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 $T_{OFF} = t_{(d(off))} + t_f$

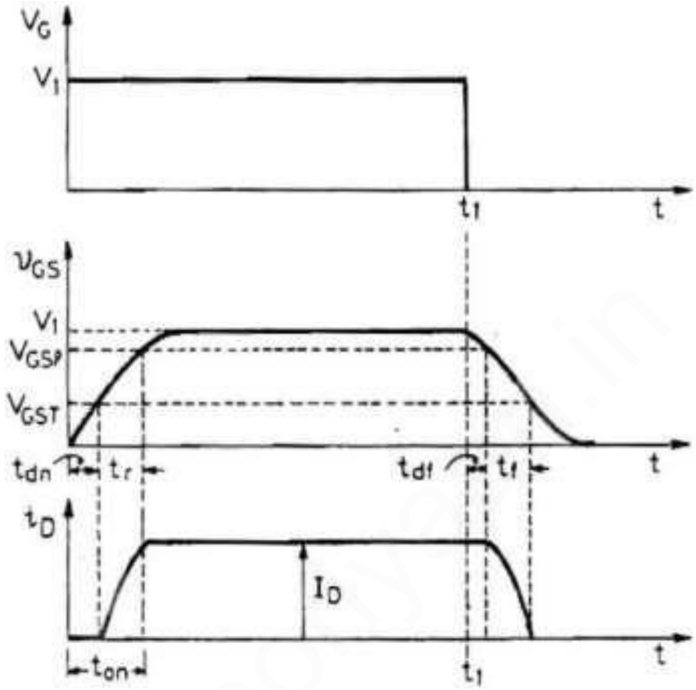


Fig.1.6.3 turn on and off characteristics of MOSFET

[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 Study of SCR (Thyristor)

The name 'thyristor ', is derived by a combination of the capital letters from **THYRatr on** and **transistor.** SCRs are solid state devices, they are compact, possess high reliability and have low loss. Because of these useful features, SCR is almost universally employed these days for all high power-controlled devices. Thyristor is a four layer, three-junction, p -n-p –n semiconductor switching device. It has three terminals; anode, cathode and

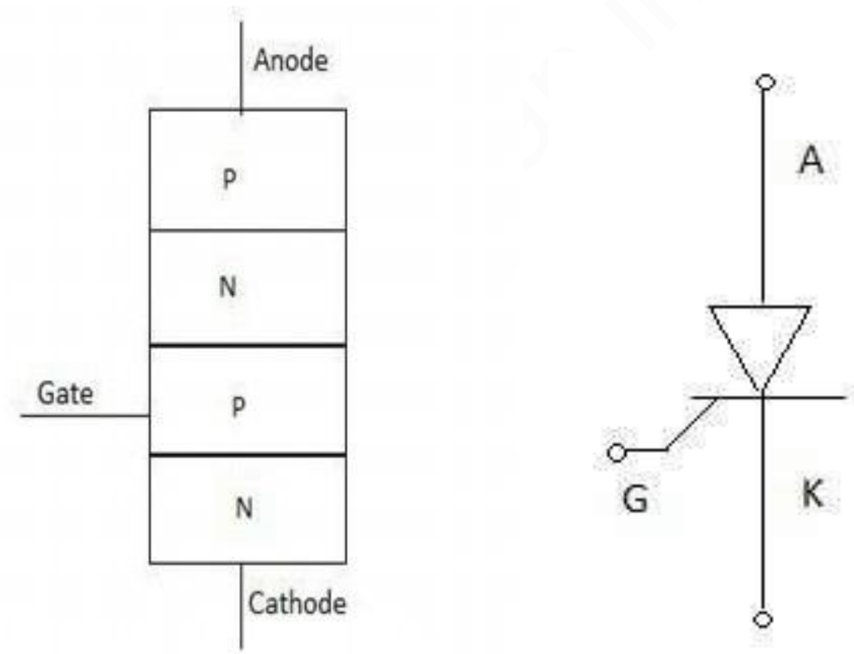


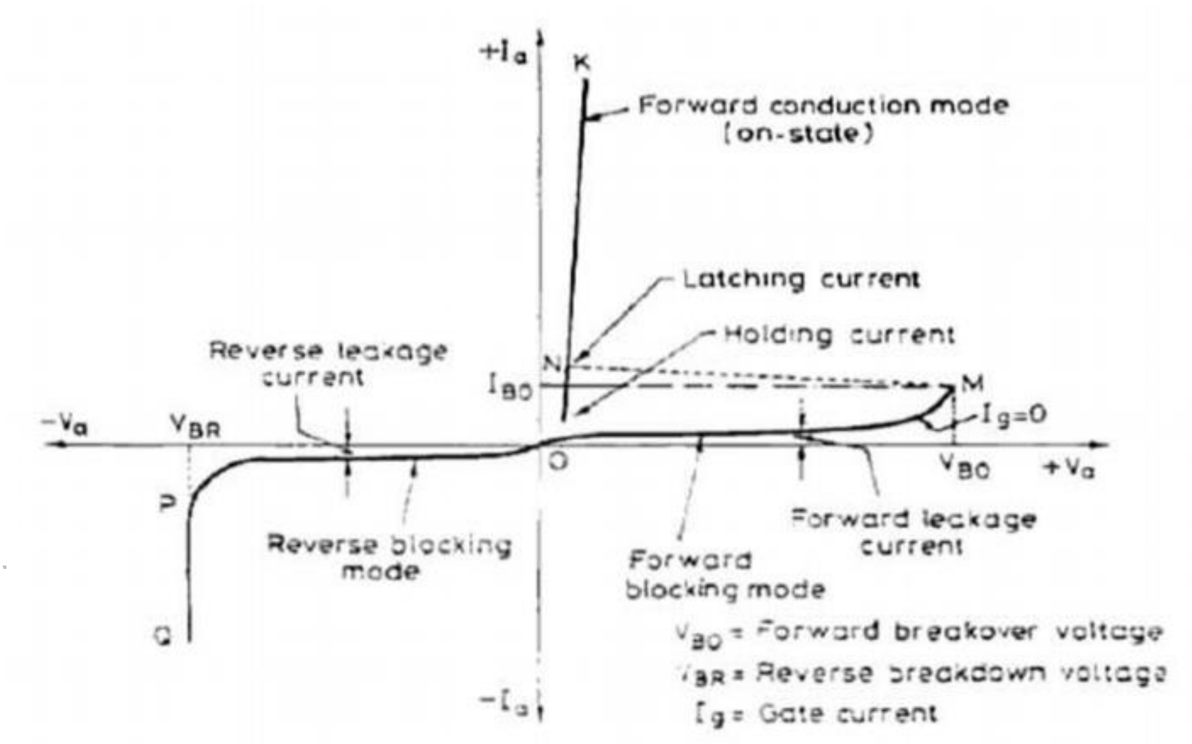
Fig 1.2.1 (a) Layer Structure (b) Symbol

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 63]

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

Static V-I characteristics of a Thyristor:

The circuit diagram for obtaining static V-I characteristics is as shown. Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source E_S.A typical SCR V-I characteristic is as shown below:



V_{BO}=Anode voltage across the thyristor terminal A,K.

Ig =Gate current

Va =Anode voltage across the thyristor terminal A,K.

Ia =Anode current

SCR have 3 modes of operation:

1. Reverse blocking mode
2. Forward blocking mode (offstate)
3. Forward conduction mode (on state)

Reverse Blocking Mode

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased.junctions J1 and J2 are reverse biased where junction j2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.Small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.

Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage V_{BR} ,an avalanche occurs at J1 and J3.and the reverse current increases rapidly. As a large current associated with V_{BR} and hence more losses to the SCR.This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

2. Forward Blocking Mode

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

3. Forward Conduction Mode

Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:

1. By exceeding the forward breakover voltage.
2. By applying a gate pulse between gate and cathode.

During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

Different turn ON methods for SCR

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

1. Forward voltage triggering

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

- Junction J1 and J3 is forward biased.
- Juntion J2 is reverse biased.
- As the anode to cathode voltage is increased breakdown of the reverse biased junction J2 occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward breakover voltage.

- The conduction of current continues even if the anode cathode voltage reduces below V_{BO} till Ia will not go below I_h. Where I_h is the holding current for the thyristor.

2. Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding V_{BO} is never employed as it may destroy the device. The magnitude of V_{BO} , so forward breakovervoltage is takenasfinal voltagerating of thedevice during the design of SCR application. First step is to choose a thyristor with forward breakover voltage (say 800V) higher than the normal working voltage.

The benefit is that the thyristor will be in blocking state with normal workingvoltage applied across the anode and cathode with gate open. When we require the

turning ON of a SCR a positive gate voltage between gate and cathode is applied. The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n- layer. Now the thyristor is forward biased, so some of these electron reach junction J2.

As a result width of J2 breaks down or conduction at J2 occur at a voltage less than V_{BO} .As Ig increases V_{BO} reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can't turn ON. In this process power loss is less and also low applied voltage is required for triggering.

3. dv/dt triggering

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided. When SCR is forward biased, junction J1 and J3 are forward biased and junction J2 is reversed biased so it behaves as if an insulator is place between two conducting plate. Here J1 and J3 acts as a conducting plate and J2 acts as an insulator. J2 is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction J2 breaks and starts conducting. Ahigh value of changing current may damage the SCR. So SCR may be protected from high dv/dt.

$$q = cv$$

$$I_a = c\frac{dv}{dt}$$

$$I_a \; \alpha \; \frac{dv}{dt}$$

4. Temperature triggering

During forward biased, J2 is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat decipitation of junction J2 occurs. When this heat reaches a sufficient value J2 will break and conduction starts. Disadvantages This type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily. It is very costly as protection is costly.

5. Light triggering

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn ON of SCR. Such SCR are known

as Light activated SCR (LASCR).

1.1 Study of Switching Device

It is one of the contemporary subjects of electrical engineering which has seen a lot of advancements in recent times and has impacted human life in almost every sphere. We use many power electronic applications in our daily life, without even realizing it. Now the question in front of us is, "what is power electronics?"

Introduction about Powerelectronics

Power electronics can be defined as the hybrid of power engineering, analogue electronics. We derive the fundamentals of each subject and apply it in an amalgamated way so as toget a regulated form of electrical energy. Electrical energy in itself is not usable until it is converted into a tangible form of energy such as motion, light, sound, heat etc. In order to regulate these forms of energy, an effective way is to regulate the electrical energy itselfand this forms the content of the subject power electronics. We can trace the overwhelming advancement in the subject back to the development of commercial thyristors or silicon controlled rectifiers (SCR) by General Electric Co. in 1958. Before this the control of electrical energy was mainly done using thyratrons and mercury arc rectifiers which works on the principle of physical phenomena in gases and vapors.

After SCR, many power electronic devices have emerged like GTO, IGBT, SIT, MCT, TRIAC, DIAC, IEGT, IGCT and so on. These devices are rated for several hundreds of volt and ampere unlike the signal level devices which work at few volts and mill amperes.

In order to achieve the purpose of power electronics, the devices are made to work as nothing more than a switch. All the power electronic devices act as a switch and have two modes, i.e. ON and OFF.

For example, a BJT (Bipolar Junction Transistor) has three regions of operation in its output characteristics cut-off, active and saturation. Inanalogue electronics where the BJT is supposed to work as an amplifier, the circuit is so designed to bias it in active region of operation. However in power electronics BJT will work in cutoff region when it is OFF and in saturation region when it is ON.

Now that the devices are required to work as a switch, they must follow the basic characteristic of a switch, i.e. when the switch is ON, it has zero voltage drop

Figure 1.1.1 Idealswitch

[Source:"PowerElectronicsCircuits,DevicesandApplications"byM.H.Rashid,Page:4]

across it and carries full current through it, and when it is in OFF condition, it has full voltage drop across it and zero current flowing through it. The figure below depicts the above statement.

Now since in both the mode either of the quantity V or I is zero, the switch power also turns out to be zero always. This characteristic is easy to visualize in a mechanical switch and the same has to be followed in power electronic switch also.

However practically there always exists a leakage current through the devices when in OFF condition, i.e I leakage ≠ 0 and there is always a forward voltage drop in ON condition, i.e Von ≠ 0. However the magnitude of Von or I leakage is very less and hence the power across the device is also very less, in order of few mill watts. This power is dissipated in the device and hence proper heat evacuation from the device is an important aspect. Apart from this ON state and OFF state losses, there are switching losses also in power electronic devices. This is mainly while the switch toggles from one mode to another and V and I across the device changes.

In power electronics both the losses are important parametersof any device and essential in determining its voltage and current ratings. The power electronic devices alone are not that useful in practical applications and hence require to be designed with a circuit along with other supporting components. These supporting components are like the decision making part which controls the power electronic switches in order to achieve the desired output. This includes the firing circuit and the feedback circuit. The block diagram below depicts a simple power electronic system.

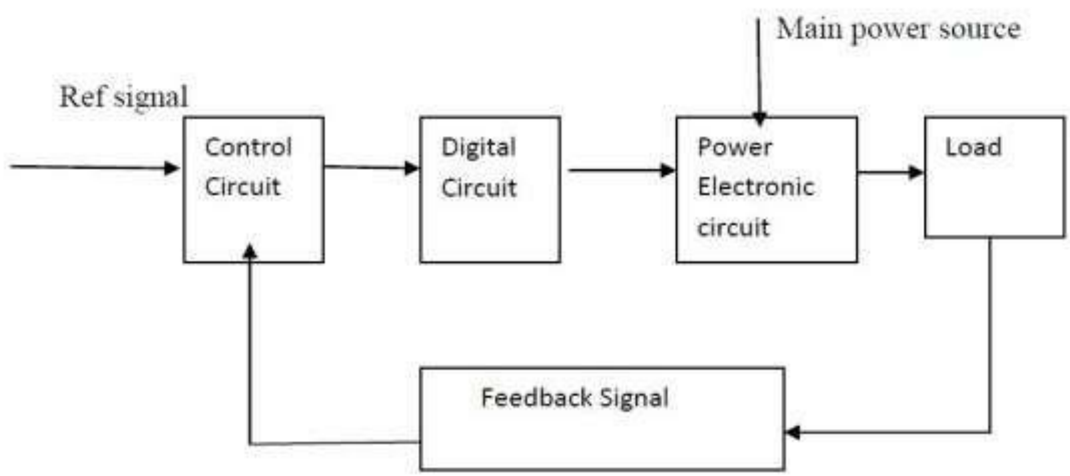


Figure 1.1.2 Power Electronic system

[Source:“Power Electronics” byP.S.Bimbra,Khanna Publishers Page:3]

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

The Control Unit takes the output feedback from sensors and compares it with references and accordingly gives input to the firing circuit. Firing circuit is basically a pulse generating circuit which gives pulse output in a fashion so as to control the power electronic switchesin the main circuit block.

The net result is that the load receives the desired electrical power and hence delivers the desired result. A typical example of the above system would be speed control of motors.You can learn more about power electronics by studying our basic electronics questions. Majorly there are five types of power electronic circuits, each having different purposes-

1. Rectifiers – converts fixed AC to variable DC (such as half wave rectifiers or fullwave rectifiers)
2. Choppers – converts fixed DC to variable DC
3. Inverters – converts DC to AC having variable amplitude and variable frequency
4. Voltage Regulators – converts fixed AC to variable AC at same input frequency
5. Cyclo converters – converts fixed AC to AC with variable frequency

Power Semiconductor Devices

The first SCR was developed in late 1957. Power semiconductor devices are broadly categorized into 3 types:

1. Power diodes

2.Transistors

3.Thyristors

1.3 Study of TRIAC

Triacs are electronic components that are widely used in AC power control applications. They are able to switch high voltages and high levels of current, and over both parts of an AC waveform. This makes triac circuits ideal for use in a variety of applications wherepower switching is needed.

An SCR is a unidirectional device as it can conduct from anode to cathode only and not from cathode to anode. A triac can, however, conduct in both the directions. A triac is thus a bidirectional thyristor with three terminals. It is used extensively for the controlof power in ac circuits . Triac is the word derived by combining the capital letters from the words TRIode and AC. When in operation, a triac is equivalent to two SCRs connected in anti parallel.

The triac is a development of the thyristor. While the thyristor can only control current over one half of the cycle, the triac controls it over two halves of an AC waveform.

The triac can be considered as a pair of parallel but opposite thyristors with the two gates connected together and the anode of one device connected to the cathode of the other.

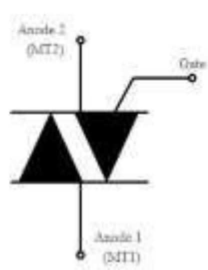


Fig 1.3.1 Symbol of TRIAC

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 123]

As the triac can conduct in both the directions, the terms anode and cathode are not applicable to triac. Its three terminals are usually designated as MTl (main terminal 1), MT2 and the gate by G. The gate G is near terminal MTl. The cross-hatched strip shows that G is connected to N3 as well as P2.Similarly terminal MTI is connected to P2 and N2, terminal MT2 to P1 and N4 . With no signal to gate, the triac will block both half cycles of the applied voltage in case peak value of this voltage is less than the breakover voltage vBDl or VBD2 of the triac, Fig.

The triac can, be turned on in each half cycle of the applied voltage by applying a positive or negative voltage to the gate with respect to terminal MTl. For convenience, terminal MTI is taken as the point for measuring the voltage and current at the gate and MT2 terminals.

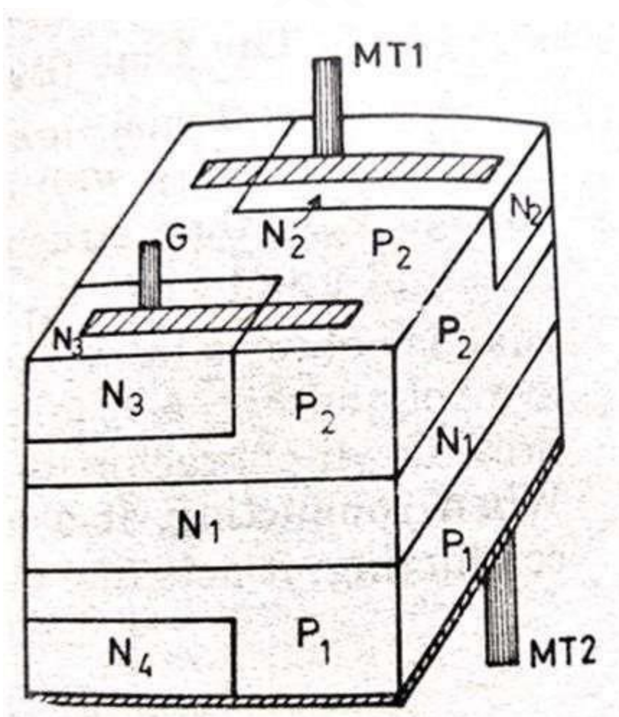


Fig.1.3.2 cross sectional view of TRIAC

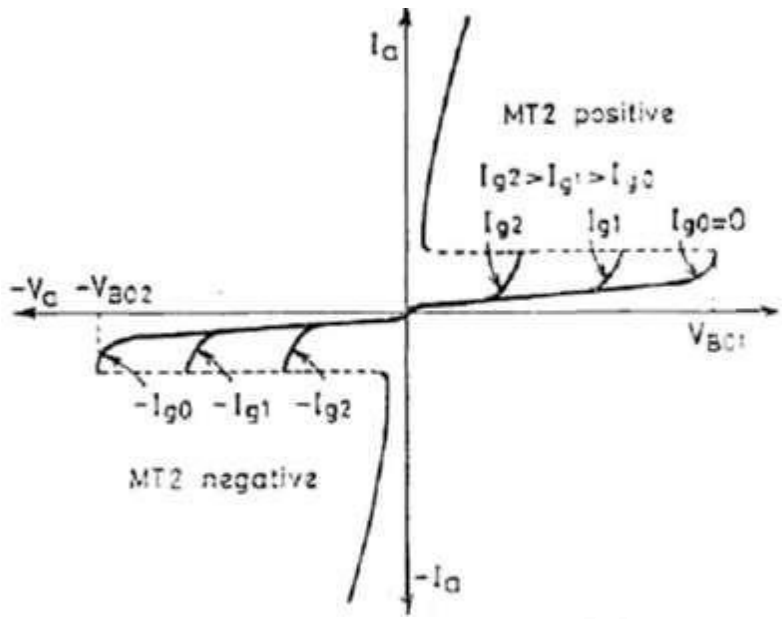


Fig.1.3.3 Static VI characteristics of TRIAC

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 124]

TRIGERRING MODES OF OPERATION OF TRIAC

1. Terminal MT2 and gate are positive with respect to terminal MT1
2. Terminal MT2 is positive but gate is negative with respect to terminal MT1
3. Terminal MT2 and gate are negative with respect to terminal MT1
4. Terminal MT2 is negative but gate is positive with respect to terminal MT1

MT2 is positive and gate current is also positive.

- When MT2 is positive with respect to MTI, junction PI NI, P2 N2 are forward biased but junction NI P2 is reverse biased.
- When gate terminal is positive with respect to MTI, gate current flows mainly through P2 N2 junction like an ordinary SCR.

- When gate current has injected sufficient charge into P2 layer, reverse biased junction NI P2 breaks down just as in a normal SCR.
- Triac starts conducting through PI N I P2 N2 layers.
- Thus when MT2 and gate terminals are positive with respect to MTl, triac turns on like a conventional thyristor. Under this condition, triac operates in the first quadrant of Fig.
- The device is more sensitive in this mode. It is recommended method of triggering if the conduction is desired in the first quadrant.

MT2 is positive but gate current is negative.

- When gate terminal is negative with respect to MTl, gate current flows through P2 N3 junction, Fig, 1.11 (b) and reverse biased junction N1 P2 is forward biased as in a normal thyristor.
- Triac starts conducting through P1 NI P2 N3 layers initially.
- With the conduction of PI N1P2 N 3, the voltage drop across this path falls but potential of layer between P2 N2 rises towards the anode potential of MT2.
- The right hand portion of P2 is clamped at the cathode potential of MTl, a potential gradient exists across layer P2, its left hand region being at higher potential than itsright hand region.
- A current shown dotted is thus established in layer P2 from left to right. This current is similar to conventional gate current of an SCR. As a consequence, right-hand part of triac consisting of main structure PI NI P2 N2 begins toconduct.
- The device structure PI N1 P2 N3 is pilot SCR and the structure PINI P2N2 as the main SCR.

- The anode current of pilot SCR serves as the gate current for the main SCR.
- With the device MT2 positive but gate current negative is less sensitive and therefore, more gate current is required.

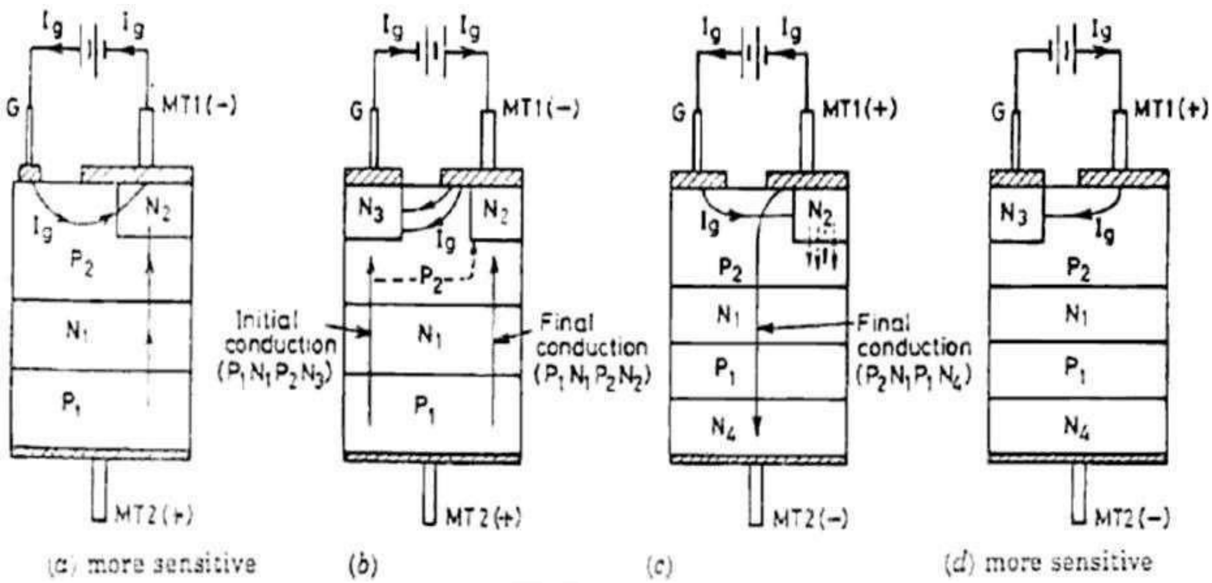


Fig 1.11. Modes of operation of TRIAC

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 124]

MT2 is negative but gate current is positive.

- The gate current Ig forward biases P2 N2 junction
- Layer N2 injects electrons into P2 1ayer as shown by dotted arrows.
- The reverse biased junction N1P 1 breaks down as in a conventional thyristor.
- The structure P2 N1 PI N4 is completely turned on.
- As the triac is' turned on by remote gate N2, the device is less sensitive in the thirdquadrant with positive gate current.

Both MT2 and gate current are negative.

- In this mode, N3 acts as a remote gate,
- The gate current 1g flows from P2 to N3 as in a normal thyristor.
- Reverse-biased junction N1 P1 is broken and finally, the structure P2 N1 Pl N4 is turned oncompletely.
- The triac is turned on by remote gate N3 in third quadrant, yet the device is moresensitive.

ADVANTAGES OF TRIAC

1. It can be triggered with positive or negative polarity gate pulses.
2. It requires only a single heat sink of slightly larger size, whereas for SCR, two heat sinksshould be required of smaller size.
3. It requires single fuse for protection.
4. A safe breakdown in either direction is possible but for SCR protection should be givenwith parallel diode.

APPLICATION OF TRIAC

- They are used in control circuits.
- It is used in AC power control

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- Probability and Complex Functions
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- Open Elective – IV
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2.1 Introduction about Rectifier

- Rectifiers are ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage.
- Type of input: Fixed voltage, fixed frequency ac power
- supply.Type of output: Variable dc outpaut voltage

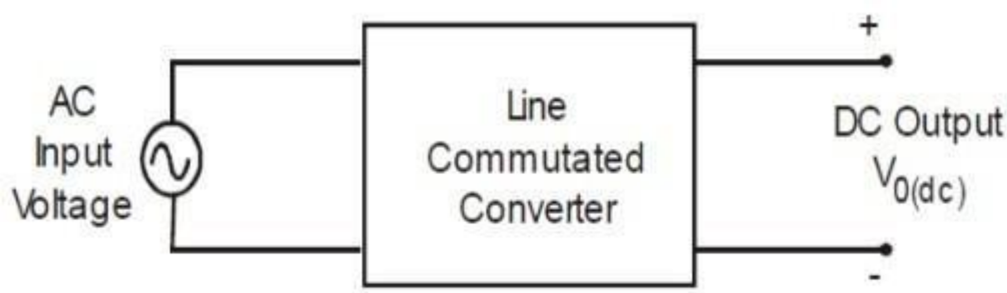


Fig 2.1.1 Block diagram of controlled rectifier

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 176]

- The input supply fed to a controlled rectifier is ac supply at a fixed rms voltage and at a fixed frequency. We can obtain variable dc output voltage by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and variable dc (average) output current by varying the trigger angle (phase angle) at which the thyristors are triggered. We obtain a uni-directional and pulsating load current waveform, which has aspecific average value.
- The thyristors are forward biased during the positive half cycle of input supply and can be turned ON by applying suitable gate trigger pulses at the thyristor gate leads. The thyristor current and the load

current begin to flow once the thyristors are triggered (turned ON) say at ωt =α. The load current flows when the thyristors conduct from ωt =α to β. The output voltage across the load follows the input supply voltage through the conducting thyristor. At ωt = β, when the load current falls to zero, the thyristors turn off due to AC line (natural) commutation. In some bridge controlled rectifier circuits the conducting thyristor turns off, when the other thyristor is (other group of thyristors are) turned ON. The thyristor remains reverse biased during the negative half cycle of input supply. The type of commutation used in controlled rectifier circuits is referred to AC line commutation or Natural commutation or AC phase commutation.

- When the input ac supply voltage reverses and becomes negative during the negative half cycle, the thyristor becomes reverse biased and hence turns off. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

APPLICATIONS OF PHASE CONTROLLED RECTIFIERS

1. DC motor control in steel mills, paper and textile mills.
2. AC fed traction system using dc traction motor.
3. Electro-chemical and electro-metallurgical processes.
4. Magnet power supplies.
5. Portable hand tool drives.

6. Variable speed industrial drives.

7. Battery charges.

8. High voltage DC transmission.

9. Uninterruptible power supply systems (UPS).

The phase controlled converters are simple and less expensive and are widely used in industrial applications for industrial dc drives. These converters are classified as two quadrant converters if the output voltage can be made either positive or negative for a given polarity of output load current. There are also single quadrant ac to dc converters where the output voltage is only positive and cannot be made negative for a given polarity of output current. Of course single quadrant converters can also be designed to provide only negative dc output voltage. The two quadrant converter operation can be achieved by using fully controlled bridge converter circuit and for single quadrant operation we use a half controlled bridge converter.

CLASSIFICATION OF PHASE CONTROLLED RECTIFIERS

The phase controlled rectifiers can be classified based on the type ofinput power supply as

Single Phase Controlled Rectifiers- which operate from single phase acinput power supply.

Three Phase Controlled Rectifiers -which operate from three phase ac inputpower supply.

2.2 Two Pulse Converter

FULLY CONTROLLED BRIDGE CONVERTER

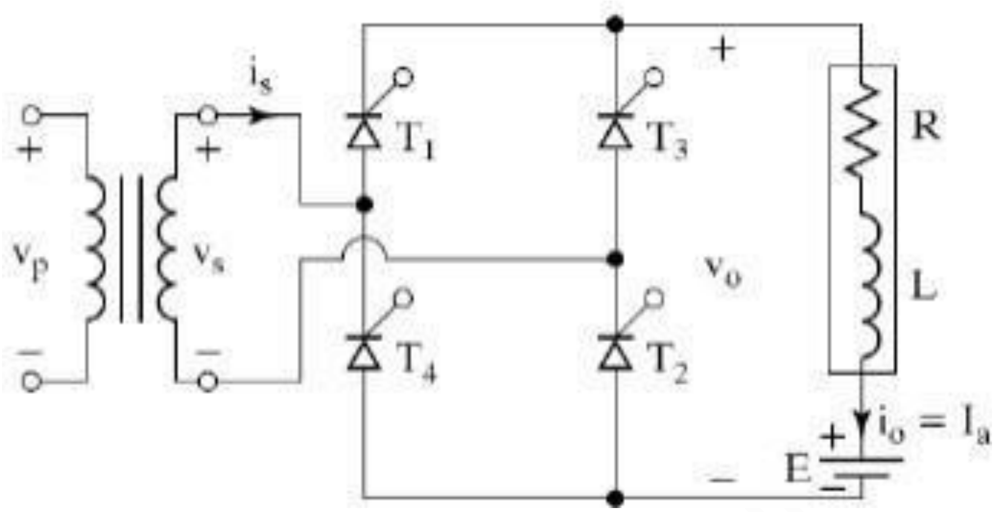


Figure 2.2.1 SINGLE PHASE FULL CONVERTER

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

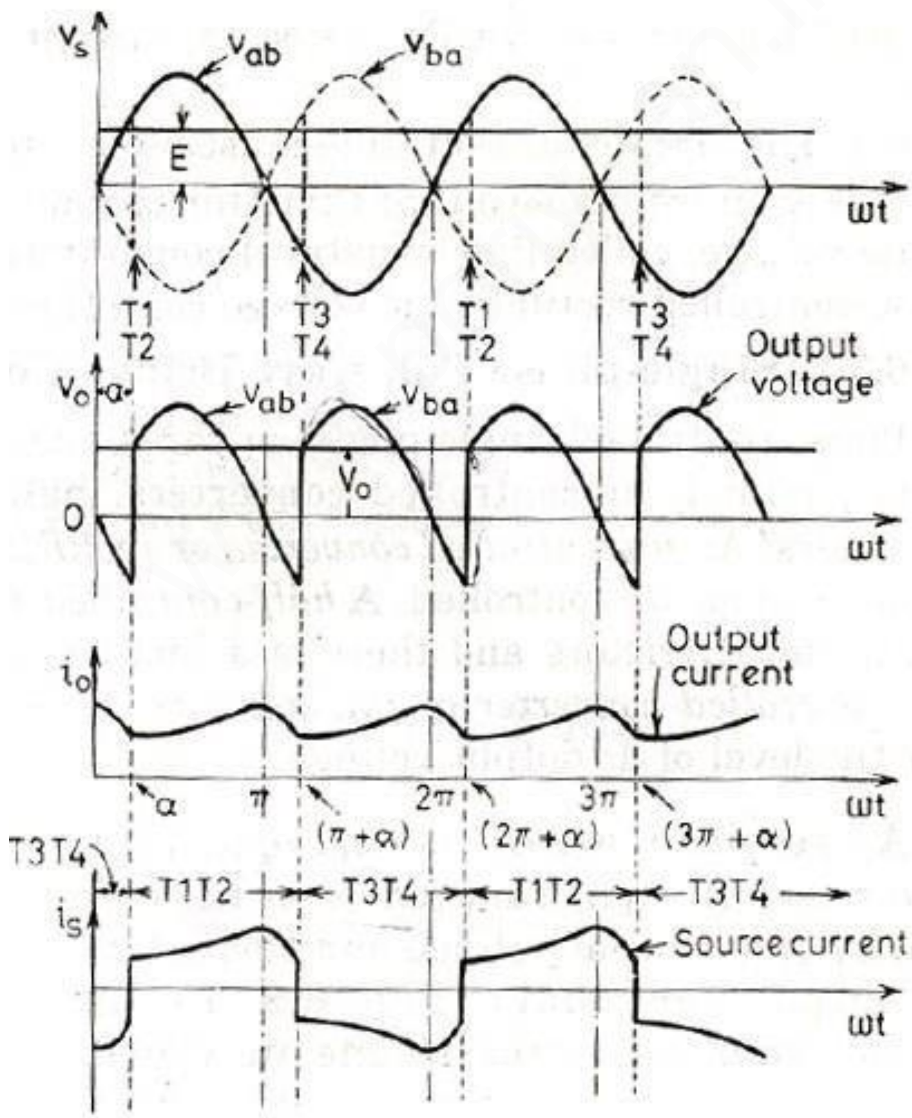
CONSTRUCTION

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 timeinterval 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 2.2.2 FULL CONVERTER WAVEFORM

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 192)



During the negative half cycle of input supply voltage for $\omega t = \pi$ to 2π the thyristors T3and T4are forward biased. T3 and T4are triggered at $\omega t = (\pi+\alpha)$. 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 $\omega t = \alpha$ 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 $\omega t = \alpha$ to π.

During the time period $\omega t = \pi$ to $(\pi+\alpha)$, 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 $\omega t = \pi$ to $(\pi+\alpha)$ 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.

2.3 Three Pulse Converter

INTRODUCTION TO 3-PHASE CONTROLLED RECTIFIERS

Three phase converters are 3-phase controlled rectifiers which are usedto 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.

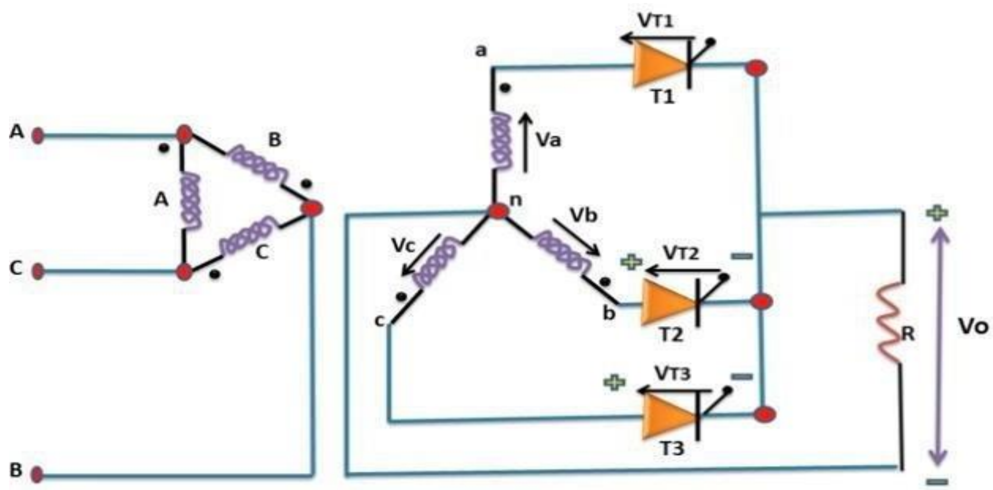
Filtering requirements are simplified for smoothing out load voltage and load current.Three phase controlled rectifiers are extensively used in high power variable speed industrial dc drives.

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

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

Figure 2.3.1 Three pulse converter circuit diagram

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



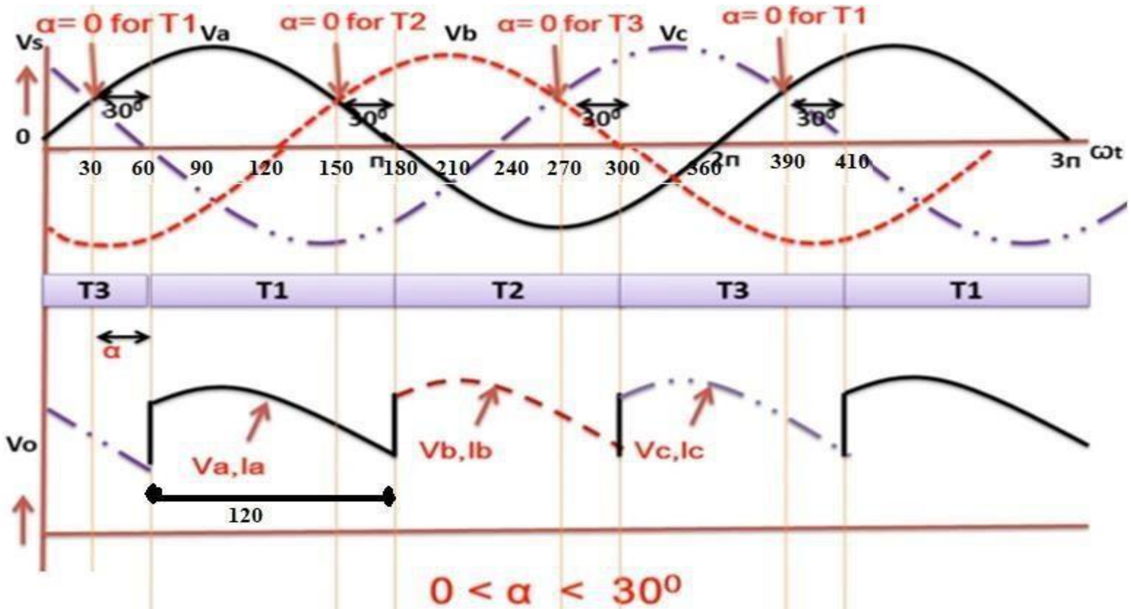


Figure 2.3.2 Three pulse converter Waveforms

[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.

2.4 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

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 thepolarity 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.

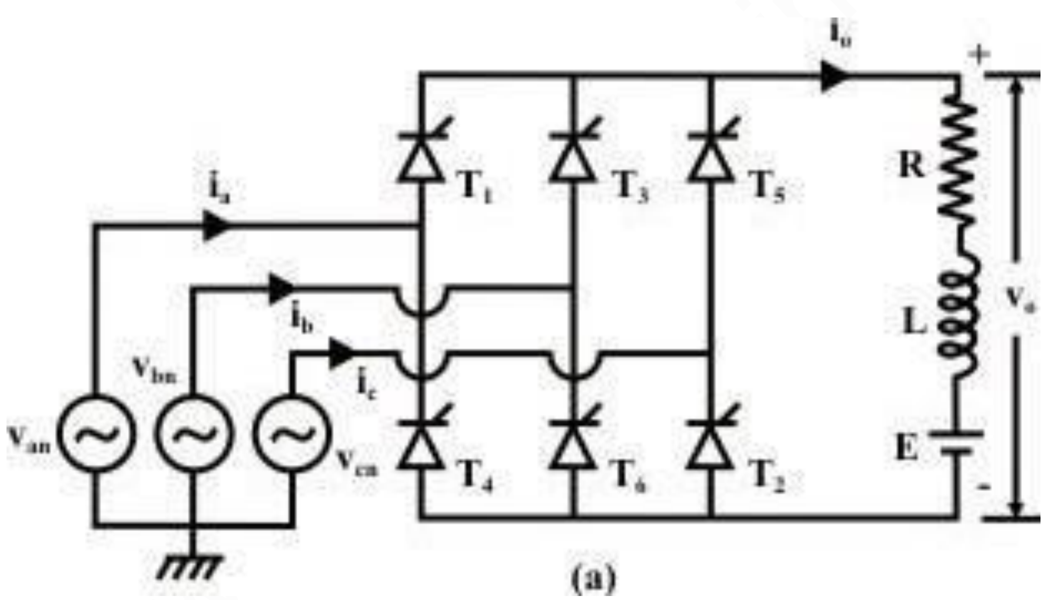


Figure 2.4.1 Six pulse converter

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

The three thyristors (T1 ,T3 andT5) will not work together at the sametime 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 sametime 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 sametime.

- 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.

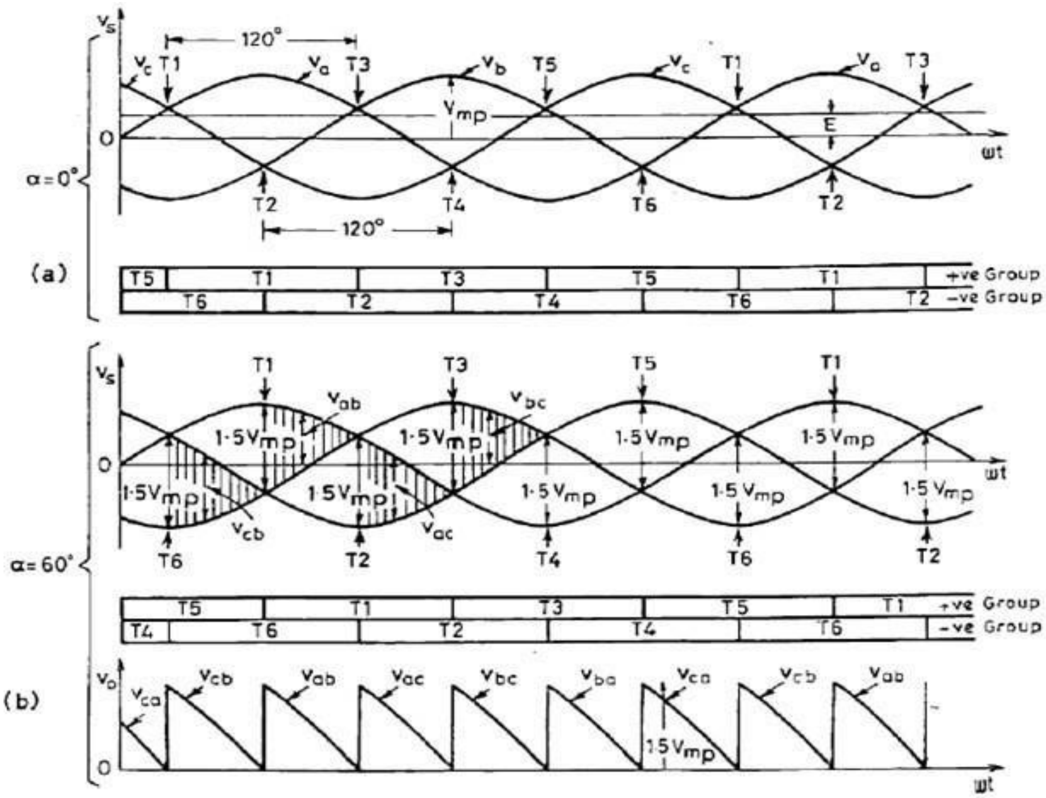


Figure 2.4.2 Six pulse converter Waveforms

[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+12
- 0+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 $\omega t = 30^\circ+\alpha$, 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 $\omega t = 30+\alpha$ to $90^\circ+\alpha$ thyristors T 1and T 6 conduct together and the line to line supply voltage Vab appears across the load. At $\omega t = 90^\circ+\alpha$, the thyristor T2 is triggered and T6 is reverse biased immediately and T6 turns off due to natural commutation. During the time period $\omega t = 90^\circ+\alpha$ to $150^\circ+\alpha$, 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.

2.5 PERFORMANCE PARAMETERS

The various parameters to compare the performance of power electronicsconverter are listed below:

1. Output dc power (average or dc output power delivered to the load)

$$P_{O(dc)} = V_{O(dc)} \times I_{O(dc)} \;\; ; \text{ i.e., } P_{dc} = V_{dc} \times I_{dc}$$

Where

$V_{O(dc)} = V_{dc} =$ average or dc value of output (load) voltage.

$I_{O(dc)} = I_{dc} =$ average or dc value of output (load) current.

2. Input Displacement Factor (DSF):

DSF=cos α

3. Output Ac power

$$P_{O(ac)} = V_{O(RMS)} \times I_{O(RMS)}$$

4. Rectification efficiency:

$$\text{Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}}$$

$$\% \text{ Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}} \times 100$$

5. AC component

The output voltage can be composed of two components

- The dc component $V_{O(dc)}$ = DC or average value of output voltage.
- The ac component or the ripple component

  $V_{ac} = V_{r(rms)}$= RMS value of all the ac ripple components.

The total RMS value of output voltage is given by

$$V_{O(RMS)} = \sqrt{V_{O(dc)}^2 + V_{r(rms)}^2}$$

Therefore

$$V_{ac} = V_{r(rms)} = \sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}$$

6. Voltage Ripple Factor

The Ripple Factor (RF) which is a measure of the ac ripple content in the output voltage waveform. The output voltage ripple factor defined for the output voltage waveform is given by

$$r_v = RF = \frac{V_{r(rms)}}{V_{O(dc)}} = \frac{V_{ac}}{V_{dc}}$$

7. Current Ripple Factor

Defined for the output (load) current waveform is given by

$$r_i = \frac{I_{r(rms)}}{I_{O(dc)}} = \frac{I_{ac}}{I_{dc}}$$

Where

$$I_{r(rms)} = I_{ac} = \sqrt{I^2_{O(RMS)} - I^2_{O(dc)}}$$

the peak to peak ac ripple load current is the difference between the maximum and the minimum values of the output load current

$$I_{r(pp)} = I_{O(\max)} - I_{O(\min)}$$

8. Transformer Utilization Factor (TUF)

A transformer is most often used both to introduce a galvanic isolation between the rectifier input and the AC mains and to adjust the rectifier AC input voltage to a level suitable for the required application. One of the parameters used to define the characteristics of the transformer is the Transformer Utilization Factor (TUF):

$$TUF = \frac{P_{DC}}{Effective\ Transformer\ VA\ Rating}$$

2.6 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 .

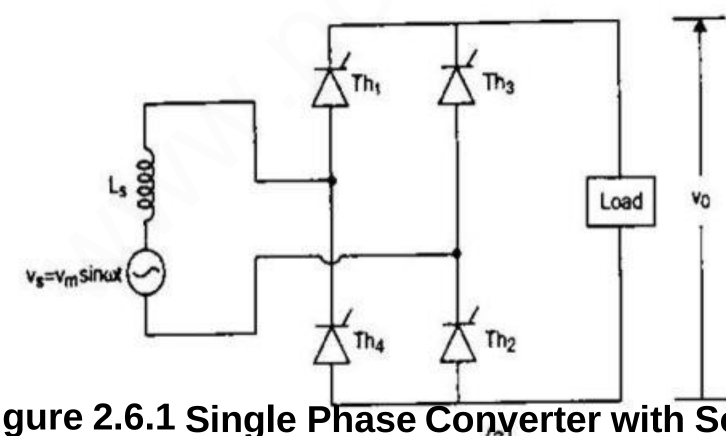
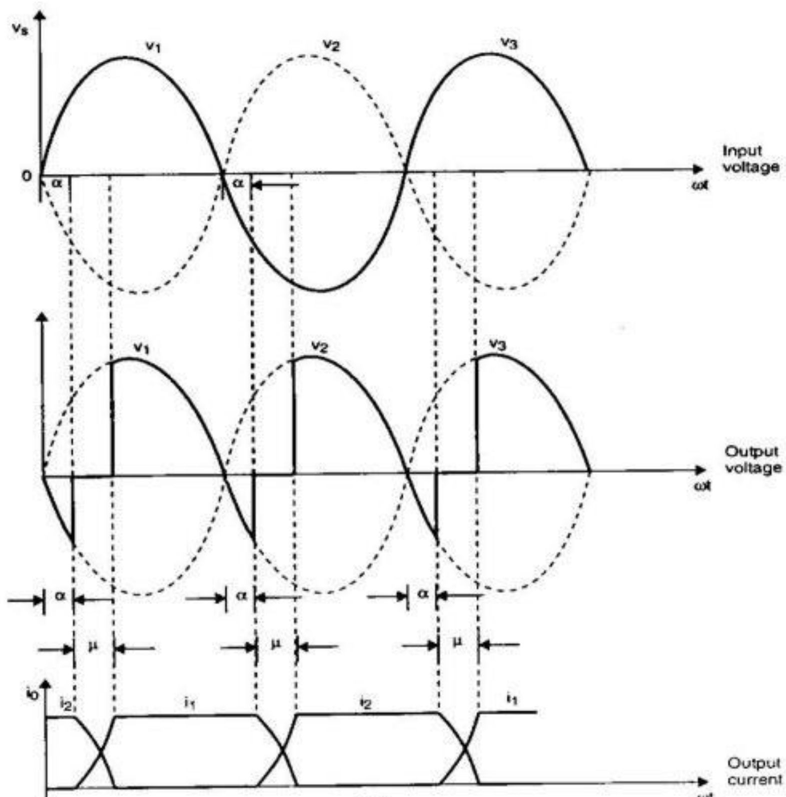


Figure 2.6.1 Single Phase Converter with Source Inductance

[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



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(b)

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

2.7 Firing Schemes for Converters

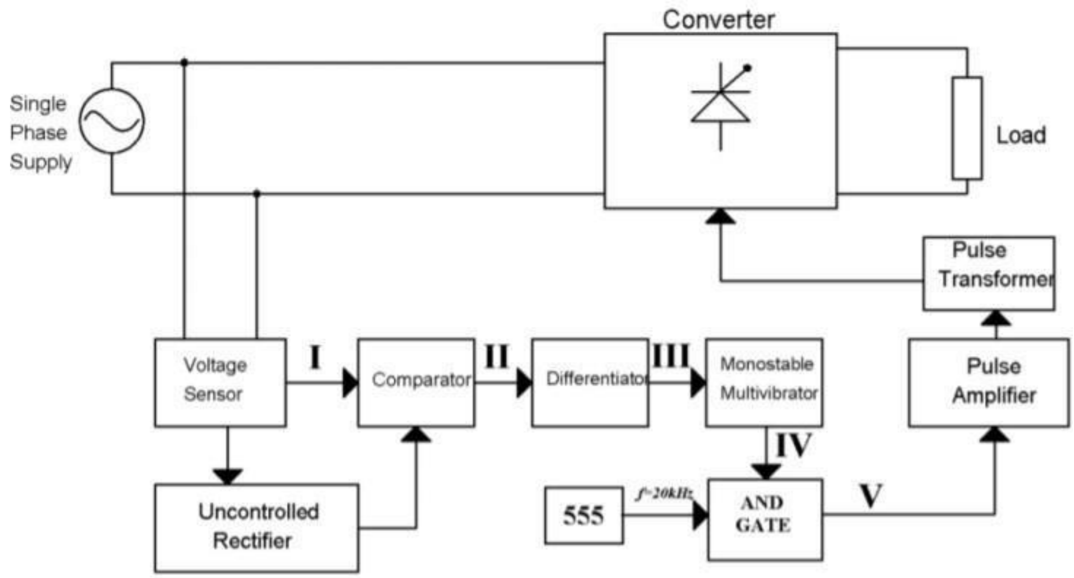
The firing circuit consists of step down transformer, uncontrolled rectifier, comparator, differentiator, mono stable multi vibrator, oscillator, AND gate, pulse amplifier and pulse transformer.

The complete circuit diagram of triggering circuit is shown in Fig. 2.24. A single-phase transformer with center tapped secondary windings has been used. The main purpose of this transformer is to step down 50Hz, 220 V to 6-0-6 V. The secondary voltage of the transformer is compared with a dc reference signal using a 741C op-amp comparator to produce an alternating rectangular waveform of a variable pulse width.

The output of the comparator ideally swings between +5 and -5 V at every crossing transformer output dc reference voltage. Using a variable resistor, the dc reference voltage can be altered and hence the rectangular waveform of variable pulse width is obtained at output terminal.

Figure 2.7.1 Firing circuit for full converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 224]*



A simple R-C differentiator is used to differentiate the rectangular voltage waveform. The elements R and C are selected as 10KΩ and 0.01μF, respectively. Monostable multivibrator often called a on shot multivibrator, is a pulse generating circuit in which the duration of this pulse is determined by the RC network connected externally to the 555 timer. A 555 timer produces an output pulse using a positive going edge trigger to produce a delay angle between 0º and 90º for the conversion mode of operation.

The differentiator is blocked by a connected diode. The number of comparators and monostable blocks are 2 blocks to produce firing pulses for conversion and inversion mode together. The values of R9 and C7 for the monostable are chosen so that the pulse width is approximately 0.5ms. Once triggered, the circuit's output will remain in the high state until the set time elapses. The output will not change its state even if an input trigger is applied again during this time interval. The output will remain in the low state until a trigger is again applied. IC 555 timer is used as oscillator.

The square wave output waveform of of 20kHz by connecting suitable resistor and capacitor. Pulse gating of thyristor is not suitable for RL loads, this difficulty can be overcome by using continuous gating. However, continuous gating may lead to increased thyristor losses and distortion of output pulse. So, a pulse train generated by modulating the gate pulse at high frequency is used to trigger the thyristor. This high frequency wave is known as carrier wave and is generated by using 555 timer.The outputs of monostable multivibrator and oscillator are applied to the AND gate. IC 7408 two input AND gate is used for this purpose. A long duration pulse may saturate the pulse transformer and the firing pulse may be distorted so high frequency modulation is necessary.

The duty cycle is kept less than 50 percent, so that the magnetic flux in the transformer can be reset. The modulation pulse also reduces the gatedissipation.

2.8 Dual converter

- **Dual converter**, the name itself says two converters.
- It is really an electronic converter or circuit which comprises of two converters. One will perform as a rectifier and the other will perform as an inverter.
- Therefore, we can say that double processes will occur at a moment. Here, two full converters are arranged in anti-parallel pattern and linked to the same dc load. These converters can provide four quadrant operations.

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 230]*

The basic block diagram is shown below.

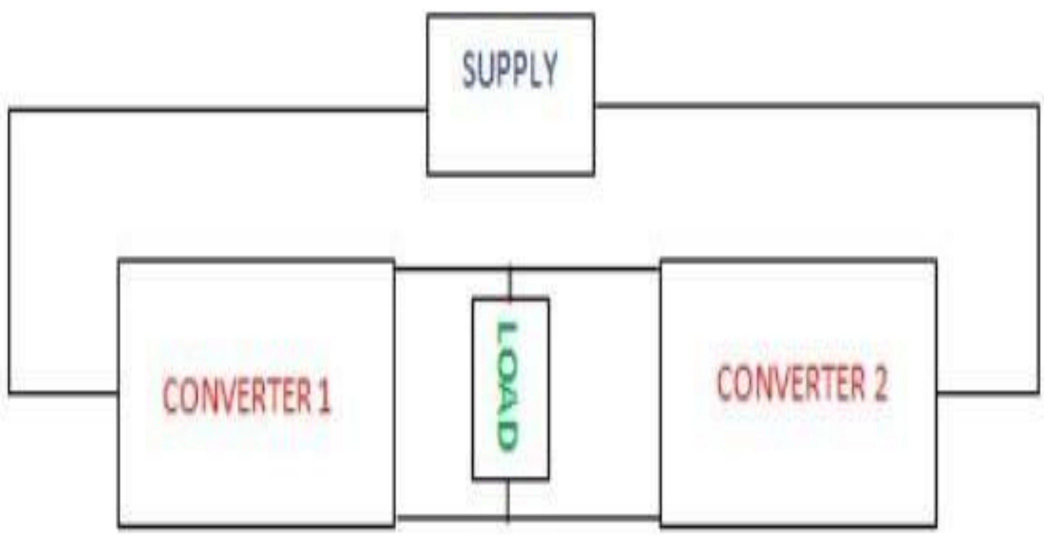


Figure 2.8.1 Block diagram of dual converter

Modes of Operation of Dual Converter

There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

- One converter will perform at a time. So there is no circulatingcurrent between the converters.
- During the converter 1 operation, firing angle (α_1) will be $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.

Circulating Current Mode

- Two converters will be in the ON condition at the same time. Socirculating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α_1) +firing angle of converter 2 (α_2) = 180^o.
- Converter 1 performs as a controlled rectifier when firing angle be $0<\alpha_1< 90^o$ and Converter 2 performs as an inverter when the firing angle be $90^o<\alpha_2< 180^o$. In this condition, V_{dc} and I_{dc} are positive.
- Converter 1 performs as an inverter when firing angle be $90^o<\alpha_1< 180^o$ and Converter 2 performs as a controlled rectifier when the firing angle be $0<\alpha_2< 90^o$ In this condition,V_{dc} and I_{dc} are negative.

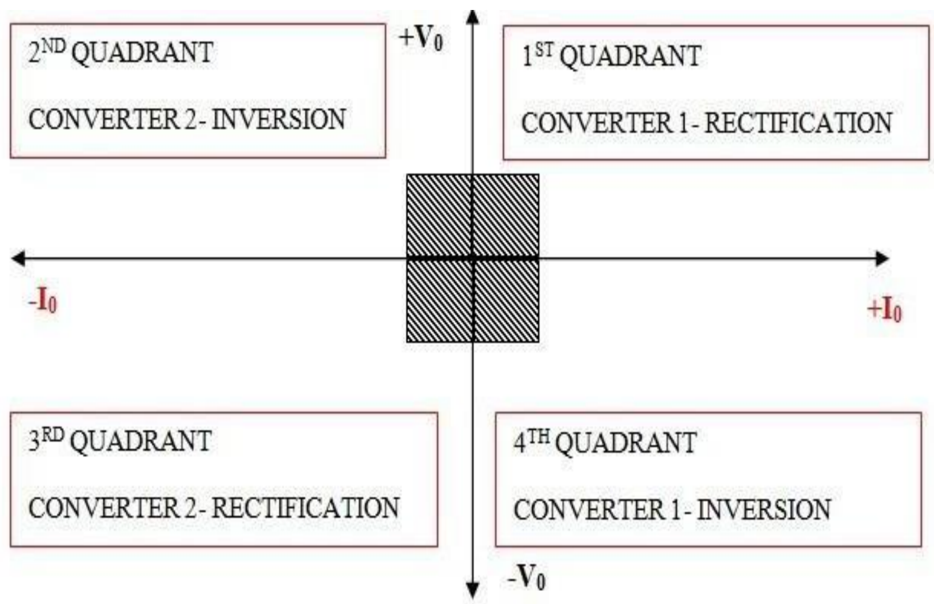


Figure 2 .8.2 Four quadrant operation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 230]*

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D1 and D2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V01 and converter 2 is V02. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the thyristors have to be controlled.

Average output voltage of Single-phase converter

$= 2Vm \cos\alpha/\pi$

Average output voltage of Three-phase converter

= 3Vml cos

Output voltage, Vo =

VO1+VO2

Types of Dual Converters

They are of two types: Single-phase dual converter and three-phase dual converter.

Single Phase Dual Converter

The source of this type of converter will be single-phase supply. Consider, the converter is in non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC as output.

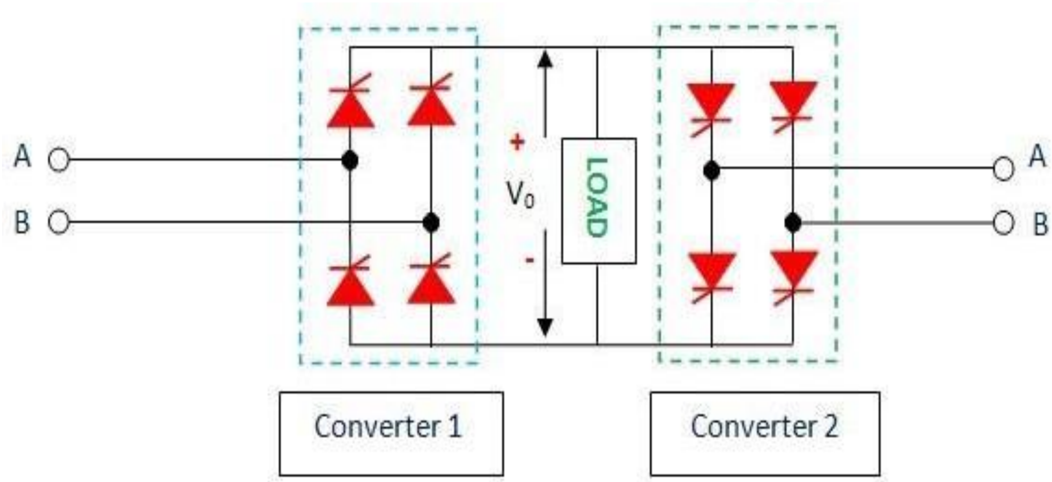


Figure 2.8.3 Single phase Dual converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 231]*

Three Phase Dual Converter

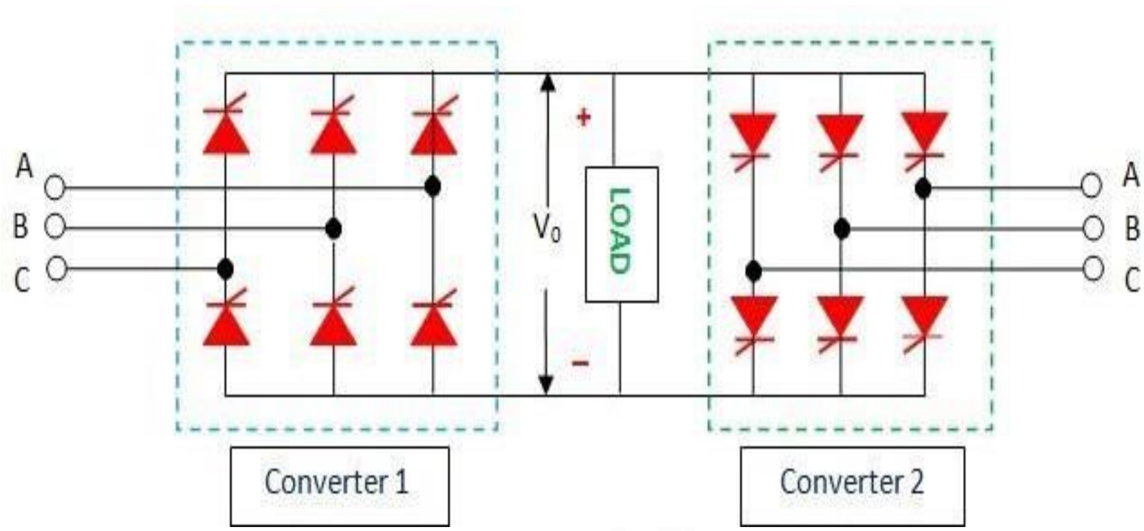


Figure 2.8.4 Three phase Dual converter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 231]*

Application of Dual Converter

- Direction and speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Here, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second do the DC to AC conversion and the output that we get is the three- phase AC. Applications where the output is up to 2 megawatts. The circuit is shown below.

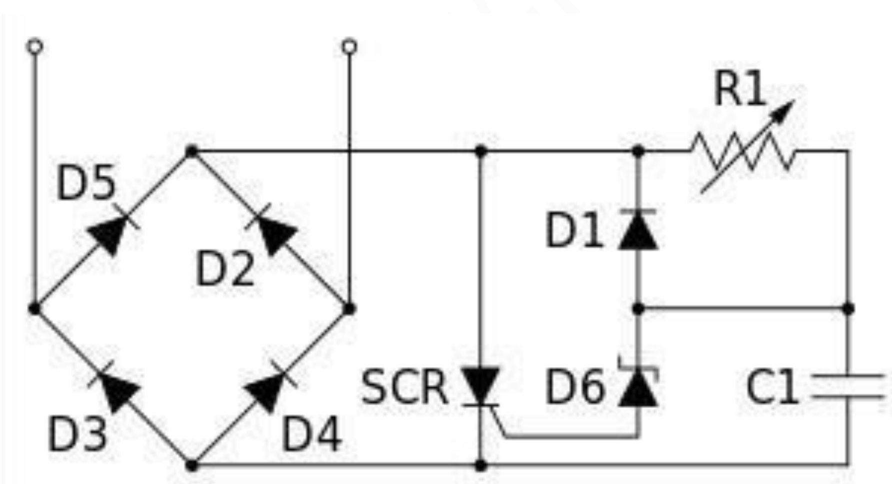
2.9 Applications of converter

LIGHT DIMMERS

Semiconductor dimmers switch on at an adjustable time (phase angle) after the start of each alternating current half-cycle, thereby altering the voltage waveform applied to lamps and so changing its RMS effective value. Because they switch instead of absorbing part of the voltage supplied, there is very little wasted power. Dimming can be almost instantaneous and is easily controlled by remote electronics. This development also made it possible to make dimmers small enough to be used in place of normal domestic light switches.

Figure 2.9.1 An electrical schematic for a SCR-based light dimmer

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 219]



In the electrical schematic shown, a typical silicon-controlled rectifier (SCR) based light dimmer dims the light through phase-angle control. This unit is wired in series with the load. Diodes (D2, D3, D4 and D5) form a bridge, which generates pulsed DC. R1 and C1 form a circuit with a time constant. As the voltage increases from zero (at the start of every halfwave) C1 will charge up. When C1 is able to make Zener diode D6 conduct and inject current into the SCR, the SCR will fire. When the SCR conducts, D1 will discharge C1 via the SCR. The SCR will shut off when the current falls to zero and the supply voltage drops at the end of the half cycle, ready for the circuit to start work on the next half cycle. This circuit is called a Leading-Edge Dimmer or Forward Phase Dimming.

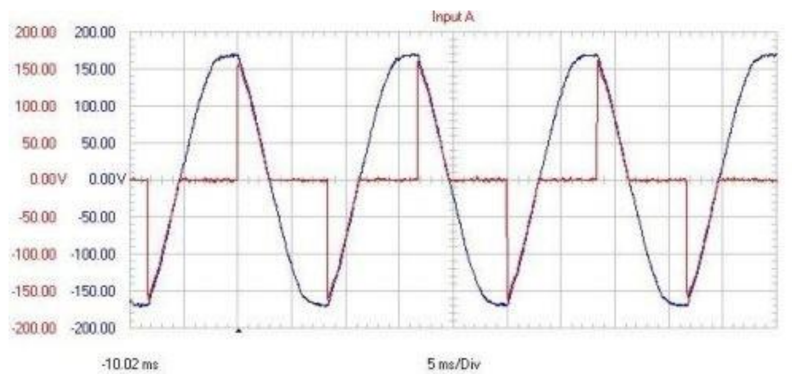


Figure 2.9.2 Phase control waveform of SCR-based light dimmer

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 220]

Waveform of the output voltage of a thyristor dimmer set for 60 volts RMS output, with 120 V input. The red trace shows the output device switching on about 5.5 ms after the input (blue) voltage crosses zero. Switching the thyristor on earlier in each half cycle gives a higher output voltage and brighter lights.

3.1 Introduction-DC-DC Converters-Chopper

There are two basic types of dc-dc converter circuits, termed asStep up and step down chopper.

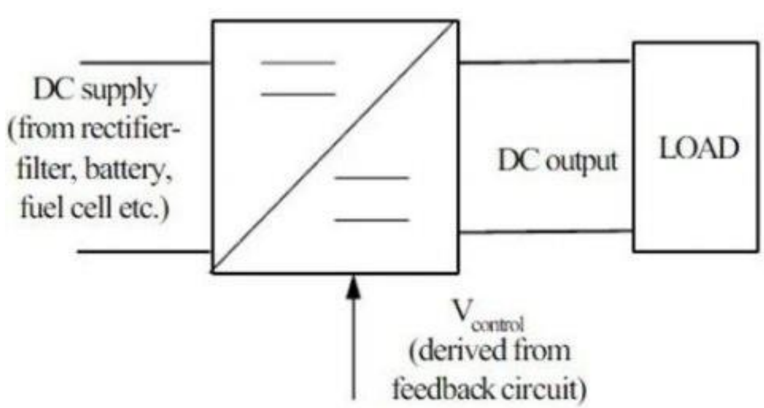
- ❖ In all of these circuits, a power device is used as a switch.
- ❖ In all these circuits, the thyristor is connected in series with load to a dc supply, or a positive (forward) voltage is applied between anode and cathode terminals. The thyristor turns off, when the current decreases below the holding current, or a reverse (negative) voltage is applied between anode and cathode terminals. So, a thyristor is to be force- commutated, for which additional circuit is to be used, where another thyristor is often used.
- ❖ Later, GTO's came into the market, which can also be turned off by a negative current fed at its gate, unlike thyristors, requiring proper control circuit. The turn on and turn-off times of GTOs are lower than those of thyristors. So, the frequency used in GTO based choppers can be increased, thus reducing the size of filters.
- ❖ Earlier, dc-dc converters were called 'choppers', where thyristors are used. It may be noted here that converter (dc-dc) is a 'step-up chopper'. With the advent of bipolar junction transistor (BJT), which is termed as self- commutated device, it is used as a switch, instead buck converter (dc-dc) is called as 'step-down chopper', whereas boost of thyristor, in dc- dc converters. This device (NPN transistor) is switched on by a positive current through the base and emitter, and then switched off by withdrawing the above signal. The collector is connected to a positive voltage.

❖ Now-a days, MOSFETs are used as a switching device in low voltage and high current applications. It may be noted that, as the turn-on and turn- off time of MOSFETs are lower as compared to other switching devices, the frequency used for the dc-dc converters using it (MOSFET) is high, thus, reducing the size of filters as stated earlier.

❖ These converters are now being used for applications, one of the most important being Switched Mode Power Supply (SMPS). Similarly, when application requires high voltage, Insulated Gate Bi-polar Transistors (IGBT) are preferred over BJTs, as the turn-on and turn-off times of IGBTs are lower than those of power transistors (BJT), thus the frequency can be increased in the converters using them. So, mostly self-commutated devices of
transistor family as described are being increasingly used in dc- dc converters.

DEFINITION:

- Converting the unregulated DC input to a controlled DC output with adesired voltage level.



- **DC to DC converter** is very much needed nowadays as many industrial applications are dependent upon DC voltage source. The performance of these applications will be improved if we use a variable DC supply. It will help to improve controllability of the equipments also. Examples of such applications are subway cars, trolley buses, battery operated vehicles etc.

  We can control and vary a constant DC voltage with the help of a chopper. Chopper is a basically static power electronics device which converts fixed DC voltage/power to variable DC voltage or power. It is nothing but a high speed switch which connects and disconnects the load from source at a high rate to get variable or chopped voltage at the output.

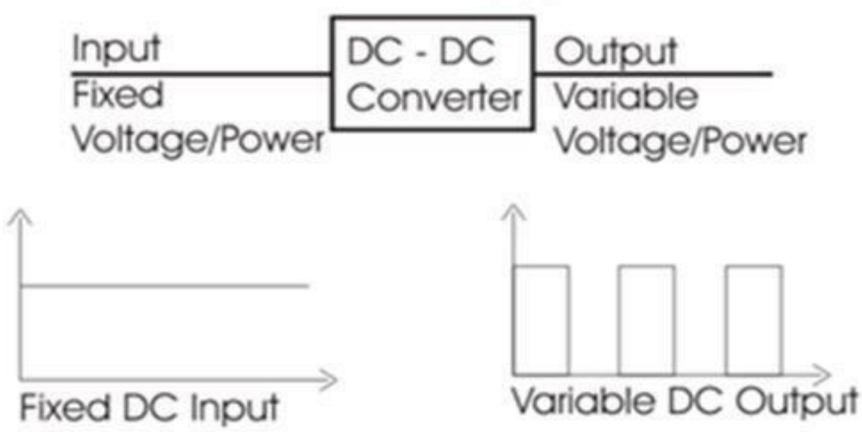


Figure 3.1.2 DC-DC Power conversion block diagram

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 249]*

Chopper can increase or decrease the DC voltage level at its opposite side. So, chopper serves the same purpose in DC circuit transformers in case of ac circuit. So it is also known as DC transformer.

DEVICES USED IN CHOPPER

Low power application: GTO, IGBT, Power BJT, Power MOSFET etc. High power application: Thyristor or SCR.

DC-DC converters types

- ❖ Vo<Vin - Buck converter
- ❖ Vo>Vin - Boost converter
- ❖ Vo<Vin or Vo>Vin - Buck-Boost converter,

APPLICATIONS OF CHOPPER

DC to DC converters are applied for many applications such as inSwitched Mode Power Supply System.

DC motors as speed controllers.

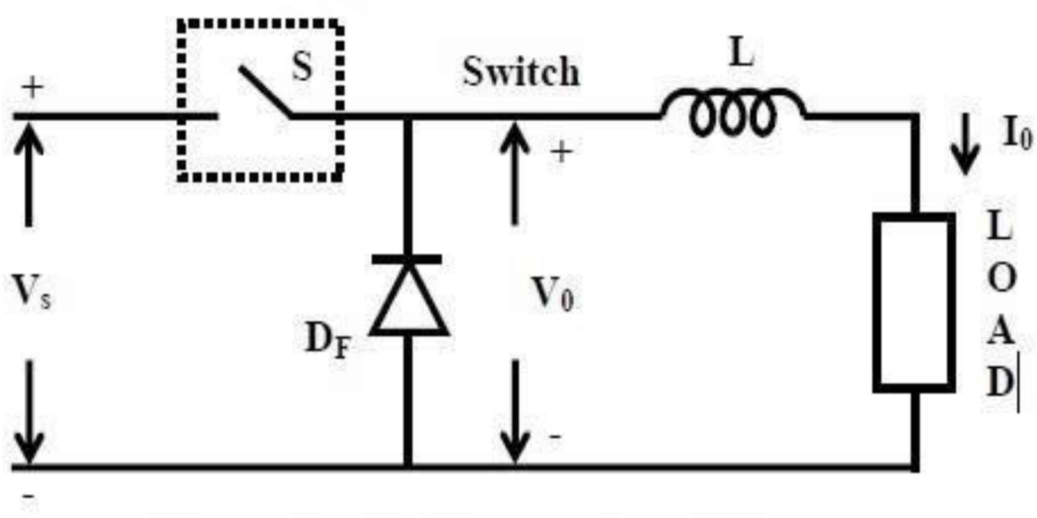
DC voltage boosters. Battery chargers.

Railway systems. Electric cars etc…

3.2 Step down & Step up chopper

A buck converter (Step down chopper) is shown in Fig. Only a switch is shown, for which a device as described earlier belonging to transistor family is used. Also a diode (termed as free wheeling) is used to allow the load current to flow through it, when the switch (i.e., a device) is turned off. The load is inductive (R-L) one. In some cases, a battery (or back emf) is connected in series with the load (inductive). Due to the load inductance, the load current must be allowed a path, which is provided by the diode; otherwise, i.e., in the absence of the above diode, the high induced emf of the inductance, as the load current tends to decrease, may cause damage to the switching device. If the switching device used is a thyristor, this circuit is called as a step-down chopper, as the output voltage is normally lower than the input voltage. Similarly, this dc-dc converter is termed as buck one, due to reason given later.

Figure 3.2.1 Step down chopper



Normally, due to turn-on delay of the device used, the duty ratio (k) is not zero, but has some positive value. Similarly, due to requirement of turn-off time of the device, the duty ratio (k) is less than 1.0. So, the range of duty ratio is reduced. It may be noted that the output voltage is lower than the input voltage. Also, the average output voltage increases, as the duty ratio is increased. So, a variable dc output voltage is obtained from a constant dc input voltage. The load current is assumed to be continuous as shown in Fig. b. The load current increases in the ON period, as the input voltage appears across the load, and it (load current) decreases in the OFF period, as it flows in the diode, but is positive at the end of the time period, T

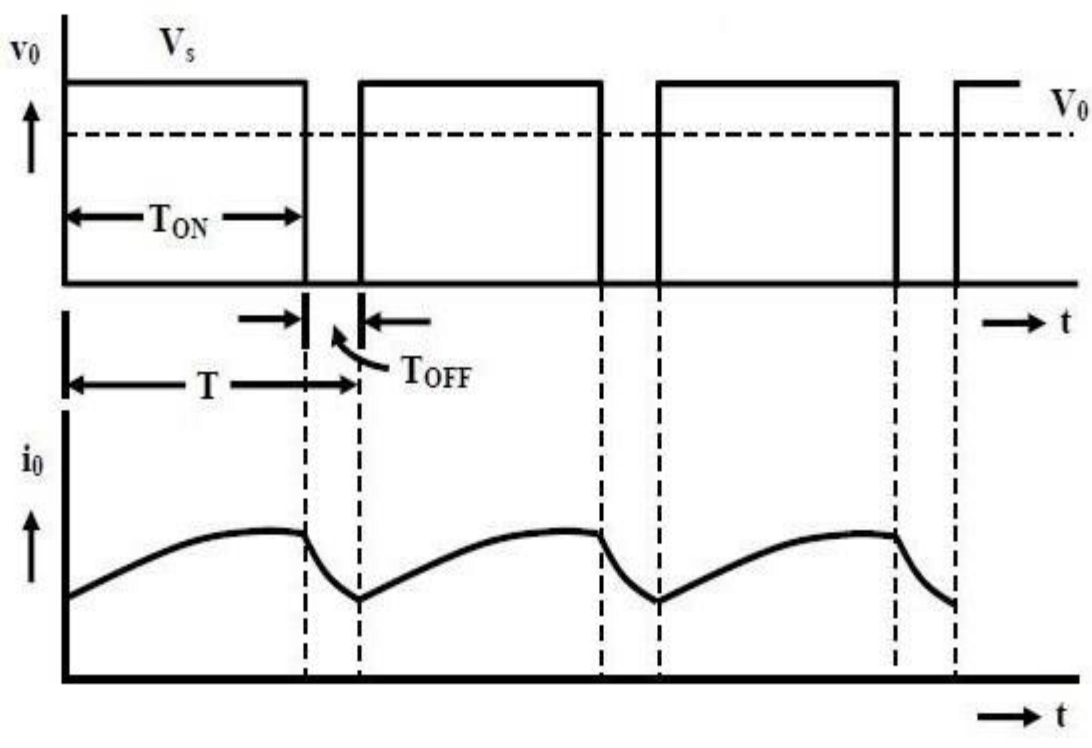


Figure 3.2.2 Step down chopper waveform

Step up chopper

A boost converter (Step up chopper) is shown in Fig. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The load is of the same type as given earlier. The inductance of the load is small. An inductance, L is assumed in series with the input supply. The position of the switch and diode in this circuit may be noted, as compared to their position in thebuck converter .

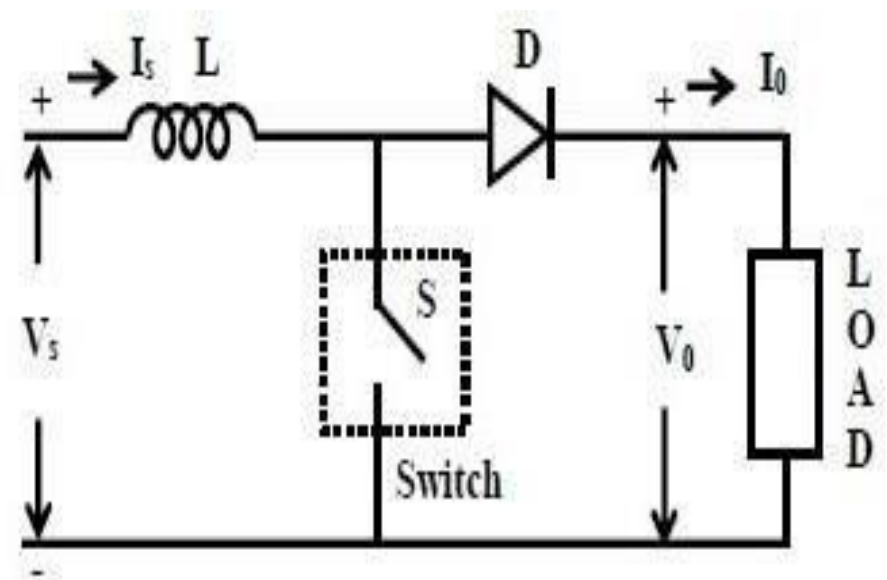


Figure 3.2.3 Step up chopper

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 252]

In this case, the output voltage is higher than the input voltage, as contrasted with the previous case of buck converter (dc-dc). So, this is called boost converter (dc-dc), when a self- commutated device is used as a switch. Instead, if thyristor is used in its place, this is termed as step-up chopper. The variation (range) of the output voltage can be easily computed.

3.3 Control strategy of Chopper

There are mainly two techniques or methods to control the output voltage of a chopper ie Time Ratio Control Method and Current Limit Control. The output voltage of chopper depends on the duty cycle. By changing the duty cycle, the output voltage can be varied.

Time-ratio Control

In the time ratio control the value of the duty ratio, TTkON/= is varied. There are two ways, which are constant frequency operation, and variable frequency operation.

Constant Frequency Operation:

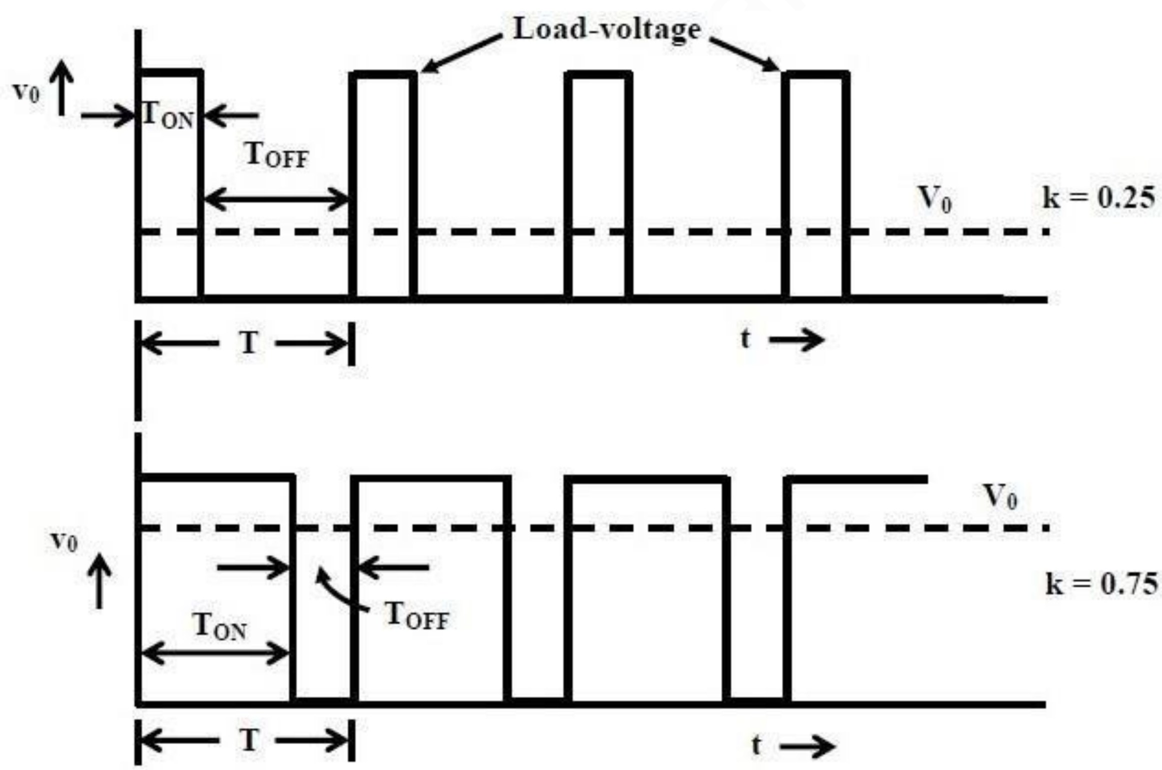


Figure 3.3.1 Constant Frequency System

In this control strategy, the ON time, T_{ON} is varied, keeping the frequency , or time period (f=1/T) constant. This is also called as pulse width modulation control (PWM). Two cases with duty ratios, as (a) 0.25 (25%), and (b) 0.75 (75%) are shown in Fig. Hence, the output voltage can be varied by varying ON time, T_{ON}.

Variable Frequency Operation

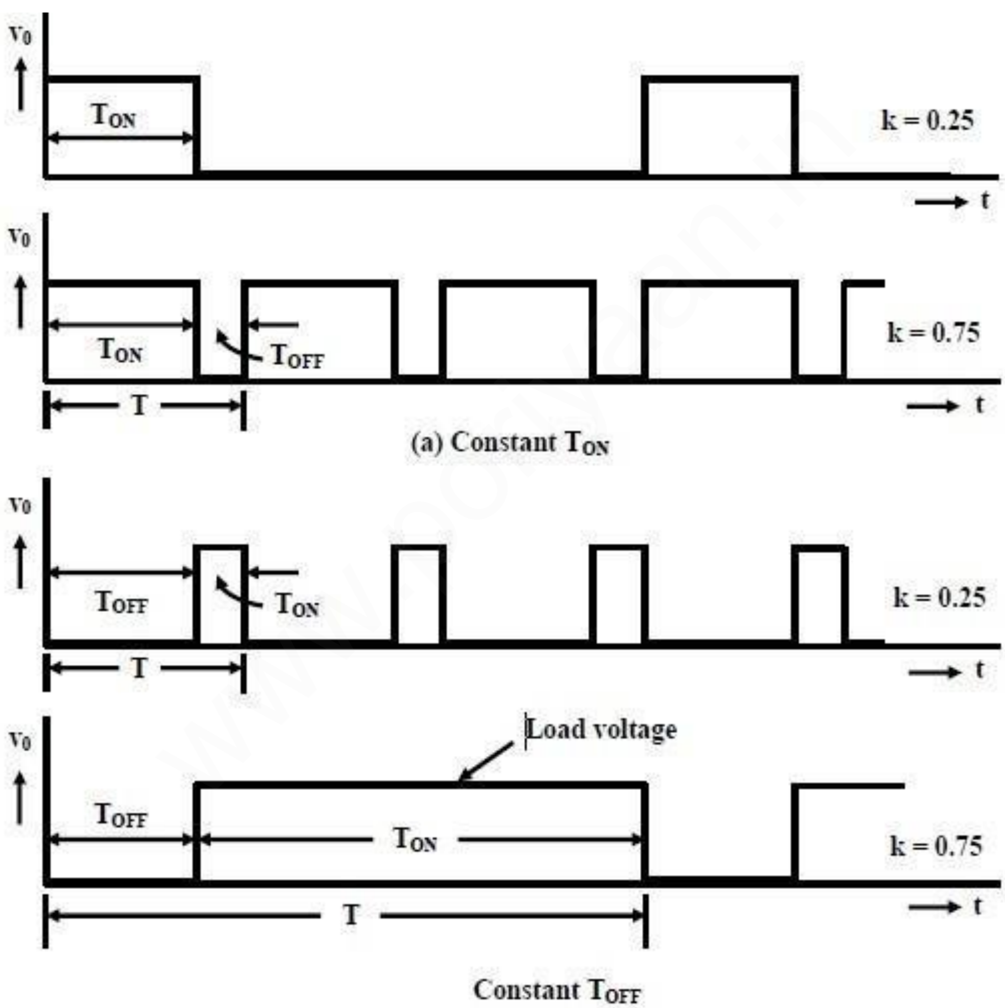


Figure 3.3.2 Variable Frequency System

In this control strategy, the frequency (f=1/T), or time period T is varied, keeping either (a) the ON time, constant, or (b) the OFF time, constant. This is also called as frequency modulation control. Two cases with (a) the ON time, constant, and (b) the OFF time, constant, with variable frequency or time period are shown in Fig. The output voltage can be varied in both cases, with the change in duty ratio.

There are major disadvantages in this control strategy. These are:

(a) The frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.

(b) For the control of a duty ratio, frequency variation would be wide. As such, there is a possibly of interference with systems using certain frequencies, such as signaling and telephone line, in frequency modulation technique.

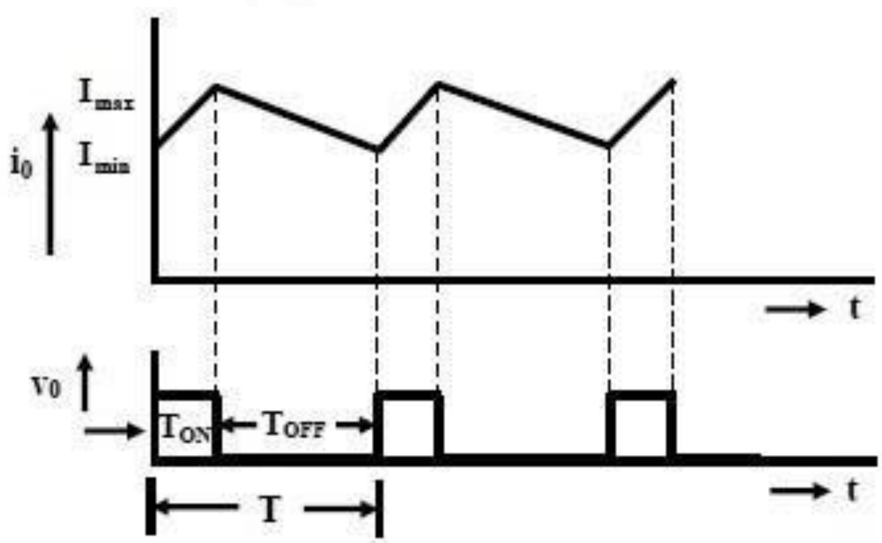
(c) The large OFF time in frequency modulation technique, may make the load current discontinuous, which is undesirable.

Thus, the constant frequency system using PWM is the preferredscheme for dc-dc converters.

Current Limit Control

As can be observed from the current waveforms for the types of dc-dc converters described earlier, the current changes between the maximum and minimum values, if it (current) is continuous. In the current limit control strategy, the switch in dc-dc converter (chopper) is turned ON and OFF, so that the current is maintained between two (upper and lower) limits. When the current exceed upper (maximum) limit, the switch is turned OFF. During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, , and decreases exponentially. When it reaches lower (minimum) limit, the switch is turned ON. This type of control is possible, either with constant frequency, or constant ON time, . This is used only, when the load has energy storage elements, i.e. inductance, L. The reference values are load current or load voltage. This is shown in Fig. In this case, the current is continuous, varying between and , which decides the frequency used for switching. The ripple in the load current can be reduced, if the difference between the upper and lower limits is reduced, thereby making it minimum. This in turn increases the frequency, thereby increasing the switching losses.

Figure 3.3.3 Current Limit Control



3.4 Types of choppers

The semiconductor devices are arranged appropriately in a chopperto work in any of the four quadrants.

we can classify chopper circuits according to their working in anyof these four quadrants as type A, type B, type C, type D and type E.

TYPE A CHOPPER OR FIRST QUADRANT CHOPPER

- This type of chopper is shown in the figure. It is known as first-quadrant chopper or type A chopper. When the chopper is on, $v_0 = V_S$ as a result and the current flows in the direction of the load. But when the chopper is off v_0 is zero but I_0 continues to flow in the same direction through the freewheeling diode FD, thus average value of voltage and current say V_0 and I_0 will be always positive as shown in the graph.

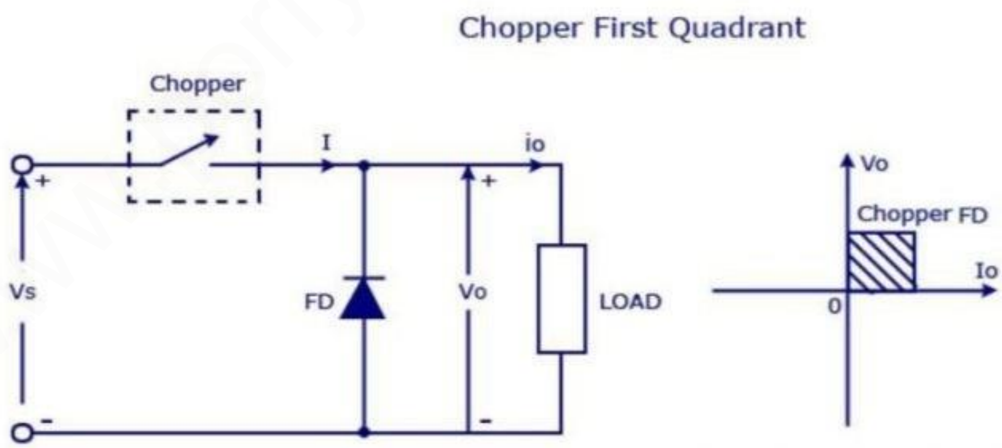


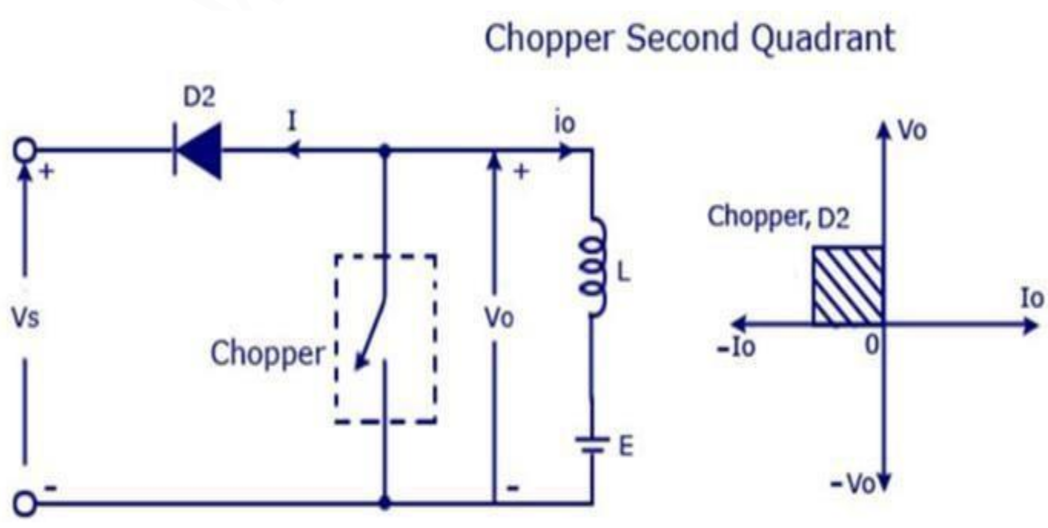
Figure 3.4.1 Type A Chopper or First–Quadrant Chopper

- In type A chopper the power flow will be always from source to theload. As the average voltage V_0 is less than the dc input voltage V_S.

TYPE B CHOPPER OR SECOND-QUADRANT CHOPPER

Type B Chopper Or Second-quadrant Chopper

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



TYPE -C CHOPPER OR TWO-QUADRANT TYPE-A CHOPPER

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

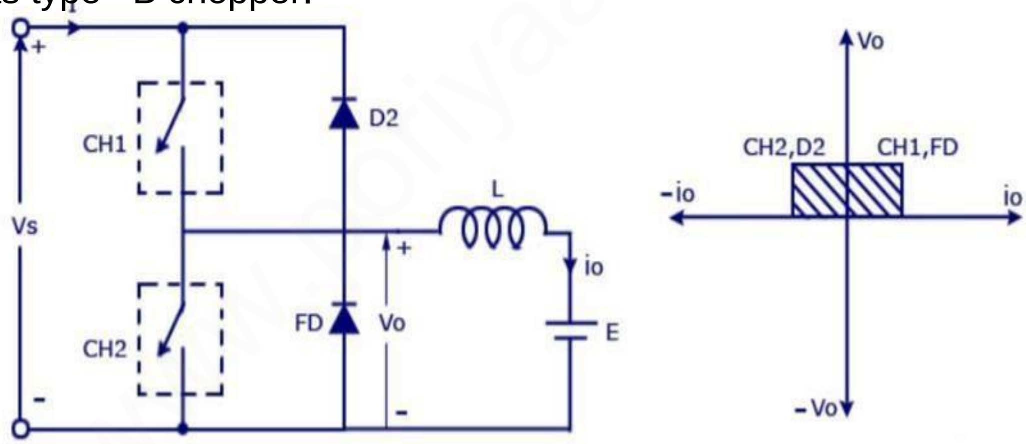
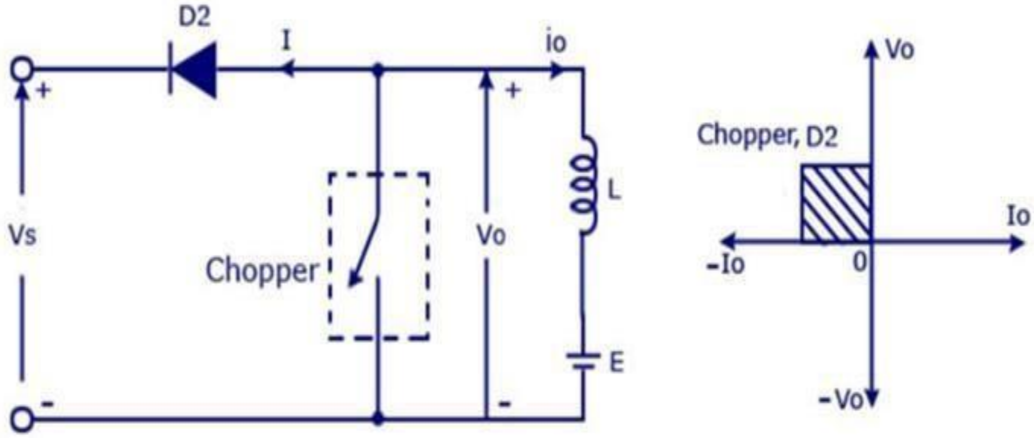


Figure 3.4.3 Type -C Chopper Or Two-quadrant Type-A Chopper

The average voltage will be always positive but the average load current might be positive or negative. The power flow may be life the first quadrant operation ie from source to load or from load to source like

Chopper Second Quadrant



the second quadrant operation. The two choppers should not be turned on simultaneously as the combined action my cause a short circuit in supply lines. For regenerative braking and motoring these type of chopperconfiguration is used.

TYPE D CHOPPER OR TWO-QUADRANT TYPE –B CHOPPER

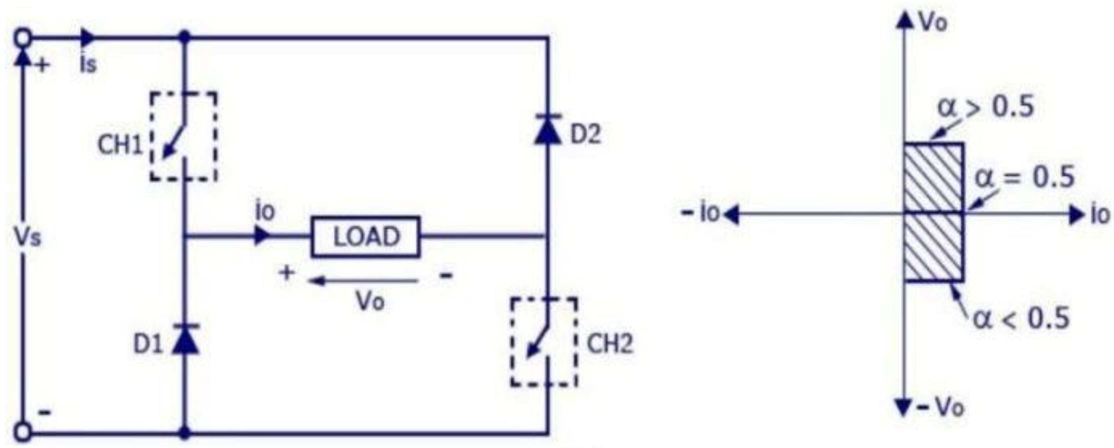


Figure 3.4.3 Type D Chopper Or Two-quadrant Type-B Chopper

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

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

$$V0 = (V_S T_{on} - V_S T_{off}) / T$$

$$= V_S.(T_{on} - T_{off}) / T$$

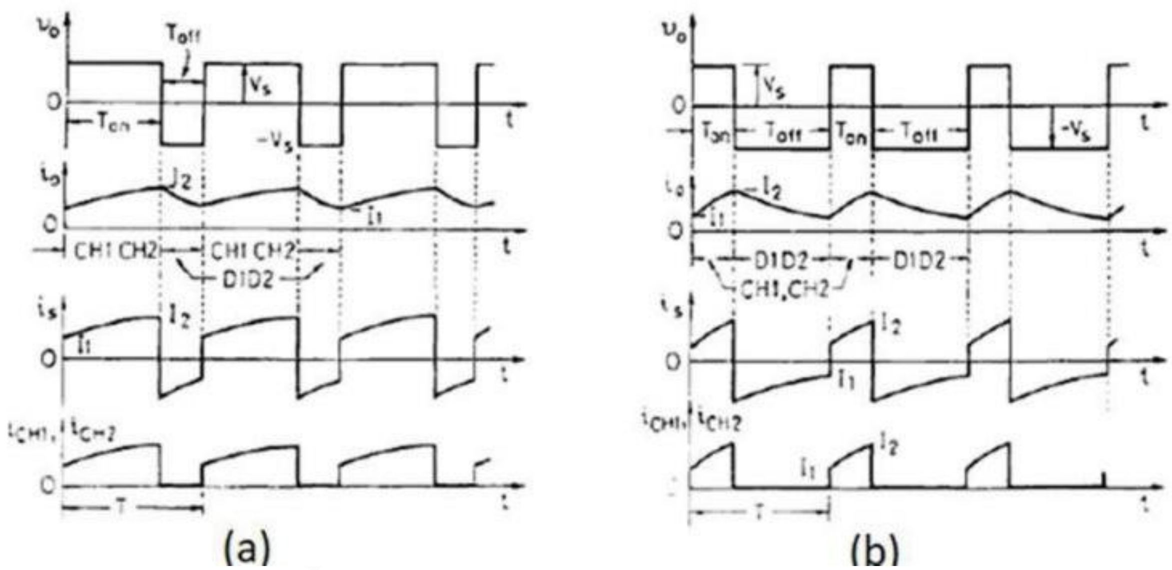


Figure 3.4.4 Type D Chopper waveform

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 256]

(a) Ton>Toff , Vo is Positive, First Quadrant Operation and

(b) Ton<Toff , Vo is Negative, Fourth Quadrant Operation

TYPE –E CHOPPER OR THE FOURTH-QUADRANT CHOPPER

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

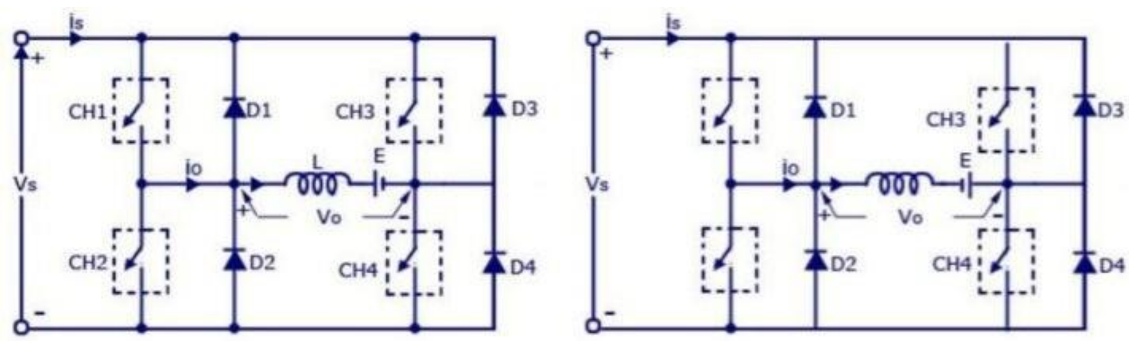


Figure 3.4.5 E-type Chopper with load emf E and E Reversed

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 257]

FIRST QUADRANT

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

SECOND QUADRANT

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

THIRD QUADRANT

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

FOURTH QUADRANT

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

3.5 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).

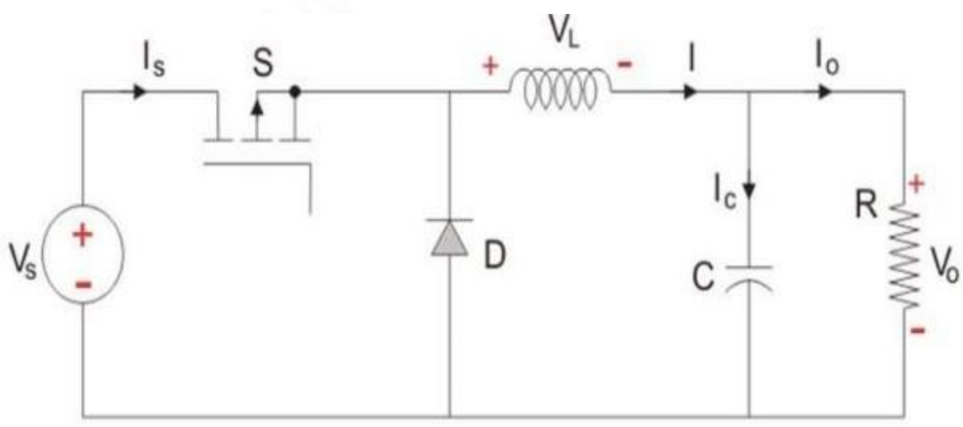


Figure 3.5.1 BUCK REGULATOR

[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

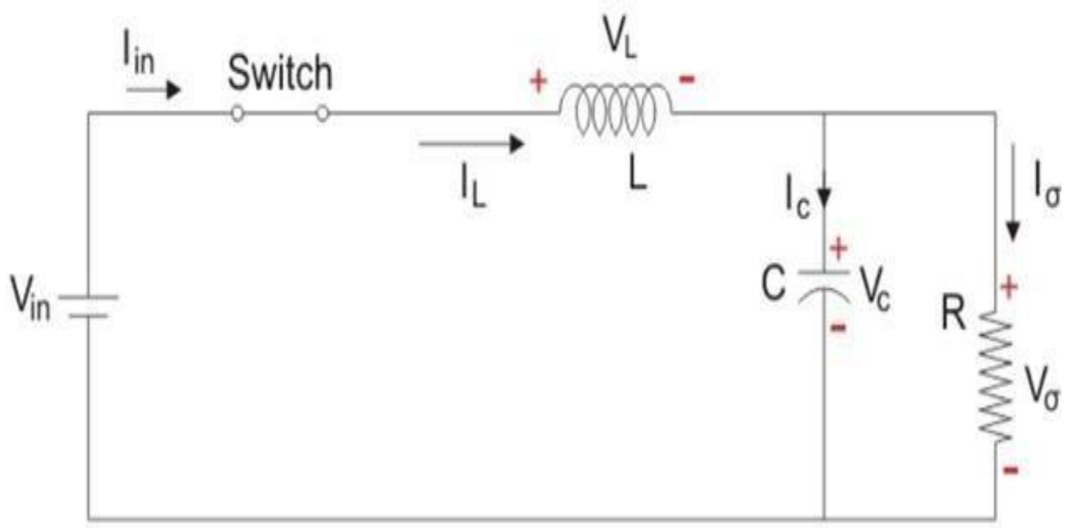


Figure 3.5.2 Buck converter- Mode II circuit diagram

[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.

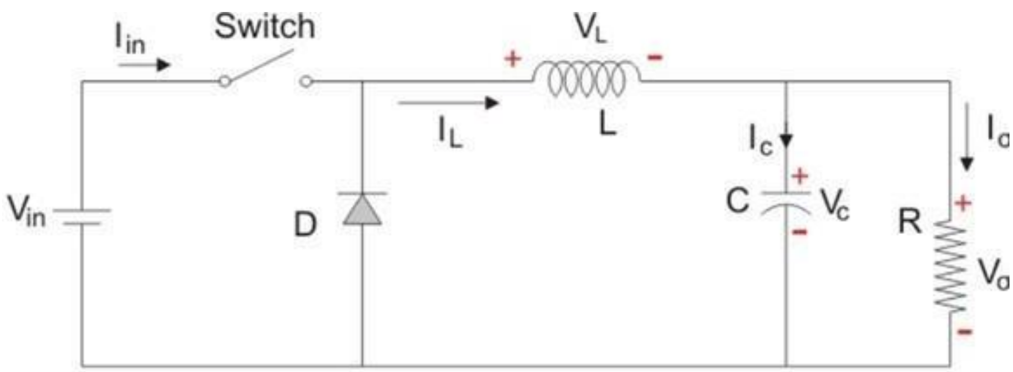


Figure 3.5.3 Buck converter- Mode II circuit diagram

[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

$V_0 = f.\ T_{on}\ .V_S$

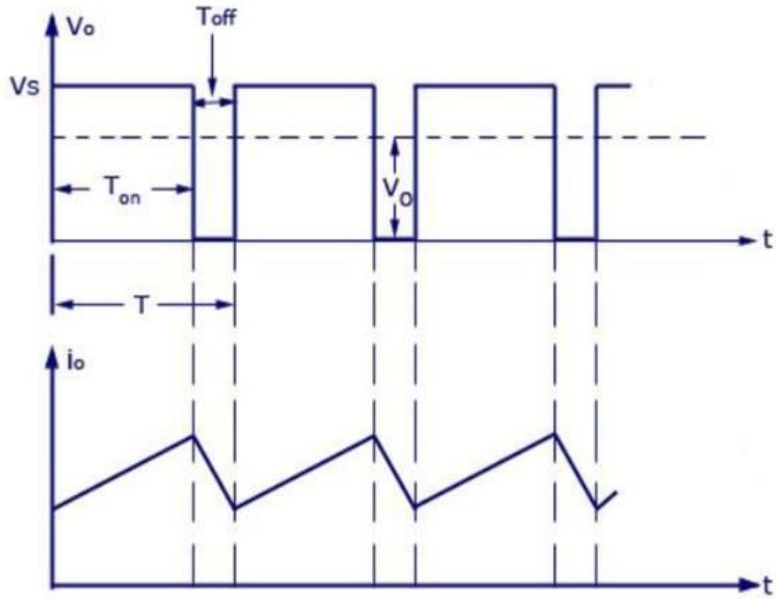


Figure 3.5.4 Buck converter Output Voltage and Current Waveforms

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

3.6 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.

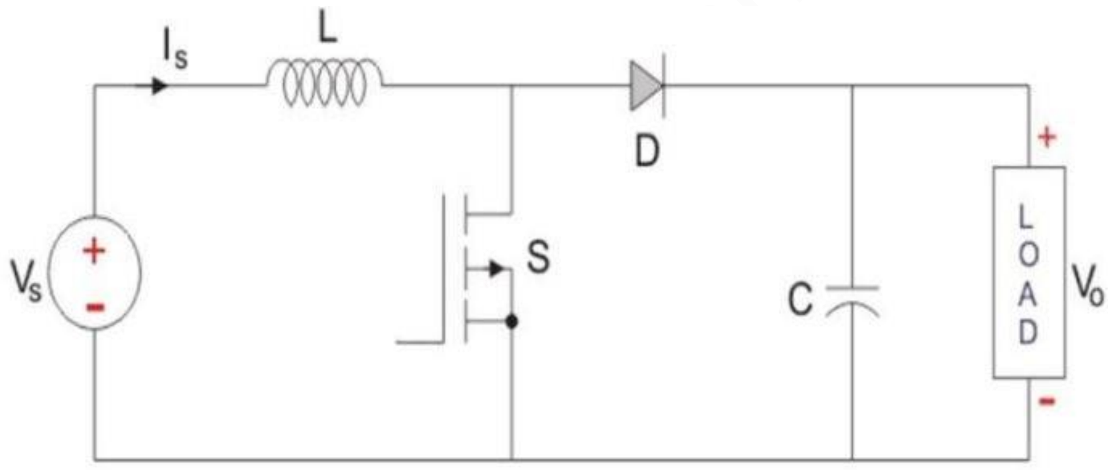


Figure 3.6.1 Block diagram of Boost convert

- 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

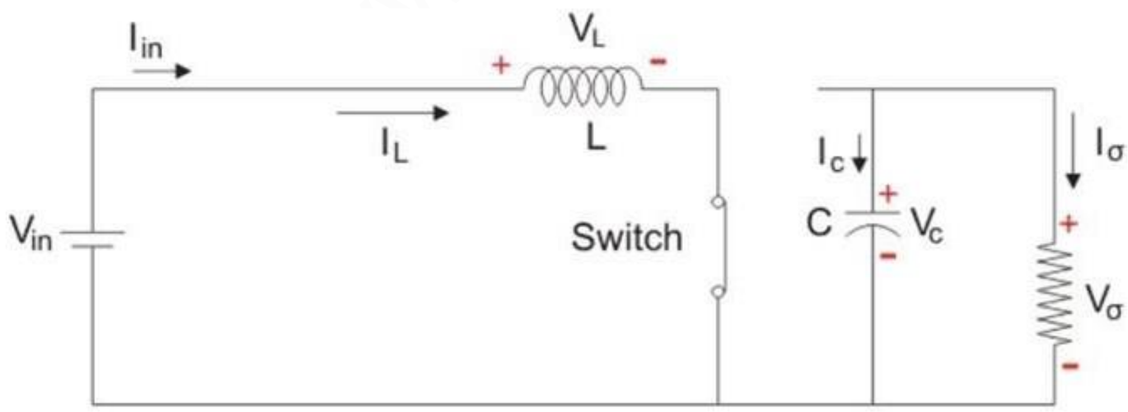


Figure 3.6.2 Boost converter- Mode I circuit

- 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

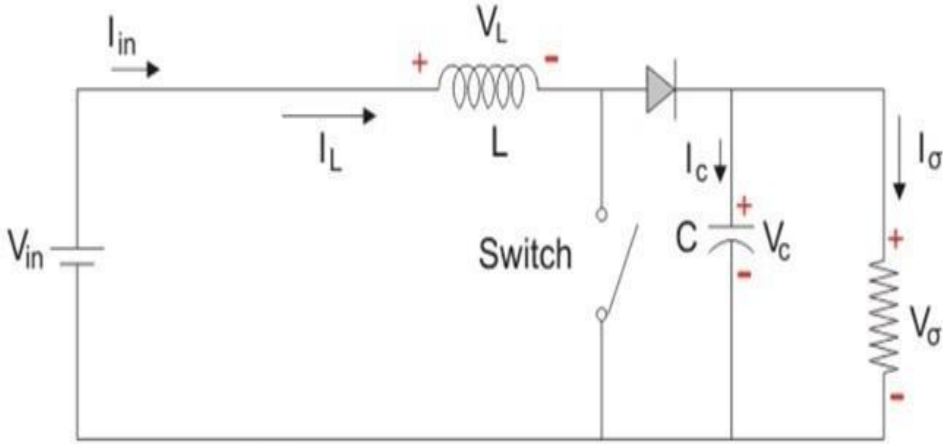


Figure 3.6.3 Boost converter- Mode II circuit diagram

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

When the chopper is OFF, the KVL can bewritten 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 , sourcecurrent 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 energyinput 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 bythe 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 energiessay W_{in} and W_{off} are equal.

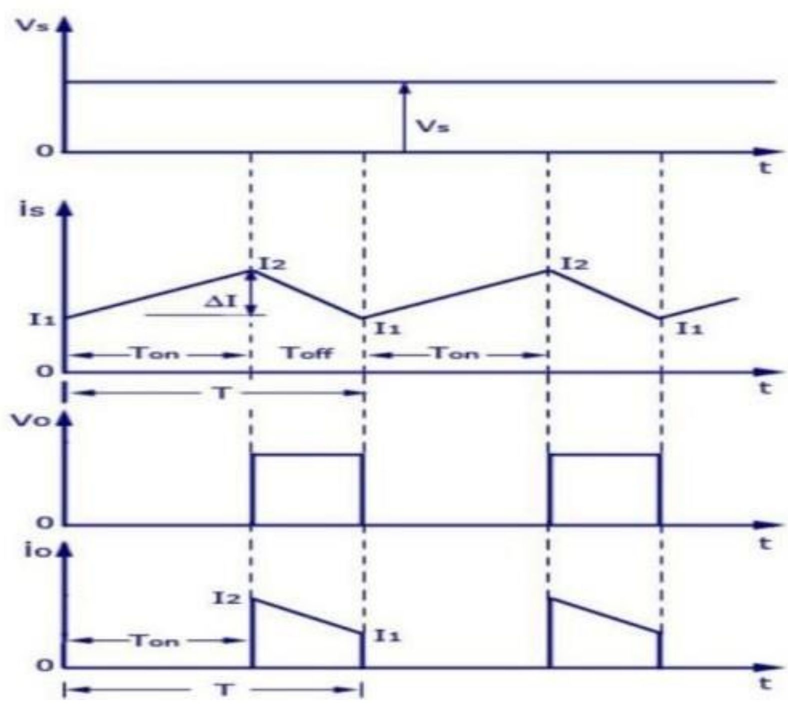


Figure 3.6.4 Boost converter Waveforms

Boost converter Output Voltage

So equating these two we will get

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

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

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

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

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.

3.7 BUCK -BOOST CONVERTER

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

A typical Buck-Boost converter is shown below

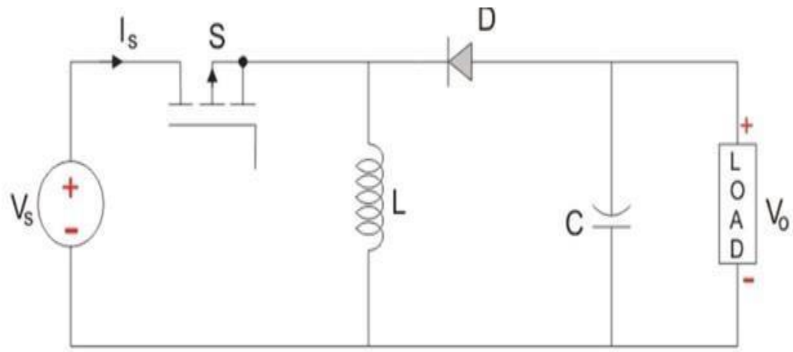


Figure 3.7.1 Buck- Boost converter circuit

- 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

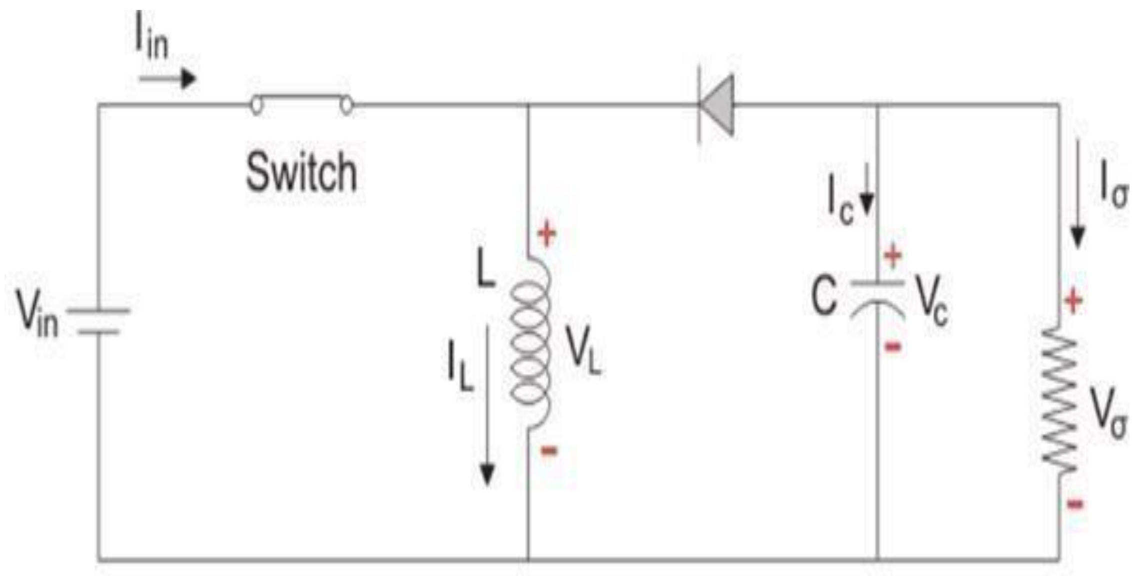


Figure 3.7.2 Buck- Boost converter- Mode I circuit

[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

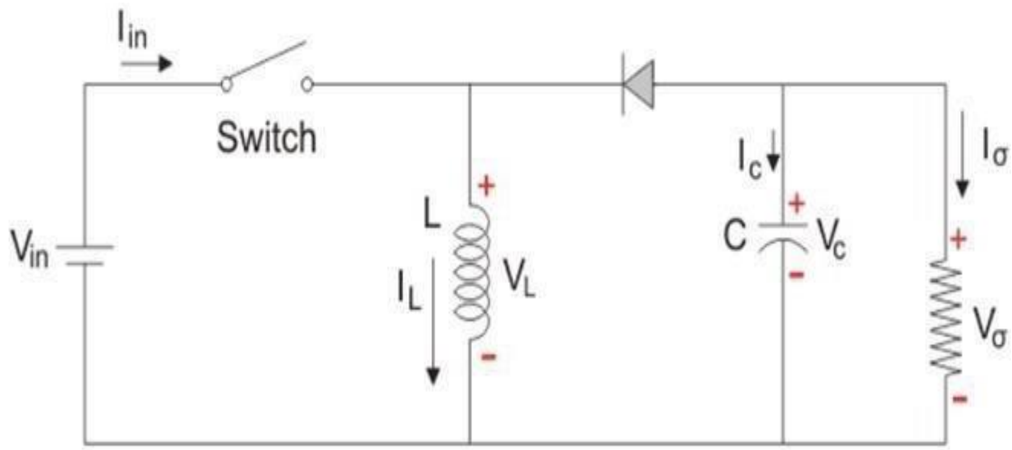


Figure 3.7.3 Buck- Boost converter- Mode II circuit diagram

[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.

3.8 Resonant converter

A resonant converter is a type of electric power converter that contains a network of inductors and capacitors called a "resonant tank", tuned to resonate at a specific frequency.

There are multiple types of resonant

converter: Series resonant inverter

Parallel resonant

inverter Class E

Resonant Converter

Class E Resonant

Rectifier

Zero Voltage Switching Resonant

ConverterZero Current Switching

Resonant ConverterTwo Quadrant ZVS

Resonant Converter Resonant dc-link

inverter

Need for resonant converter

- Hard switching is based on on/off– Switching losses– Electromagnetic Interference (EMI) because of high dv/dt and di/dtSMPS sizedecreases with increasing switching frequency.
- Target is to use as high switching frequency as possible – Switchinglosses are reduced if voltage and/or current are zero during switching.

ZCS Resonant-Switch Converter

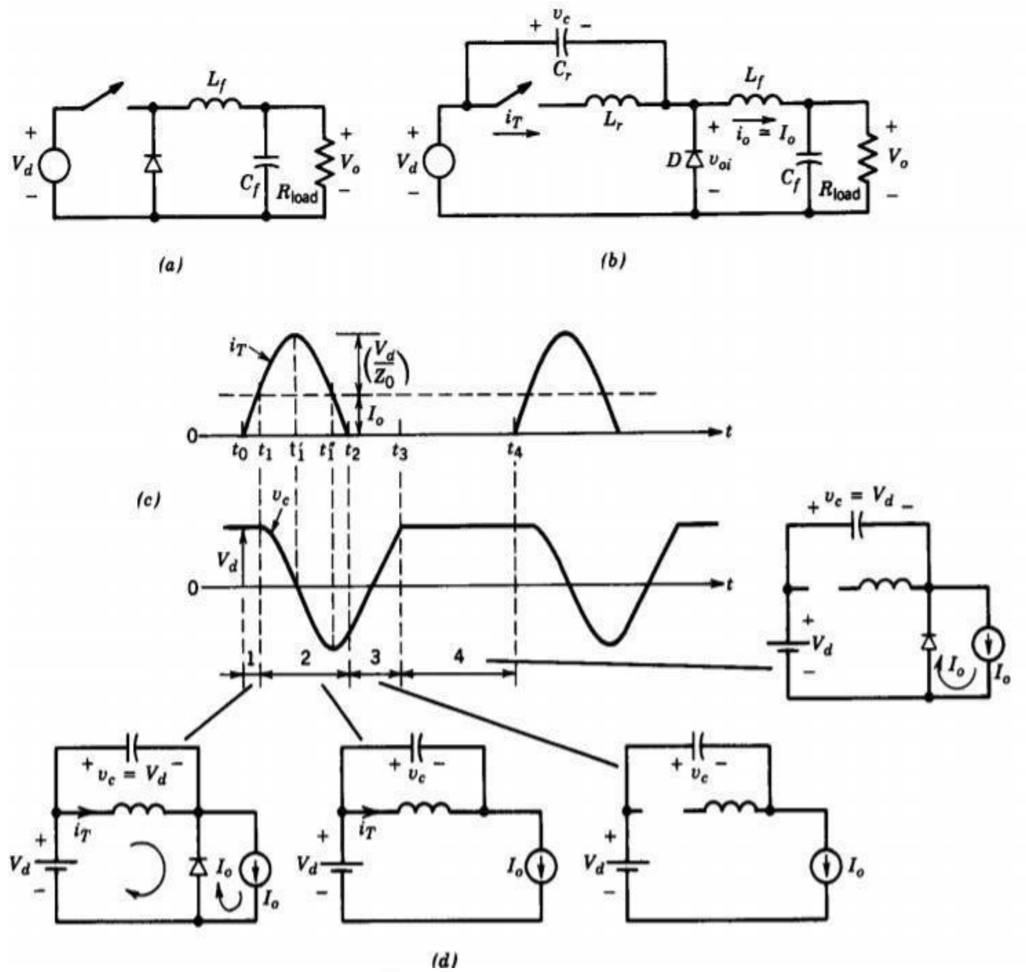


Figure 3.8.1 ZCS CONVERTER

Operation principle

- Current Io goes through the diode
- Cr is charged to the supply voltage Ud
- Switch is turned on –Diode D conducts untill at t1 current is equal to theload current
- Lr Cr is a resonant circuit discharging Cr

- At t2 current goes to zero and switch turns off
- Output current Io charges Cr to the supply
- voltage At t3 diode starts to conduct

ZVS Resonant-Switch Converter

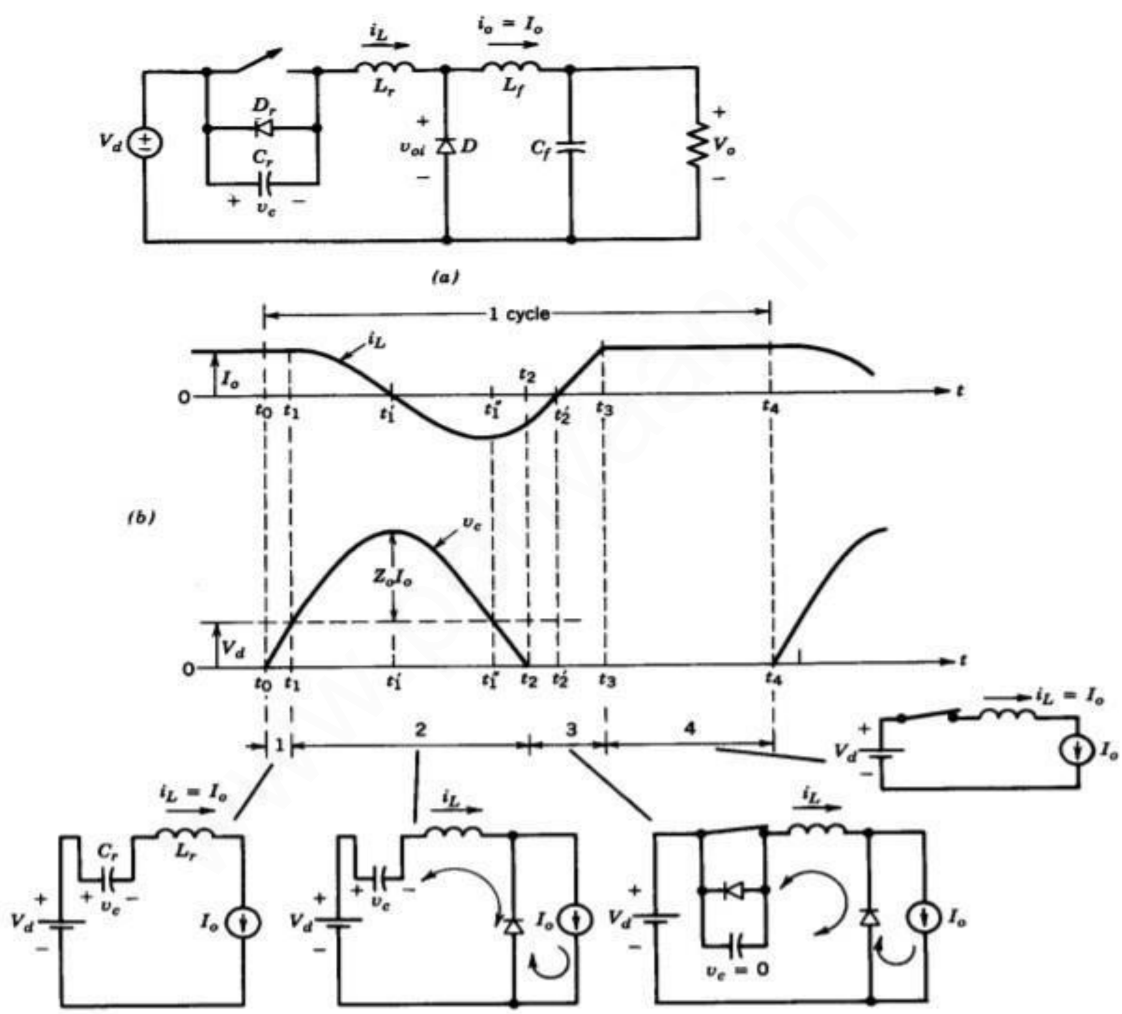


Figure 3.8.2 ZCS CONVERTER

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 295]*

3.9 BATTERY OPERATED VEHICLES

- **Definition:** The vehicles which get powered through a self-controlled battery for converting fuel into electricity, such type of vehicles are called battery powered vehicles or electrical vehicles. The lead acid battery is mostly used for powering the vehicles because of their low cost. The various types of DC and induction motors are used in battery powered vehicles.

Advantages of the battery powered vehicles:

It causes less pollution, It reduces noise pollution.

- The battery powered vehicles required less maintenance because it has no water cooling system to maintain, no filters, belts, or hoses to replace, or no oil to change.
- It is more reliable because of the presence of fuel injectors, compressors, pumps and valve.

Disadvantage of battery powered vehicles

- The battery powered vehicles are more expensive as compared tointernal combustion vehicles.
- The battery powered vehicles cannot go far on a single charge.
- Much longer time is required to charge a battery of battery poweredvehicles.

Let us consider a permanent magnet DC drive as shown in the figure below. The drive has chopper control and DC drive facility. The Lf and Cf are the filters which are used to filter the harmonics which is generated by the chopper. MS is the manual switch and RS is the reversal switch. The inductance L keep the ripple in motor current low.

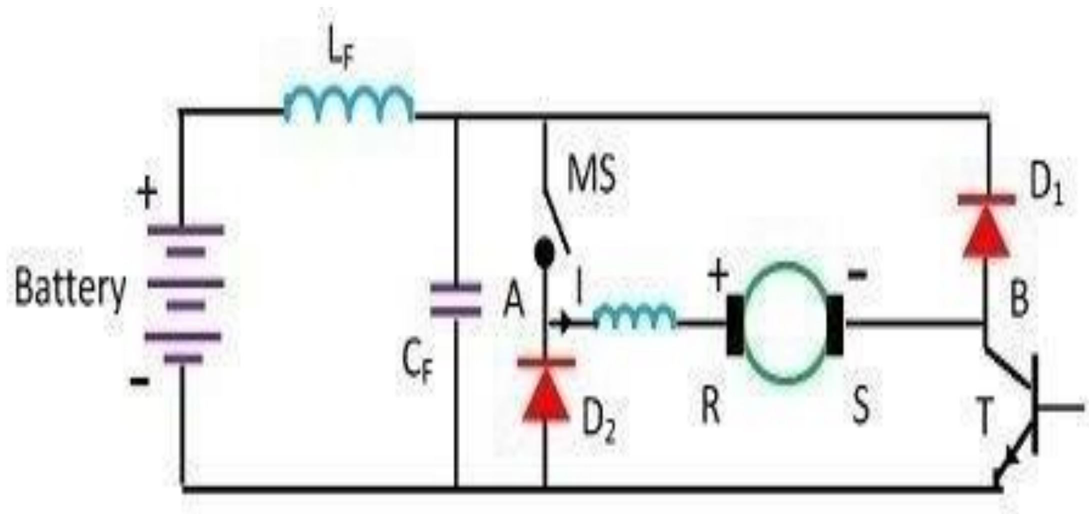


Figure 3.9.1 Dc Drive with Chopper Control

Motoring Operation

For motoring operation, the manual switch is kept close. The transistor switch operates at a constant frequency to obtaining variable DC voltage for starting and speed control. When the transistor is on the current flows through the source to L_f, MS, L, R, armature S and T. When the transistor is closed the current flows through S, D_1, MS, L and R.

Regenerative Braking Operation

For regenerative braking operation, the manual switch is kept open.The motor armature is reversed by the help of reversal switch which makes the B positive with respect to A. When the transistor is on the current flows through T, D_2 and L. When the transistor is closed the current flow through D_1, L_f and battery, D_2 and L and hence charge the battery.

4.1 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 as VSI (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 resistiveload is shown in the below figure.

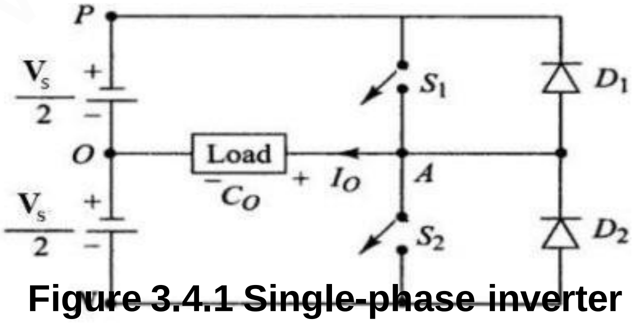


Figure 3.4.1 Single-phase inverter

[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 andD2 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 D1and 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 shownin the below figure.

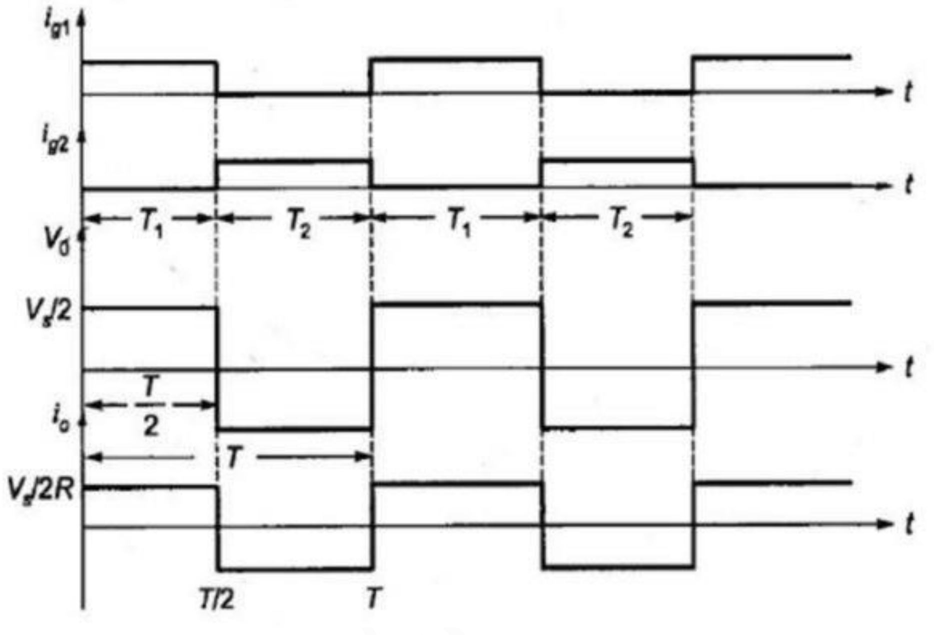


Figure 4.1.2 Single-phase inverter Waveform

4.2 Three Single Phase Inverter

- A three-phase inverter converts a DC input into a three-phase AC output.
- Its three arms are normally delayed by an angle of 120° so as to generate a three-phase AC supply.

The inverter switches each has a ratio of 50% and switching occurs after every T/6 of the time T and for 60°angle interval.

- The switches S1 and S4, the switches S2 and S5 and switches S3and S6 complement each other.
- The figure below shows a circuit for a three phase inverter. It is nothingbut three single phase inverters put across the same DC source.
- The pole voltages in a three phase inverter are equal to the pole voltagesin single phase half bridge inverter.
- Three-phase inverters are normally used for high power applications.
- The advantages of a three-phase inverter are:
- The frequency of the output voltage waveform depends on the switching rate of the switches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changingthe output phase sequence of the inverter.

Types of control signals can be applied to the switches:

1. 180° conduction
2. 120° conduction

180 DEGREE CONDUCTION MODE

- In this mode of conduction, every device is in conduction state for 180° where they are switched ON at 60° intervals. The terminals A, B and C are the output terminals of the bridge that are connected to the three-phase delta or star connection of the load.
- The operation of a balanced star connected load is explained in the diagram below. For the period 0° − 60° the points S1, S5 and S6 are in conduction mode.
- The terminals A and C of the load are connected to the source at its positive point. The terminal B is connected to the source at its negative point.
- In addition, resistances R/2 is between the neutral and the positive end while resistance R is between the neutral and the negative terminal.
- Output voltage can be controlled by varying the dc-link voltage.

In the three-phase inverter, each SCR conducts for 180° of a cycle. Thyristor pair in each arm, i.e. Tl , T4 ; T3, T6 and T5 , T2 are turned on with a time interval of180°.T1 conducts for 180°and T4 for the next 180° of a cycle.Thyristors in the upper group, i.e. T1, T3, T5 conduct at an interval of 120°. It implies that if T1 is fired at wt = 0°, then T3 must be fired at wt =120° and T5 at wt =240°.

Similarly for lower group of SCRs. On the basis of this firing scheme, a table is prepared .In this table, first row shows that T1 from upper group conducts for 180°, T4 for the next 180° and then again T1 for 180 ° and so on.

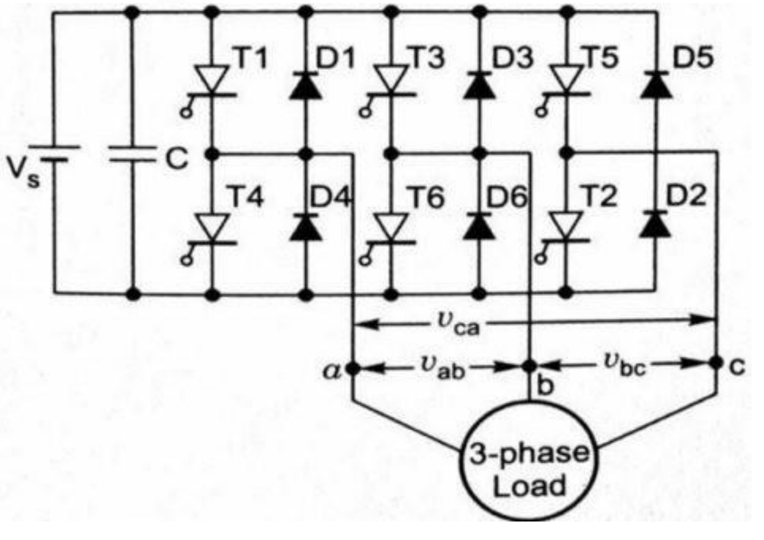
In the second row, T3 from the upper group is shown to start conducting 120° after T1 starts conducting. After T3 conduction for 180°,T6 conducts for the next 180 ° and again T3 for the next 180 ° and so on.

In the third row, T5 from the upper group starts conducting 120° after T3 or 240° after T1. After T5 conduction for 180°, T2 conducts for the next 180°,T5 for the next 180° and so on.

The table shows that T5, T6, T1 should be gated for step I ; T6, T1, T2 for step II T1, T2, T3 for step III; T2, T3, T4 for step IV and so on. Thus the sequence of firing the thyristors is T1, T2, T3, T4, T5, T6 ;
T1, T2 It is seen
from the table that in every step of 60° duration, only three SCRs are conducting-one from upper group and two from the lower group or two from the upper group and one from the lower group.

The load voltage is vab =vcb= Vs in magnitude

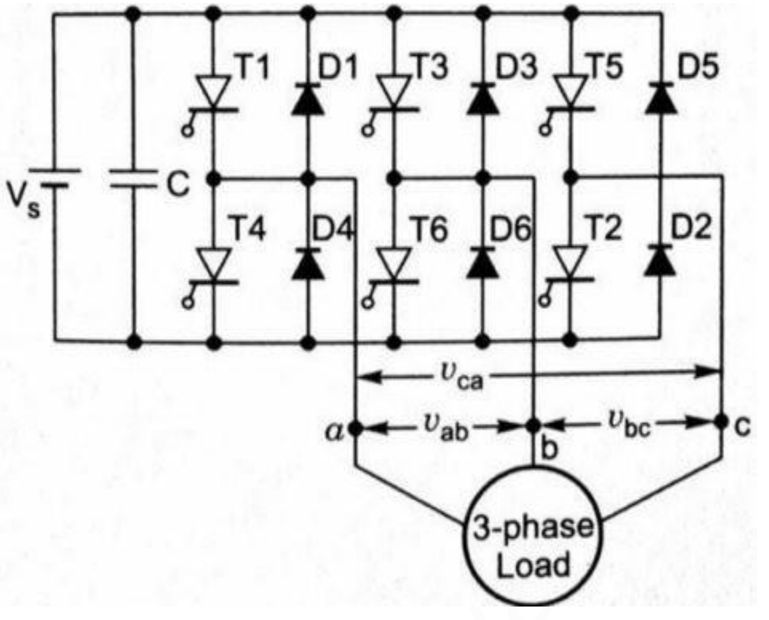
THREE PHASE INVERTER- 180 DEGREE CONDUCTION



- In the three phase inverter of each switch conduct 180° of cycle, thyristor pair in each arm i.e. S1, S4; S3, S6 and S5, S2 are turned on with a time interval of 180°. It means that S1 conduct for 180° and S4 for the next 180° of a cycle.

- Switch in the upper group i.e. S1, S3, S5 conduct at an interval of 120°. It implies that if S1 is fired at $\omega t=0°$, then S3 must be fired at $\omega t=120°$ and S5 at $\omega t=240°$. Same is proved lower group of switches.

Three Single Phase Inverter (120° conduction)



The power circuit diagram of this inverter is the same as that 180 ° mode.

- For the 120-degree mode VSI, each thyristor conducts for 120° of a cycle.
- Like 180° mode, 120° mode inverter also requires six steps, each of 60°duration, for completing one cycle of the output ac voltage.
- For this inverter a table giving the sequence of firing the six thyristors is prepared as shown in the top of Fig.
- In 120-degree mode VSI, each thyristor conducts for 120° of a cycle. Like 180° mode, 120° mode inverter also requires six steps, each of 60° duration, for completing one cycle of the output ac voltage.

- Tl conducts for 120° and for the next 60°, neither T1 nor T4 conducts. Now T4 is turned on at wt =180 ° and it further conducts for 120°, i.e. from wt =180° to wt =300°. This means that for 60° interval from wt =120° to wt = 180°, series connected SCRs T1, T4 do not conduct. At wt = 300°, T4 is turned off, then 60° interval elapses before T1 is turnedon again at wt =360°.

- In the second row, T3 is turned on at wt =120° as in 180° mode inverter. Now T3 conducts for 120°, then 60° interval elapses during which neither T3 nor T6 conducts. At wt =300°, T6 is turned on, it conducts for 120° and then 60° interval elapses after which T3 is turned on again.

- The third row- is also completed similarly. This table shows that T6, Tl should be gated for step I;T1, T2 for step II ; T2, T3 for step III and so on.

- The sequence of firing the six thyristors is the same as for the 180° mode inverter.

- During each step, only two thyristors conduct for this inverter - one from the upper group and one from the lower group ; but in 180° mode inverter, three thyristors conduct in each step.

- Load is assumed to be resistive and star connected.

- During step I, thyristors 6, 1 are conducting and as such load terminal a is connected to the positive bus of dc source whereas terminal b is connected to negative bus of dc source, Fig. 8.23 (a). Load terminal c is not connected to dc bus.

- It is seen from Fig. that phase voltages have one positive pulse and one negative pulse (each of 120 ° duration) for one cycle of output alternating voltage. The line voltages, however, if,. have six steps per cycle of output alternating voltage.

4.3 VOLTAGE CONTROL OF INVERTERS

- The various methods for the control of output voltage of inverters can beclassified 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.

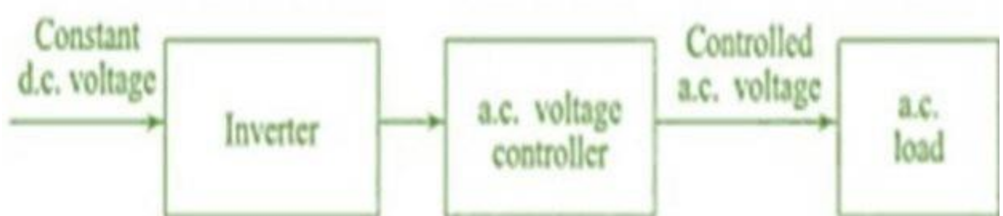


Fig 4.4.1. External Control of Output Voltage

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, uncontrolledrectifier and chopper, ac voltage controller and uncontrolled rectifier as shown in Figure .

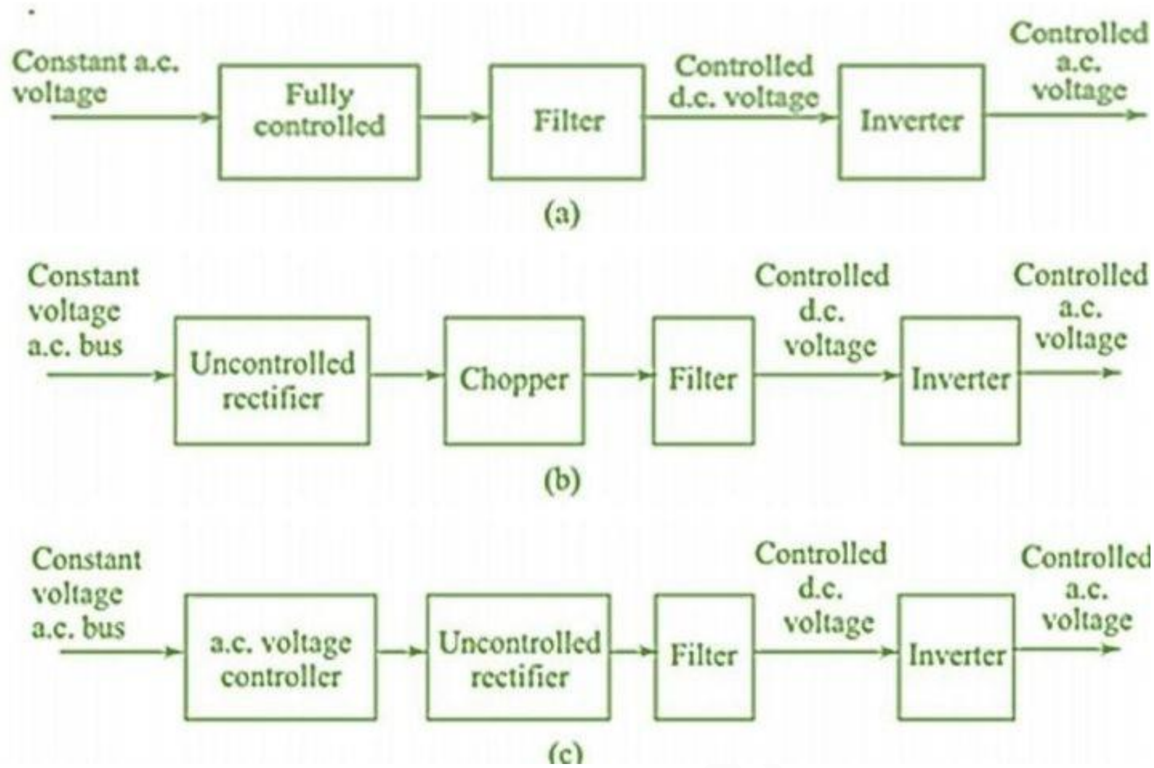


Fig 4.4.2. External Control of Input Voltage

[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.

4.4 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.

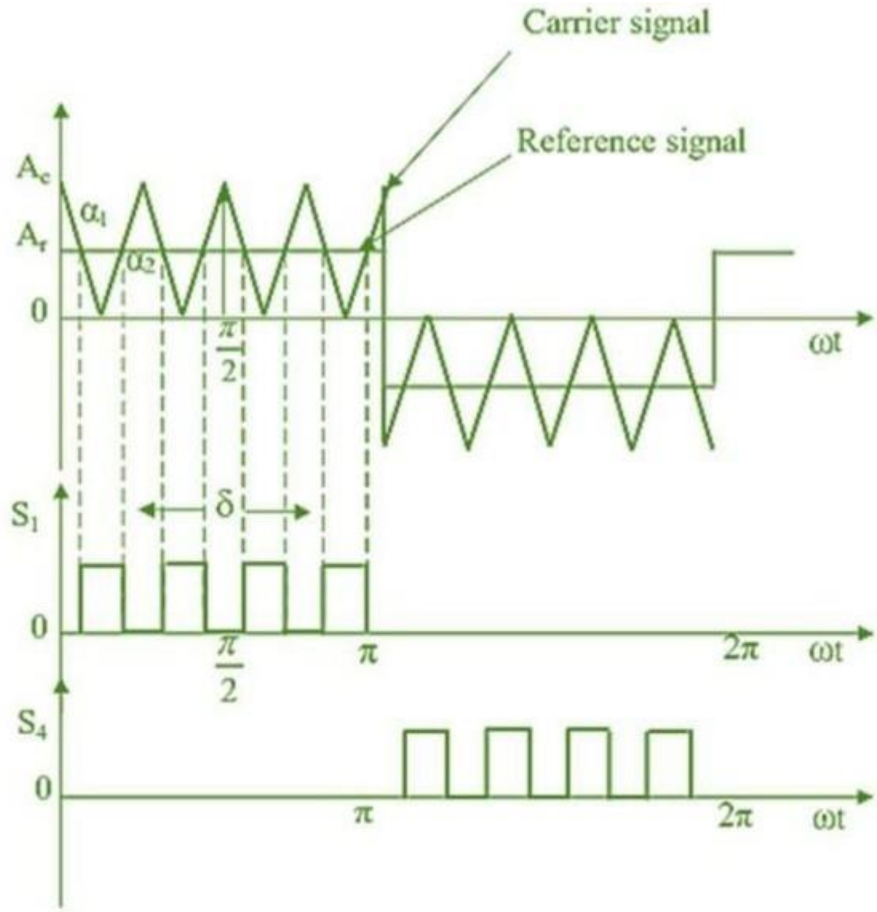


Figure 4.5.1 Multiple pulse width modulation

[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.

4.5 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.

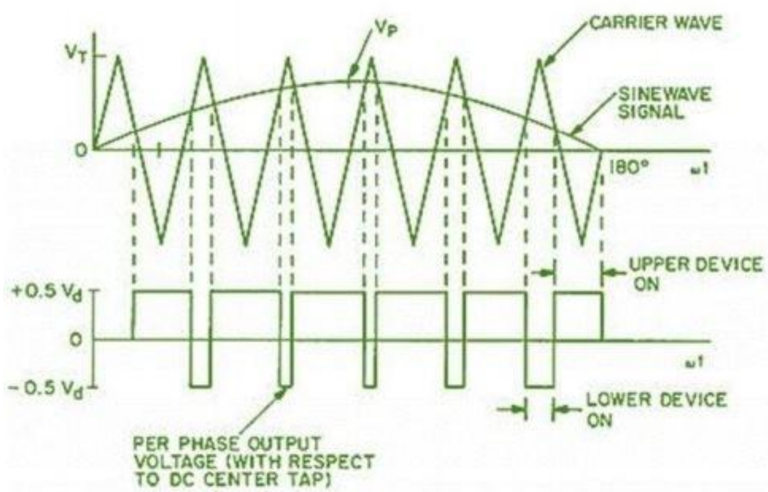


Figure 4.6.1. Multiple pulse width

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.

4.6 PWM CONTROL: MODIFIED Sinusoidal Pulse Width Modulation

When considering sinusoidal PWM waveform, the pulse width does not change significantly with the variation of modulation index. The reason is due to the characteristics of the sine wave. Hence this sinusoidal PWM technique is modified so that the carrier signal is applied during the first and last 600 intervals per half cycle as shown in Figure 5.4. The fundamental component is increased and its harmonic characteristics are improved. The main advantages of this technique is increased fundamental component, improved harmonic characteristics, reduced number of switching power devices and decreased switching losses.

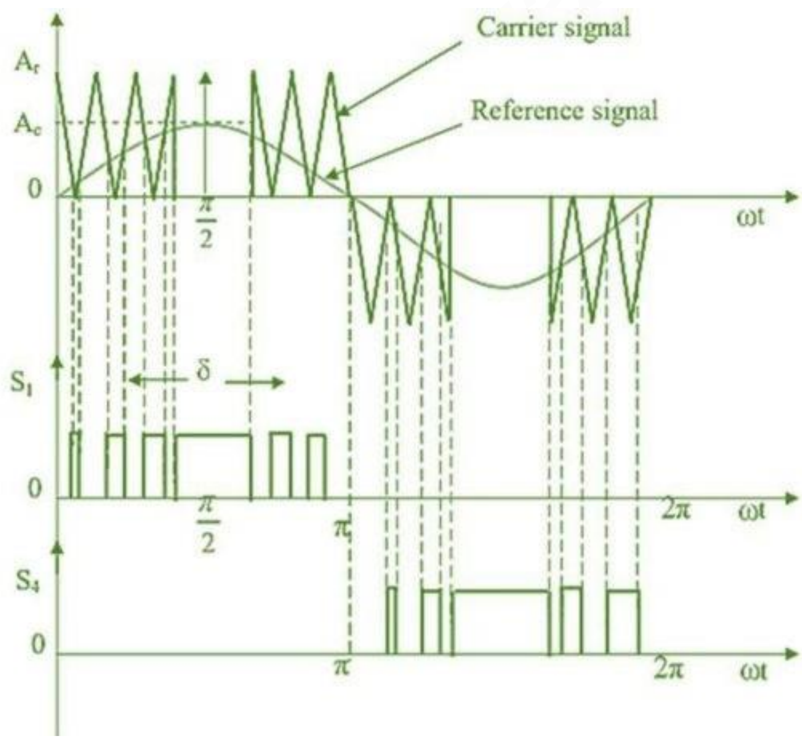


Figure 4.7.1 Modified Sinusoidal

Advantages of PWM

1. The output voltage control with method can be obtained without any additional components.

With this method, lower order harmonic can be eliminated or minimizedalong with it’s output voltage control. It reduces the filtering requirements.

4.7 INTRODUCTION TO SPACE VECTOR MODULATION

❖ SVM is another direct digital PWM technique

❖ It has become a basic power processing technique in three-phase converters.

❖ SVM based converter can have a higher output voltage output.

❖ The output voltage is about 15% more in case of SVPWM .

❖ The current and torque harmonics produced are much less .

❖ The maximum peak fundamental magnitude of the SVPWM technique is about 90.6% of the inverter capacity

❖ SVPWM is accomplished by rotating a reference vector around the state diagram, which is composed of six basic nonzero vectors forming a hexagon. The reference is sampled at fixed interval and is formed using the voltage vectors of the particular sector in which reference lies along with zero vectors.

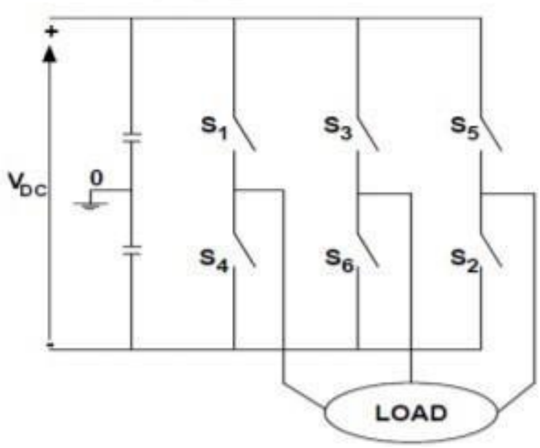


Figure 4.8.1 Basic diagram of two level three phase inverter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 358]*

From fig.It has six switches (S1-S6) and each of these is represented with an IGBT switching device. A, B and C represents the output for the phase shifted sinusoidal signals. Depending on the switching combination the inverter will produce different outputs, creating the two-level signal (+Vdc and -Vdc).

The switches 1,3 and 5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (Va, Vb, Vc)is positive (+Vdc). If the upper switches are zero, then the terminal voltage iszero.

The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100,
110, 110, and 111.

This means that there are 8 possible switching states, for which two of them are zero switching states and six of them are active switching states. These are represented by active (V1-V6) and zero (V0) vectors . The zero vectors are placed in the axis origin.

Next step is to calculate the dwell times or time for which we have to provide voltage vectors, so as to generate the Vref at that particular point of time. Vref can be found with two active and one zero vector. For sector 1 (0 to pi/3), Vref can be generated with V0, V1 and V2 as shown in fig.3. Vref in terms of the duration time can be considered as:

Vref *Ts= V1*T1+V2*T2+ V0*T0 ,Where Ts is the sampling time (3.3 *104sec) and T1, T2 andT0 are the time periods for which V1, V2 andV0 are applied for particular sample.

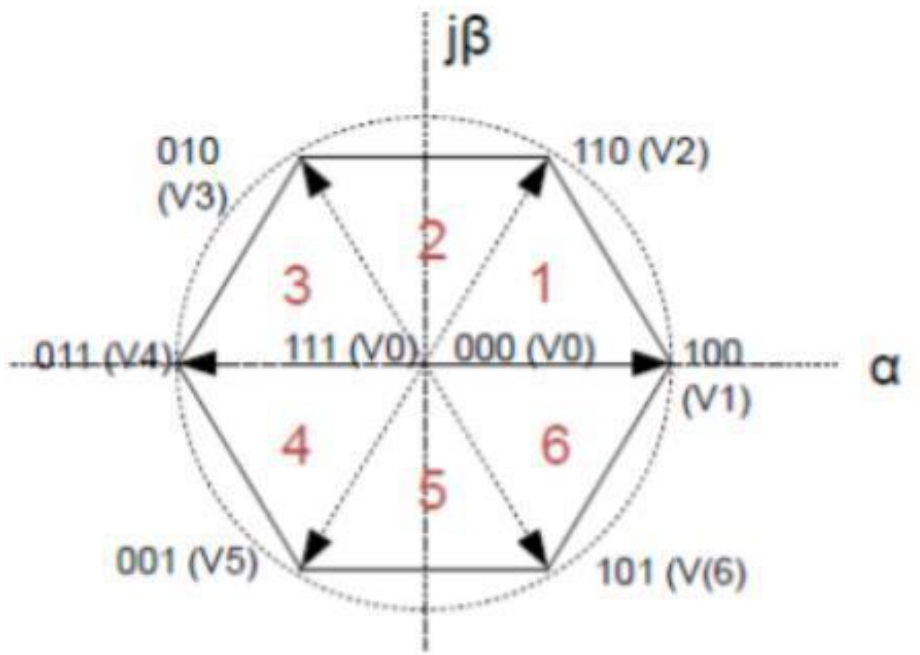


Figure 4.8.2 Space vector diagram of two level three phase inverter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 359]*

4.8 SINGLE-PHASE CURRENT SOURCE INVERTER

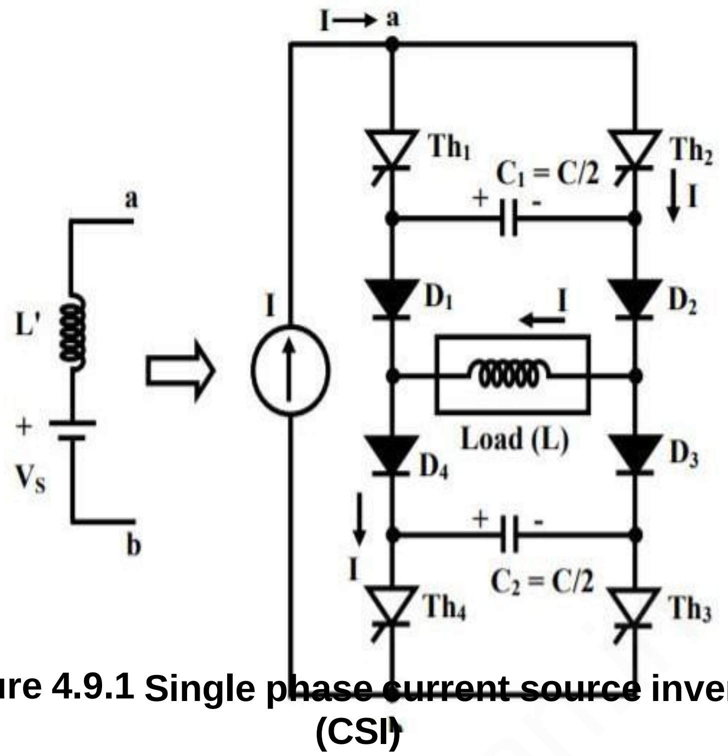


Figure 4.9.1 Single phase current source inverter (CSI)

[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.

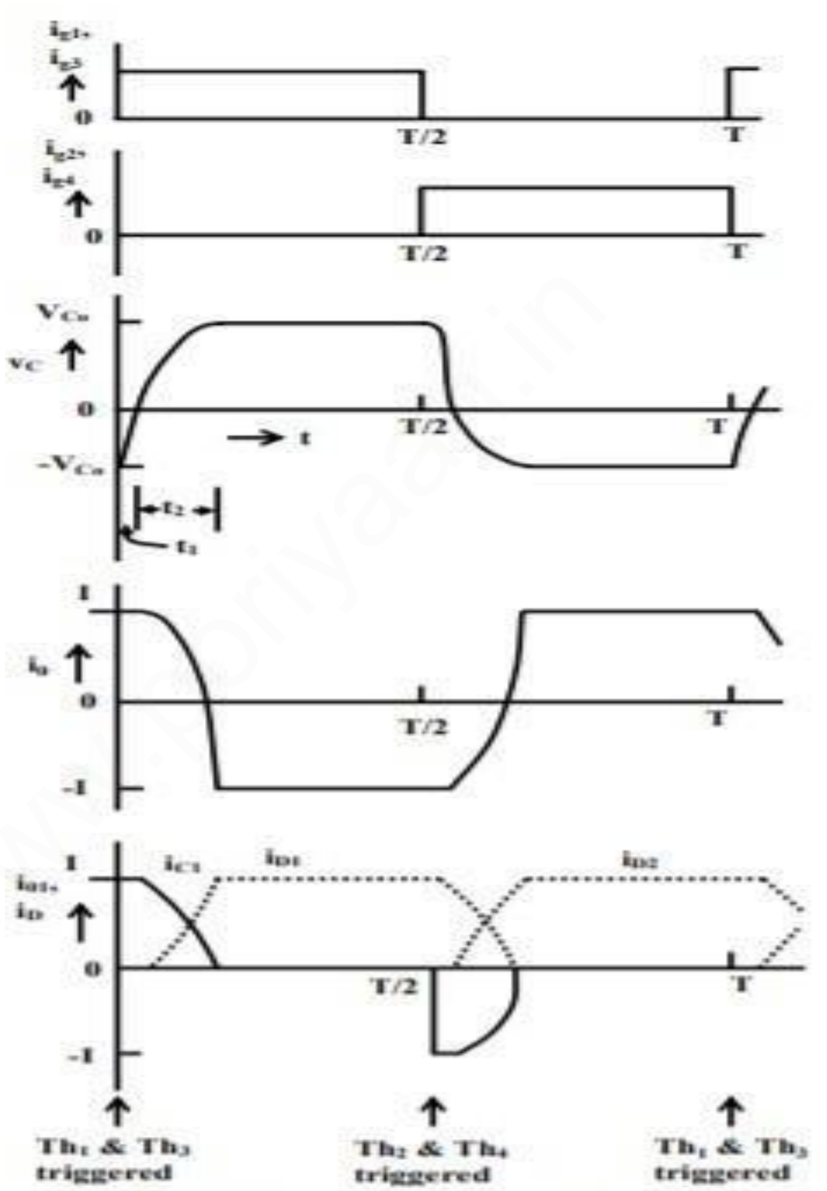


Figure 4.9.2 wave forms of Single phase current source

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.

4.9 Induction Heating

The working principle of the induction heating process is a combined recipe of Electromagnetic induction and Joule heating. Induction heating process is the non- contact process of heating an electrically conductive metal by generating eddy currents within the metal, using electromagnetic induction principle. As the generated eddy current flows against the resistivity of the metal, by the principle of Joule heating, heat is generated in the metal.

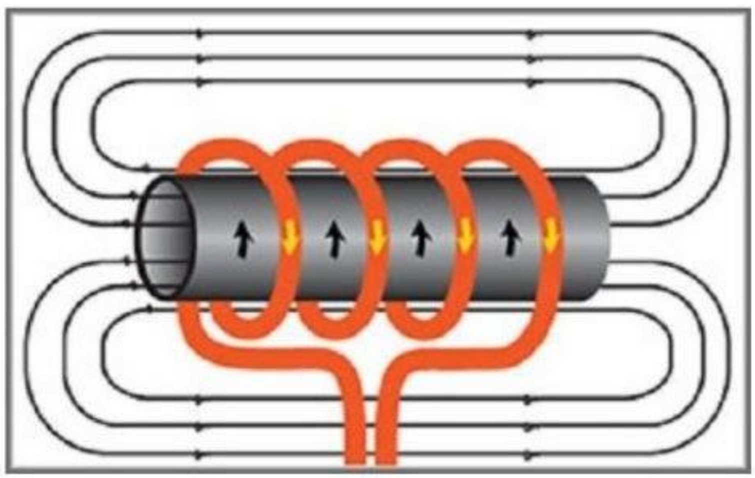


Figure 4.10.1 Induction Heating

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 436]

Principle of Induction Heating

Knowing the Faraday's law is very useful for understanding the working of induction heating. According to Faraday's law of electromagnetic induction, changing the electric field in the conductor gives rise to an alternating magnetic field around it, whose strength depends on the magnitude of the applied electric field. This principle also works vice-versa when the magnetic field is changed in the conductor. So, the above principle is used in the inductive heating process. Here a solid state RF frequency power supply is applied to an inductor coil and the material to be heated is placed inside the coil. When Alternating current is passed through the coil, an alternating magnetic field is generated around it as per Faraday's law. When the material placed inside the inductor comes in the range of this alternating magnetic field, eddy current is generated within the material.

Induction Heating Circuit Diagram

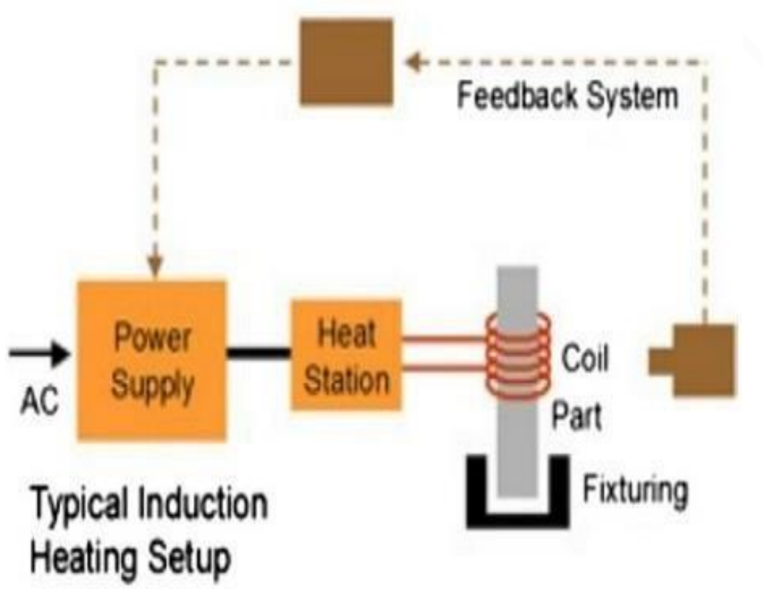


Figure 4.10.2 CIRCUIT DIAGRAM

The setup used for the induction heating process consists of an RF power supply to provide the alternating current to the circuit. A copper coil is used as inductor and current is applied to it. The material to be heated is placed inside the copper coil.

By altering the strength of the applied current, we can control the heating temperature. As the eddy current produced inside the material flows opposite to the electrical resistivity of the material, precise and localized heating is observed in this process.

Besides eddy current, heat is also generated due to hysteresis in magnetic parts. The electrical resistance offered by a magnetic material, towards the changing magnetic field within the inductor, cause internalfriction. This internal friction creates heat.

As the induction heating process is a non-contact heating process, the material to be heated can be present away from the power supply or submerged in a liquid or in any gaseous environments or in a vacuum. This type of heating process doesn’t require any combustion gases.

4.10 UPS – UNINTERRUPTIBLE POWER SUPPLY

A UPS is an uninterruptible power supply. It is a device which maintains a continuous supply of electrical power, even in the event of failure of the mains (utility) supply. A UPS is installed between the mains supply and the equipment to be protected.

UPS are used to safeguard various types of equipment. One of the common uses is computers, particularly in data centres and the critical equipment of large organizations.

A UPS works by converting the mains alternating current (a.c.) supply to a direct current (d.c.) voltage. The part of the UPS which does this is called the rectifier. Output from the rectifier is then used to charge batteries, which can supply power during a mains failure. The d.c. voltage from the rectifier (or batteries during mains failure) is the converted back to a.c. by the UPS inverter and supplies power to the equipment.

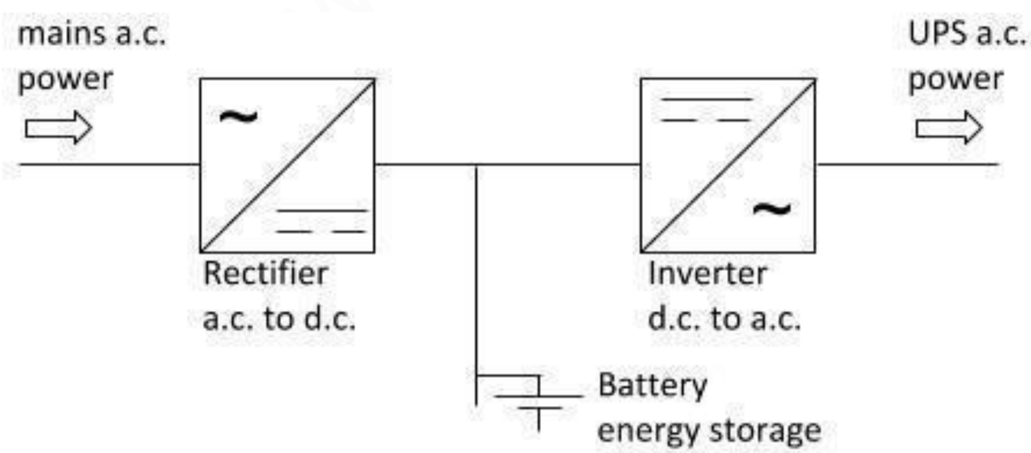


Figure 4.11.1 CIRCUIT DIAGRAM

In addition to protecting equipment in the event of mains failure, because the first convert the a.c. to d.c, a UPS has the added benefit of being able to solve other problems related to power supply quality. These include voltage dips, harmonics,frequency variations, etc.

UPS units and systems come in various sizes, from 1 or 2 kVA all they way to the MVA range. On of the problems and limiting factors with how large a UPS can be is the amount of batteries required. These can become substantial, costing a lot and taking up significant amounts of space. For smaller UPS the batteries are normally internal to the device, while for larger systems the batteries are mounted externally on racks or in cabinets.

Another element to batteries is the discharge time. Any battery backed UPS will only be rated for a certain period (5 minutes, 15 minutes, 30 minutes, etc.). For this reason, most UPS applications are centred around providing sufficient power for a limited time to enable any necessary actions - safely shut down the equipment, change over to generator power, etc.

UPS Configurations

The arrangement of rectifier, inverter, battery and other components can be carried out in different ways. Each arrangement has advantagesand disadvantages.Normally the more robust the configuration, the more expensive the UPS.

UPS are classified in two basic ways - standby and on-line.In a standby UPS, power is normally supplied directly from the mains and the inverter only switched in if the mains fails. This can have the advantages of cheaper cost and higher efficiencies. On-line UPS always supply the load via the inverter. These are more expensive, but because the inverter is always used they can resolve many power quality issues.

5.4 AC VOLTAGE CONTROL STRATEGY

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

1. Phasecontrol
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 voltage

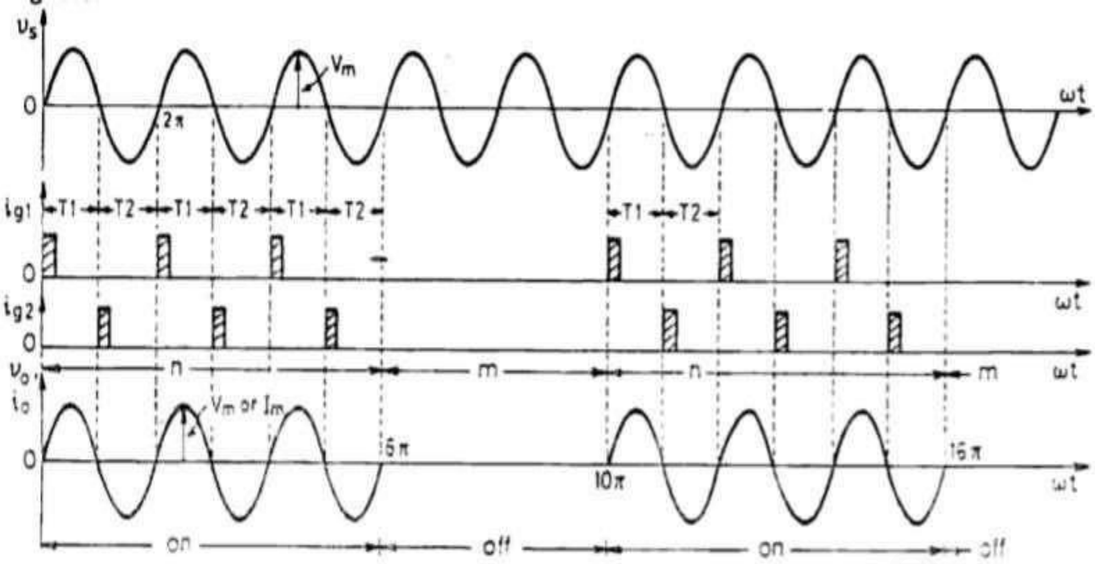


Figure 5.4.1 Integral cycle control

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

5.7 CYCLO CONVERTERS

Cyclo converters are frequency changers that convert AC power of specific frequency and voltage to different frequency and voltage of AC power without any intermediate DC link. (usually lower frequency).

A cyclo converter is a naturally commutated converter in which the output frequency and voltage can be controlled independently and continuously using a control circuit. Therefore, unlike other converters, it is a single stage frequencyconverter.

Figure 5.7.1 Block diagram of cyclo converter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 414]*

Mainly there are two types according to the output frequency which are

(1) Step-up cyclo converters

(2) Step-down cyclo converters

Step Up cyclo converter − These types use natural commutation and give an output at higher frequency than that of the input.

Step Down cyclo converter − This type uses forced commutation and Result in an output with a frequency lower than that of the input.

• Cyclo converters are further classified into three categories −

1. Single phase to single-phase − This type of cyclo converter has two full wave converters connected back to back. If one converter is operating the other one is disabled, no current passes through it.

2. Three-phase to single-phase − This cyclo converter operates in four quadrants that is (+V, +I) and (−V, −I) being the rectification modes and (+V, −I) and (−V,+I) being the inversion modes.

3. Three-phase to three-phase − This type of cyclo converter is majorly used in AC machine systems that are operating on three phase induction and synchronous machines.

- In case of step-down cyclo-converter, the output frequency is limited to a fraction of input frequency, typically it is below 20Hz in case 50Hz supply frequency. In this case, no separate commutation circuits are needed as SCRs are line commutated devices.

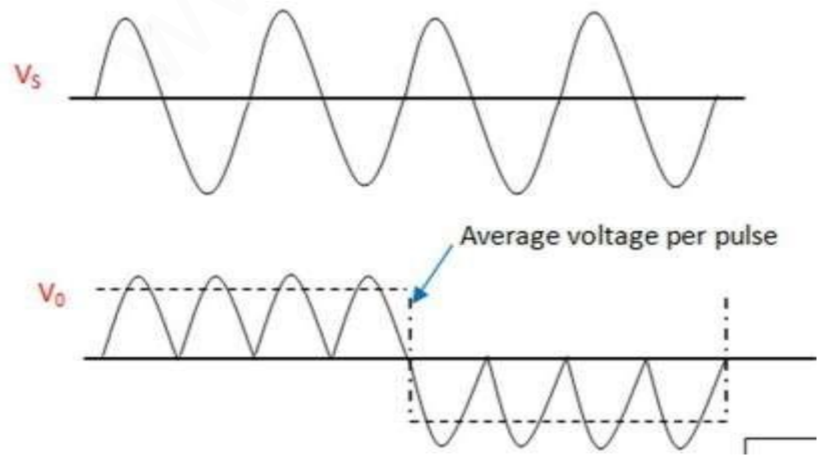


Figure 5.7.2 Voltage waveforms of stepdown cycloconverter

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.

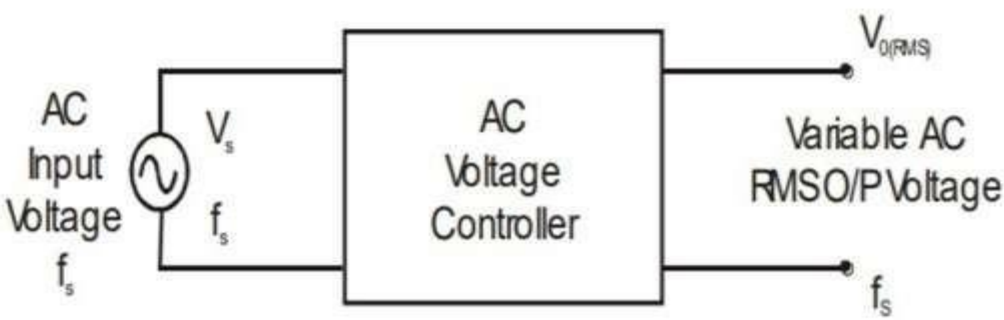


Figure 5.1.1 Block diagram of AC voltage controller

[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
- powercircuits. Inductionheating.
- 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).

5.10 MATRIXCONVERTER

A matrix converter is defined as a converter with a single stage of conversion. It utilizes bidirectional controlled switch to achieve automatic conversion of power from AC to AC. It provides an alternative to PWM voltage rectifier double sided.

Features of MatrixConverter

- Direct AC / AC Conversion.
- No DC Link
- Less bulky (compact motor drives) – Safer (hostile environments: aircraft, submarine…)
- Bidirectional power flow. 4 quadrant converter
- No restriction on input and output frequency within limits imposed by switching frequency
- Sinusoidal input and output currents waveforms • 9 bidirectional switches.

Standard: – Wind/Water Force Machines (blowers, boilers, incinerators), pumps,and general Industrial Machines.

• Specific Applications: – Compact or Integrated Motor Drives – Motor Drives for hostile environments (aircrafts, submarines) – AC/AC Power Conversions: wind energy, variable speed drives... AC / AC direct electrical power conversion

• MXN , inputs & outputs. Figure corresponds to the 3 X 3

• Variable frequency and variable voltage

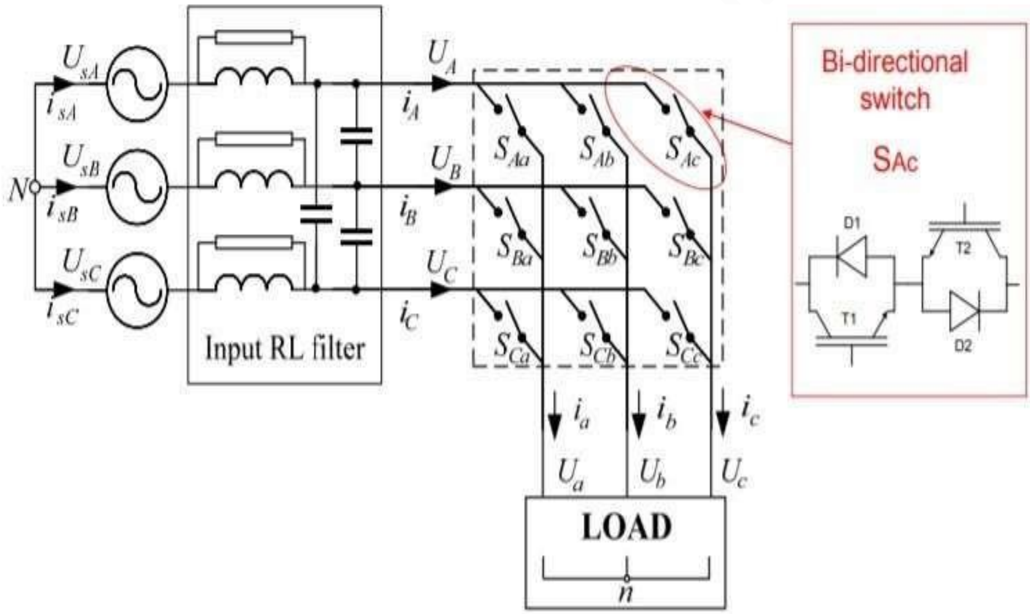


Figure 5.10.1 Matrix converter-circuit diagram

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 418]*

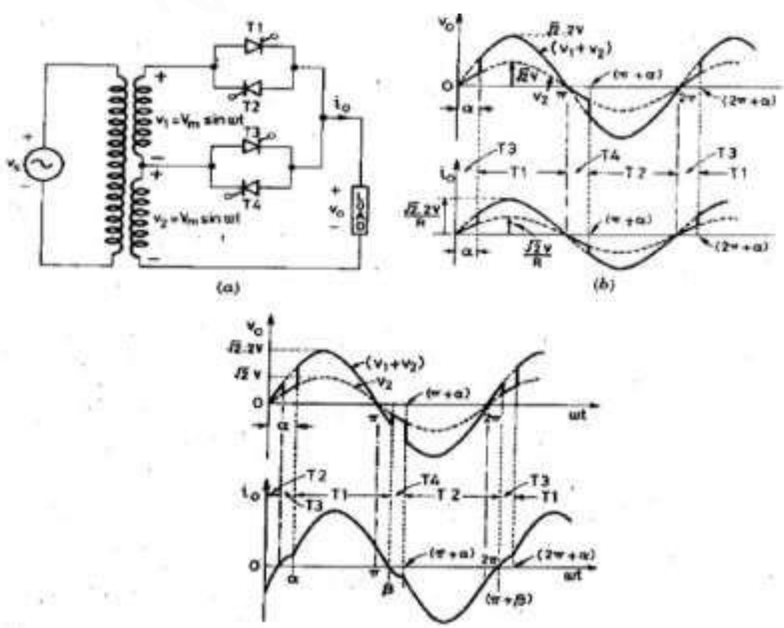
5.6 Multistage sequence control

- Whentwoormoresequencecontrolstagesareconnected, it ispossible to have an improvement in power factor and further reduction in THD (total harmonic distortion). An n-stage sequence control converter has n windings in the transformer secondary part with each rated e_S/n (the source voltage).

Two stage sequence control of AC voltage regulators

- Sequence control of ac voltage regulators are used for reduction of harmonics and the improvement of system power factor in the input current & the output voltage. Sequence control of ac regulators means the use of two or more stages of voltage controllers in parallel for the regulation of output voltage. The sequence control of ac voltage controllers can be used as voltage controllers in supply systems & for the speed control of induction motors. These types of controllers are known as synchronous tap changers or transformer tap changers.

Figure 5.6.1.two stage sequence controlled ac voltage controller



[*Source:* "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 409*]

Thyristors are used as static switches for on load changing of transformer connections. Static connections changers have the advantage of very fast switching action the changeover can be controlled to cope with the load condition & is smooth. When thyristors T3 & T4 are alternately fired with delay angle of $\alpha=0$, the load voltage is Vo=V1. If full output voltage is required, thyristors T1 & T2 are alternately fired with delay angle of $\alpha=0$ and full voltage I Vo=V1+V2. The gating pulse of thyristors can be controlled to vary the load voltage. The RMS value of load voltage Vo can be varied within three possible ranges 0 < Vo < V1, V1 < Vo < (V1+V2).

Case1: 0 < Vo < V1

To vary the RMS voltage within this range, T1 & T2 are turned off. T3 & T4 can be operated as a single-phase ac voltage regulator. The RMS load voltage is given by, $Vo=V1[1/\pi(\pi-\alpha+(\sin 2\alpha/2))]1/2$ and the firing angle range is $0<\alpha<$ Vo < (V1+V2) T3 & T4 are turned off. T1 & T2 operate as a single phase ac voltage regulator, the load voltage is $Vo=(V1+V2)[1/\pi(\pi-\alpha+(\sin 2\alpha/2))]1/2$.

Case2: V1 < Vo < (V1+V2)

- T3 is turned on at $\omega t=0$ and the secondary voltage V1 appears across the load. If T1 is turned on at $\omega t=\alpha$, T3 is reverse biased due to secondary voltage V2 & T3 is turned off. The voltage across the load is (V1+V2). At $\omega t=\pi$, T1 is self commutated & T4 is turned on. The secondary voltage V1 appears across the load until T1 is fired $\omega t=\pi+\alpha$, t4 is turned off due to reverse voltage V2 and the load voltage is (V1+V2). At $\omega t=2\pi$, T2 is self commutated, T3 is turned on again the cycle is repeated. This type of Controller is also called synchronous tap changer.

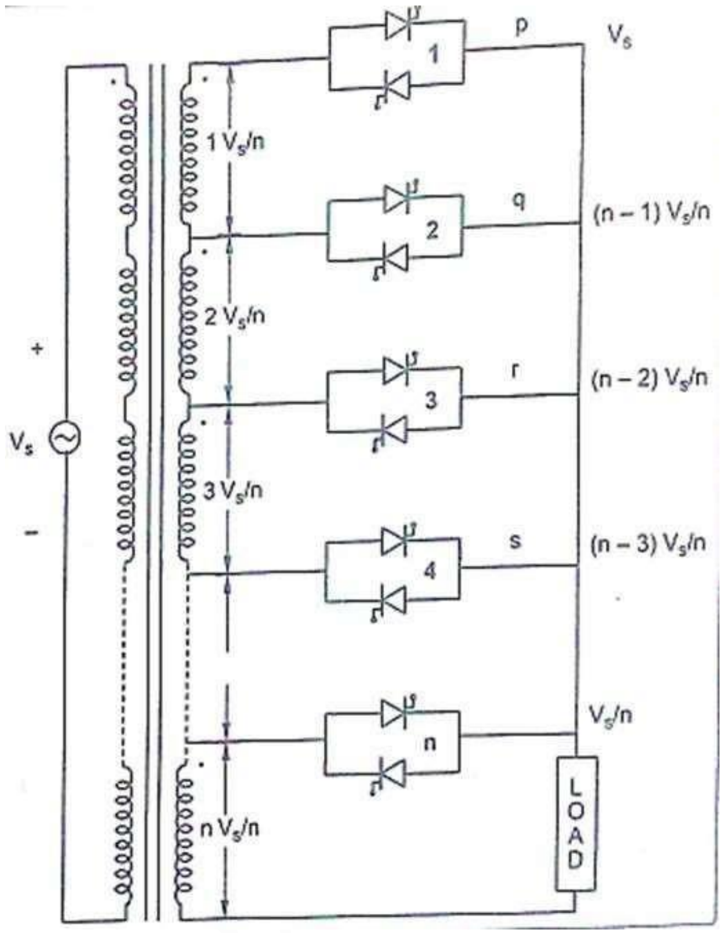


Figure 5.6.2 Multi stage sequence controlled ac voltage controller

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 409]*

The transformer has n secondary windings. Each secondary is rated for Vs/n, where Vs is the source voltage. The voltage of node p with respect to K is Vs.the load voltage at terminal Q is (n-1)V3/n and so on. If voltage control from Vsk=(n- 3)Vs/n to Vrk=(n-2)Vs/n is required, then SCR pair $ is triggerer at α=0 and firing angle of SCR pair3 is controlled from α= 0 to 180 and all other SCRs are kept off. Similarly for controlling the voltage from Vqk=(n-1)Vs/n to Vpk=Vs, SCR pair 2 is triggered at α=0, whereas for SCR pair 1,firing angle is varied from 0 to 180 keeping the remaining (n – 2) SCR pairs off. Thus the load voltage can be varied from Vs/n to Vs by an appropriate control of triggering the adjacent SCR pairs. The presence of harmonics in the output voltage depends upon the voltage variation. If this voltage variation is a small fraction of the total output voltage, the harmonic content in the output voltage is also small.

5.5 POWER FACTOR CONTROL

Power factor control, also known as correction of power factor, is the process of reducing the amount of reactive power. The power electronic device used in this case is called a power factor controller (PFC). From the power triangle (which comprises reactive, true and apparent power), the reactive power is at right angle (90°) to the true power and is used to energize the magnetic field. Although reactive power does not have a real value in electronic equipment, the bill for electricity comprises real and reactive power costs. This makes it necessary to have power factor controllers in electronicdevices.

Power factor (k) is defined as the ratio of the real power (in kW) to the reactive power (in kVAr). Its value ranges from 0 to 1. If a device has a power factor of 0.8 and above, it is said to be using power efficiently. Incorporating a PFC ensures the power factor ranges from 0.95 to 0.99.

Power factor controllers are mainly in industrial equipment to minimize reactive power generated by fluorescent lighting and electric motors. To ensure power factor is improved without causing harmonic

Distortion, the conventional capacitors should not be used Instead, filters combination of capacitors and reactors for harmonic suppression are used. The figure below shows a harmonic filter.

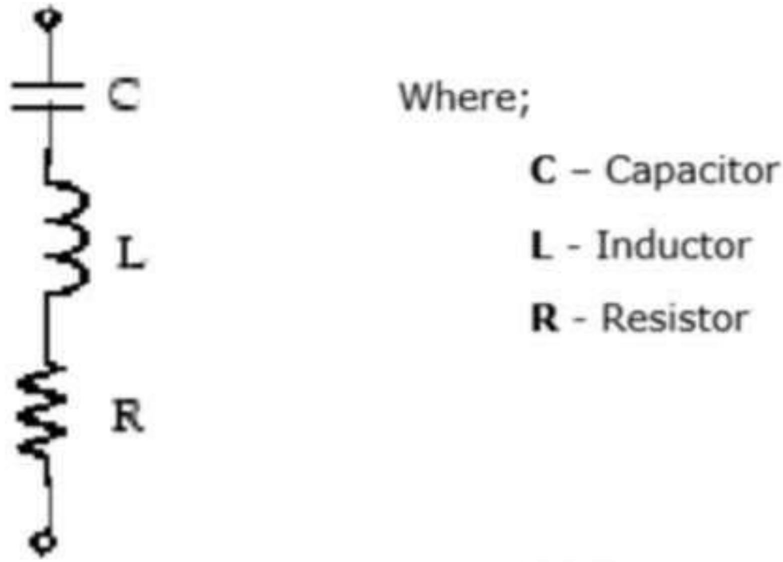


Figure 5.5.1Harmonic filter.

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 432]*

The above type of harmonic filter is referred to as a single tuned filter. A quality factor Q of this filter is defined as quality factor of its reactance (XL) at Q (tuning frequency) where Q is given by (nXL/R).

5.8 Single phase to Single phase Cyclo converter

It consists of back to back connected controlled rectifiers whose output voltage and frequency can be controlled by tuning firing angles of rectifiers. With respect to the connection of rectifiers, its structure can comprise of half-wave or full-wave bridge.

- It consists of two full-wave, fully controlled bridge thyristors, where each bridge has4 thyristors, and each bridge is connected in opposite direction (back to back) such that both positive and negative voltages can be obtainedas shown in figure below. Both these bridges are excited by single phase, 50 Hz AC supply.

- Bridge 1- +vegroupconvertersuppliesloadcurrentinthe+vehalfof theoutputcycle andbridge 2 -ve groupconverter supplies loadcurrent in the negative half of the output cycle.

- Thetwobridgesshouldnotconducttogetherasthiswillproducea short circuit at the output.

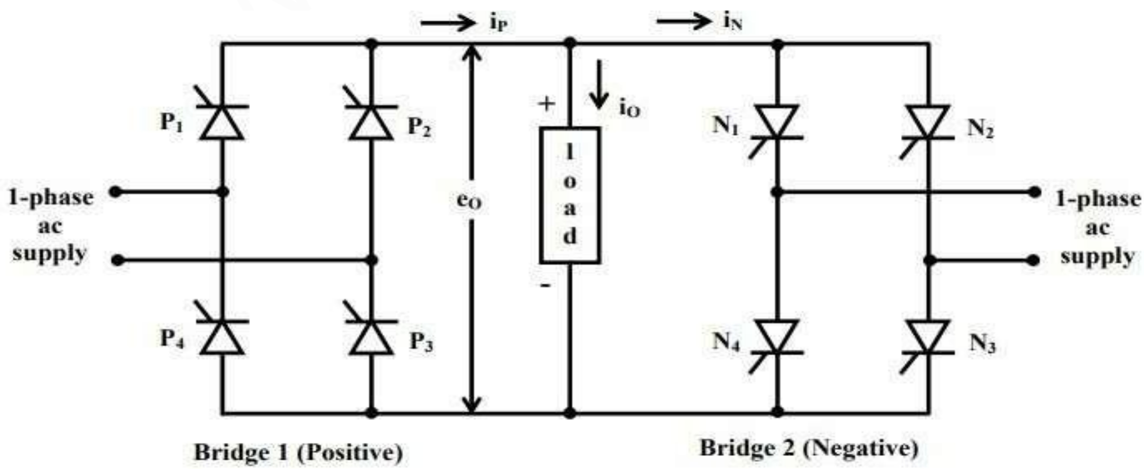


Figure 5.8.1 Single phase bridge type cyclo converter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 415]*

OPERATION

MODE-1 : To get Positive half cycle of Output Voltage

- During positive half cycle of the input voltage, positive converter (bridge-1) is turned ON and it supplies the load current. During the +ve half cycle, 0 to π ,SCR P1 & P3 are forward biased and are triggered at ωt=α. Then P1 & P3 are on state & the output is positive. The current flows from V+-P1-R-P3-V-. atωt=π, P1 & P2 areturned off. It rectifies the input voltage and produce unidirectional output voltage as we can observe four positive half cycles .

- During negative half cycle of the input, negative bridge is turned ON and it supplies load current. During –ve half of the cycle, π to 2π, SCR P3 & P4 are forward biased and is triggered at ωt=π+α. Then P2 & P4 are in on state. Again the output voltage & current is positive. Current flow is through V+-P3-R-P4-V-. at ωt=2π , SCR P2 & P4 are turned off due to natural commutation.

- Both converters should not conduct together that cause short circuit at the input.To avoid this, triggering to thyristors of bridge-2 is inhibitedduringpositivehalfcycleofloadcurrent, whiletriggering isapplied to the thyristors of bridge-1 at their gates. During negative half cycle of load current, triggering to positive bridge is inhibited while applying triggering to negative bridge.By controlling the switching period of thyristors, time periods of both positive and negative half cycles are changed and hence the frequency.

This frequency of fundamental output voltage can be easily reduced in steps, i.e., 1/2, 1/3, 1/4 and so on.

MODE-2: To get Negative half cycle of Output Voltage

- Now bridge 2 can be operated and the output is negative. During +ve half cycle 2π to 3π, SCR N1 & N3 are forward biased. It is triggered at ωt=2π+ α. Then it comes to on state. The current flows through B-N1-R-N3-C. the output voltage & current is negative. At ωt=3π SCR N1 & N3 are turned off due to natural commutation.

- During negative half cycle 3π to 4π, SCR N2 & N4 are forward biased. It is triggered at ωt=3π+α. Then it comes to on state. The current flows through C-N3-R-N4-B. now negative voltage & current is got as the output. At ωt=4π, SCR N2 & N4 are turned off due to natural commutation.

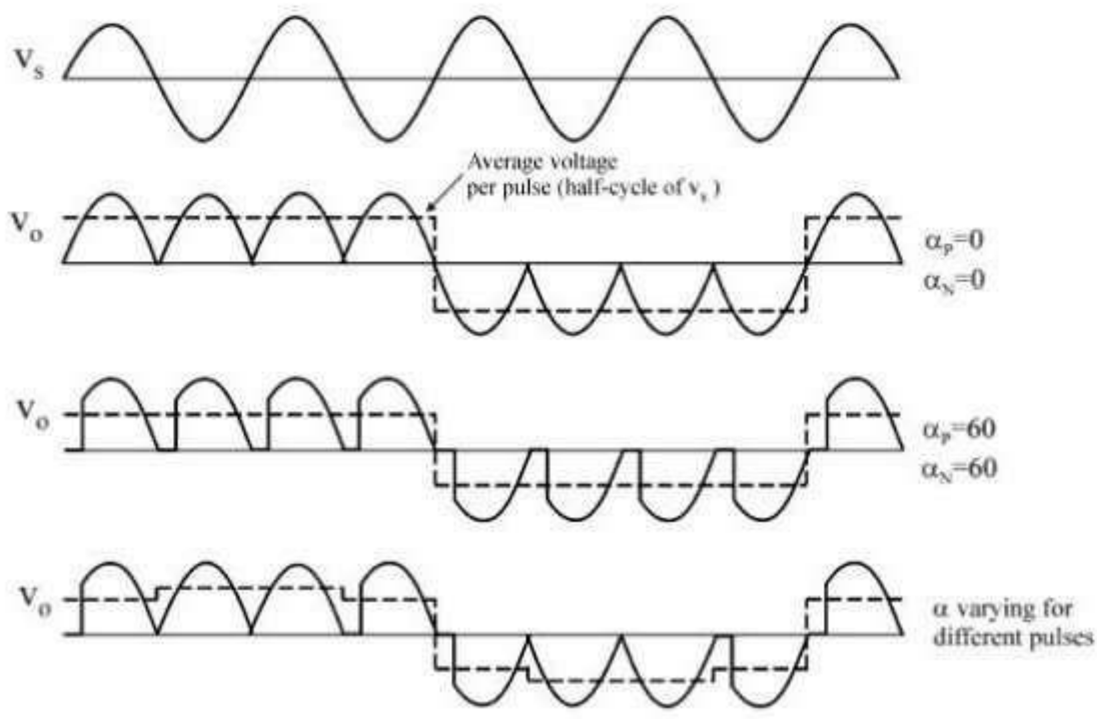


Figure 5.8.2 Wave forms of cyclo converter
[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 416*

- 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.

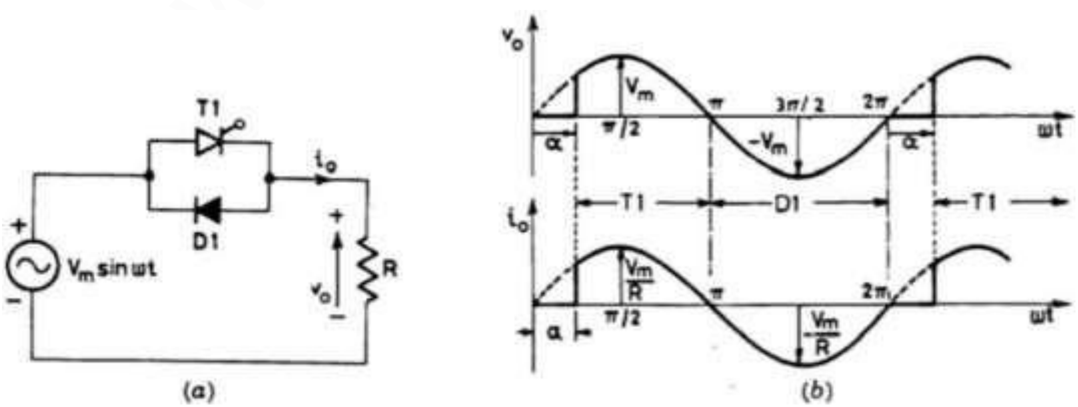


Figure 5.2.1 Single Phase AC voltage controller

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

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

$$V_{or} = \pi \quad \frac{1}{2x}\int_{\alpha}^{2\pi} V_m^2 \sin^2 \omega t d(\omega t) \Big|^{\frac{1}{2}}$$

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

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

$$v \quad \frac{V}{2} \quad \frac{*}{x} \quad 2\pi-\alpha)+\frac{\sin 2\alpha}{2}$$

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

AVERAGE VALUE OF OUTPUT VOLTAGE

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

$$'o \quad \frac{V_m}{2n}(-\cos\omega o)_{\alpha}^{2\pi}$$

$$V_{o*} = \frac{V°}{2n}(\cos o — l)$$

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 = ∏

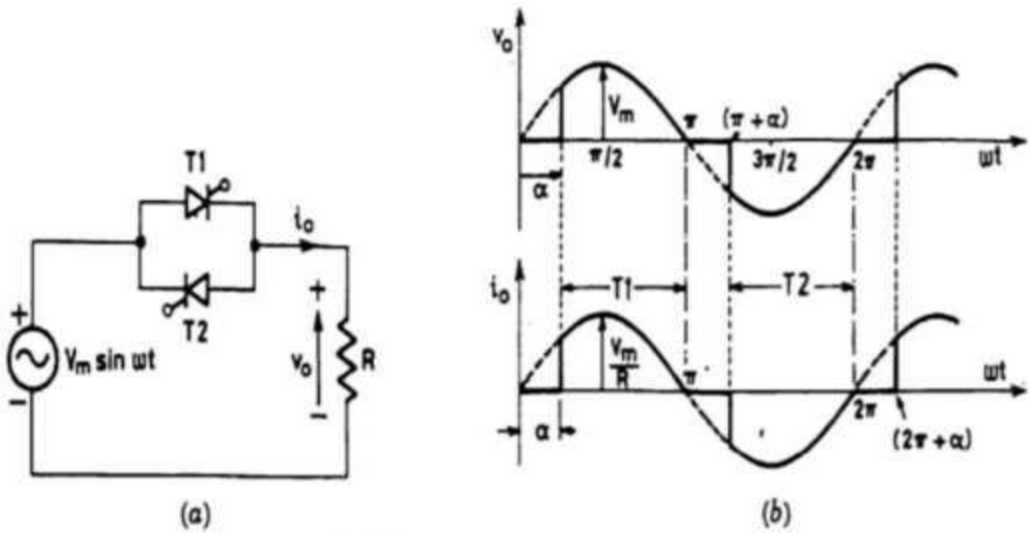


Figure 5.2.2 Single-phase full-wave ac voltage controller

[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.

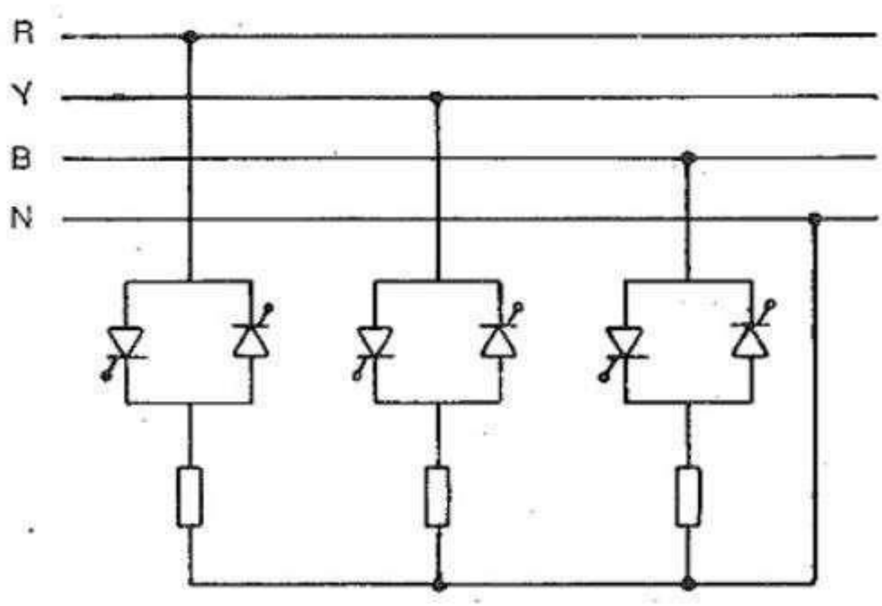


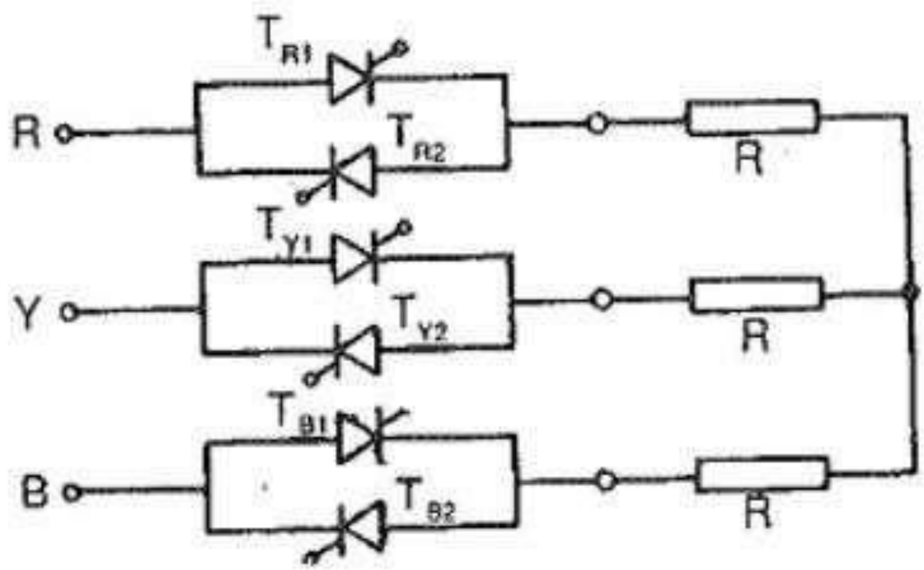
Figure 5.3.1 Block diagram of Three Phase AC voltage controller

[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 hormonics

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, thecurrent goes tozero 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

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

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

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

5.9 Three-Phase to Single-Phase Cyclo converters

- A three-phase to single phase cyclo converter also consists of positive and negative group thyristors. Positive converters will provide positive current and negative converters will provide negative current to the load.
- .These cyclo-converters can be half-wave or full bridge converters as shown in figure. Like single phase cyclo-converters, these also produce a rectified voltage at the load terminals by each group of thyristors.
- At any time, one converter will operate. The circuit of half wave and full wave cycloconverters are shown below.

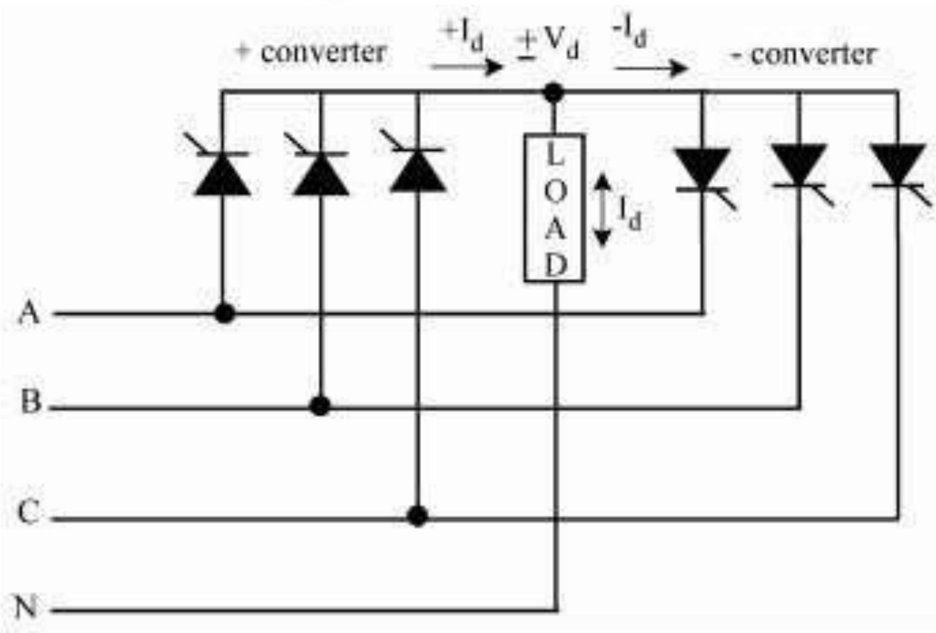


Figure 5.9.1 3phase cyclo converter

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 418]*

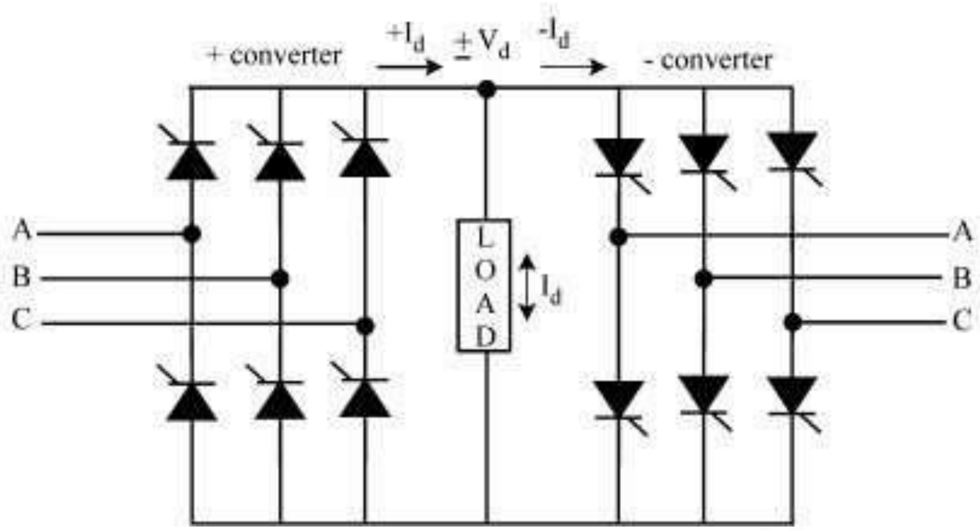


Figure 5.9.2 3phase to single phase cyclo converter

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 418]*

During positive half cycle of the input, conduction of the positive group thyristors is controlled and during negative half-cycle, conduction of negative group of thyristors is controlled in order to produce an output voltage at desiredfrequency.

OPERATION

The firing angle (α) of two converters is first decreased starting from the initial value of 90° to the final value of 0°, and then again increased to the final value of 90° , as shown in Fig. below Also, for positive half cycle of the output voltage waveforrn, bridge 1 is used, while bridge 2 is used for negative half cycle. The two half cycles are combined to form one complete cycle of the output voltage, the frequency being decided by the number of half cycles of input voltage waveform used for each half cycle of the output. As more no. of segments of near 60°(π/6} is used, the output voltage waveform becomes near sinusoidal, with its frequency also being reduced.

The initial value of firing angle delay is kept at $\alpha_1 \approx 90°$, such the average value (dc) of the output voltage in this interval of near 60° (π/6) [Vav= cos α_1 = cos 90°= 0, is zero. It may be noted that the next thyristor in sequence is triggered at $\alpha_2<90°$, as the firing angle is decreased for each segment, to obtain higher voltage Vavα cos α_2 = +ve , to form the sine waveat the output. This can beobserved from the points, M, N, O, P, Q, R & S, shown in Fig.From these segments, the first quarter cycle of the output voltage waveform from 0° to 90°, is obtained. The second quarter cycle of the above waveform from 90°to180° , is obtained, using the segments starting from the points, T, U, V, W, X &Y. It may be noted that the firing angle delay at the point, Y is α = 90° , and also the firing angle is increased from 0° (T) to 90° (Y) in this interval. When the fi ring angle delay is 0° , the average value of the segment is Vav α cos α= cos 0° = 1.0. The two quarter cycles form the positive half cycle of the output voltage waveform. In this region, the bridge I (positive) is used.

- To obtain the negative half cycle of the output voltage waveform (180° - 360°), the other bridge converter (#2) termed negative (B) is used in the same manner as given earlier, i.e. its firing angle delay ((1) is first decreased starting from the initial value of 90° to the final value of 0° , and then again increased to the finalvalue of 90°.the two half cycles together form the complete cycle of the output voltage waveform.

- In a bridge type of cyclo-converter, both positive and negative converters can generate voltages at either polarity, but negative converter only supplies negative current while positive converter supply positive current.

- Therefore, the cyclo-converter can operate in four quadrants, i.e., rectificationmodesof(+V,+i) and(-V,-i) andinversionmodesof (+V, -i) and(-V, +i)

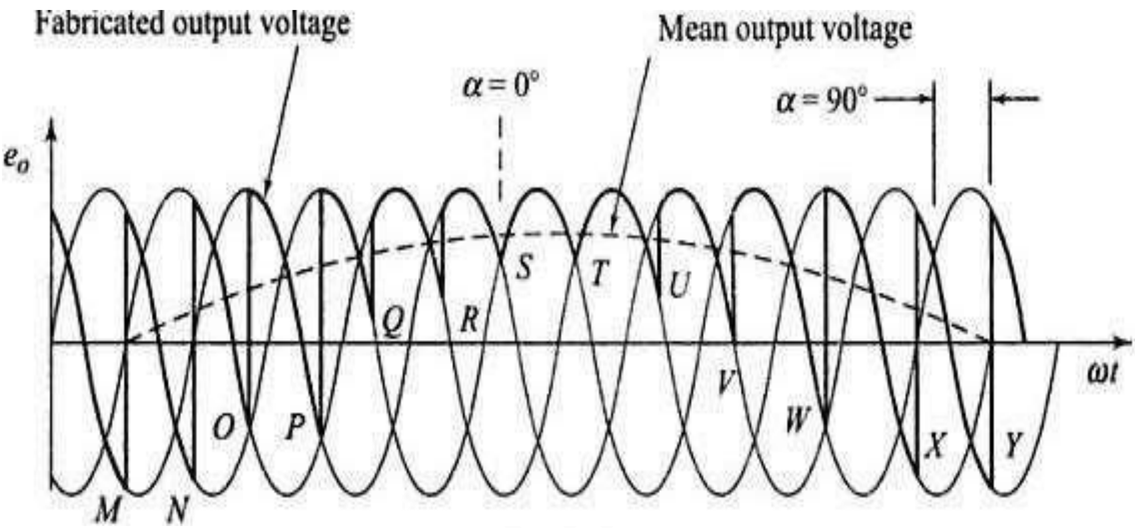


Figure 5.9.3 Output Voltage form

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 419]*

The above figure shows the conversion of three phase supply at one frequency to single phase supply of lower frequency. In this, the firing angle to a positive group of thyristors is varied progressively to produce single phase output voltage.

- At point M, the firing angle is 90 degrees and it is reduced till point S where it iszero. Againfrompoint Tto Y,thedelayangleisprogressively increased.

- This varied triggering signals to the thyristors, varies its conduction time periods and hence the frequency of the output voltage.

5.11 WELDING

- Power sources will require either a single or three phase supply at the voltage of the country in which it is intended to be used. Most equipment is provided with a series of voltage tappings and these may need to be adjusted to match the supply voltage. In the UK and the rest of Europe the supply voltages are now 230V AC single phase and 400V AC three phase. In other parts of the world, different supply voltages occur and may vary between regions. In some countries,220V AC three phase may be encountered. Three phase supplies may be limited to 30A, but higher power welding equipment may require a 45A or even a 60A supply.
- From 1999, equipment started to appear with an effective current rating on the rating plate. This value should be used to determine the cable size and fusing requirements. However, national wiring regulations should always befollowed.

- Particular attention should be paid to the supply requirements for single phase equipment. In many parts of Europe the 230V supply is 16A, but in the UK the standard plug is only 13A. Therefore, the relatively low power output of this type of equipment is further reduced if a 13A plug is fitted, so a dedicated circuit may be required. In some parts of the world the single phase mains supply may be further limited in current, but generally in these countries, three phase supplies will be readily available. Another problem to be wary of is imbalance in the supply, if high powered equipment is connected between two phases of a three hase supply. If more than one power source is installed they should be connected between different phases.

- Apart from the obvious hazards of overloading a supply, e.g. overheating and blowing fuses, problems with other equipment may be caused. If the supply has a high impedance (commonly known as soft) as may be the case in overhead cables, a high current draw may cause the voltage of the supply to fall below levels which may cause problems with other equipment.

AC-AC converter for Welding Application

- Welding is an integral and energy intensive part of the construction, manufacturing, and maintenance industries.To weld two plates ie work pieces, the melting energy is provided by establishing an arc between two electrodes, where one of them is the metallic workpiece being welded.
- There are several technologies for electric arc welding, each with their own unique power quality requirements.
- Welding technologies such as metal inert gas (MIG), Tungsten inert gas (TIG) and submerged arc welding (SAW) requires constant voltage power supply.

Power Supplies for Electric Arc Welding

➢ power supplies for electric arc welding provide a CC/CV constant current/constant voltage output that may be either AC or DC.

➢ They are partially well adapted for submerged arc weldind.

- Constant voltage (CV) DC sources were used for the constant speed wire electrode feeders.
- DC power supplies pose arc blow issues. Arc blow is less of a problem when using an AC power supply (because there is not a DC arc current). A sinusoidal output does not always perform well in sub arc welding processes because the sinusoidal wave exhibits a slow zero crossover which may result in arc rectification.
- For sub arc welding, an AC power source which receives a three phase input and provides a single phase AC output, having relatively fast zero crossings, at a frequency 1.5 times the input frequency. (step up CC)
- A welding power supply comprising a step-up cycloconverter having at least one control input and a controller coupled to the control input.