KLR COLLEGE OF ENGINEERING & TECHNOLOGY
(Affiliated to JNTUH, Approved by AICTE New Delhi, An ISO 9001:2015 Certified)
BCM Road, Paloncha-507115, Bhadradri Kothagudem(Dist.), Telangana.

LECTURE NOTES

ON

POWER ELECTRONICS

2021 - 2022

III B. Tech I Semester

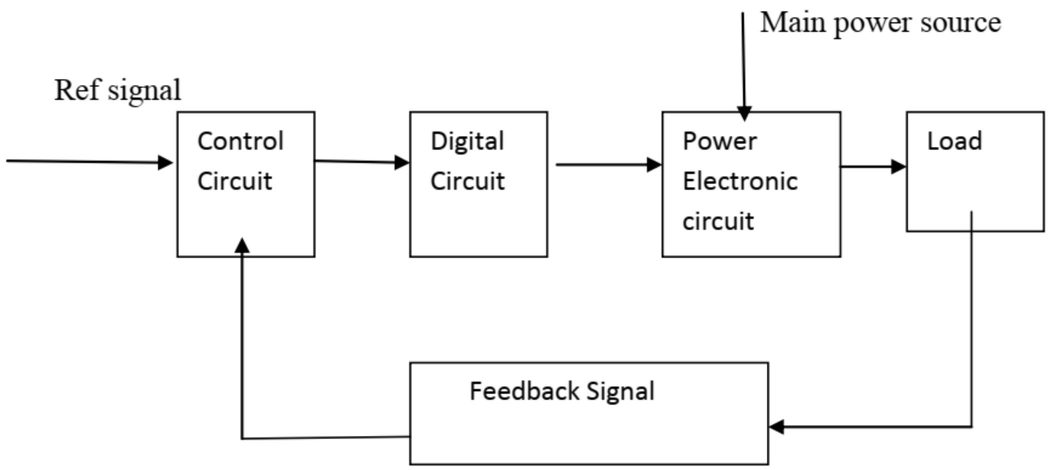
ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT-1

POWER SWITCHING DEVICES

POWER ELECTRONICS

The control of electric motor drives requires control of electric power. Power electronics haveeased the concept of power control. Power electronics signifies the word power electronics and control or we can say the electronic that deal with power equipment for power control.

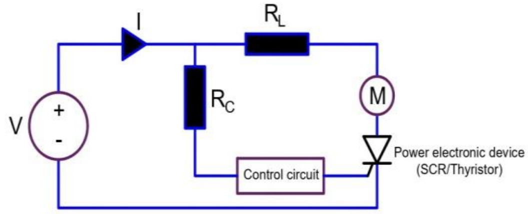


Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices have been improved tremendously.

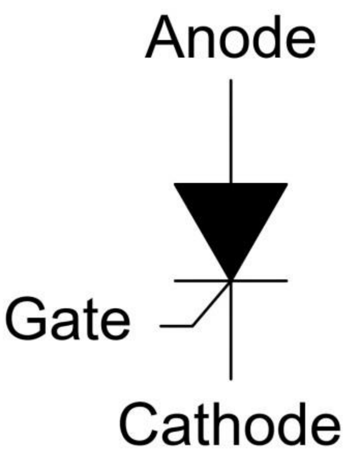
SCOPE AND APPLICATION

Power electronics systems are known for their reliability and precise controllability. That's why the scope of power electronics is huge. Whether it be Power Systems, Electrical Machines, Signal Processing, or Industrial applications, the role of power electronics is immense.

Power electronics revolutionized the way electrical systems worked and were controlled. One of the major issues that the power electronic-based systems addressed was improved efficiency with higher accuracy in the output of the applications. Earlier, we used to achieve one by sacrificing the other but power electronics changed the situation. Let's understand the working of a power electronics-based system. Let's understand the working of a power electronics-based system.



The circuit diagram shown above is that of a motor control system using SCR. SCR stands for Silicon Controlled Rectifier and is also known as Thyristor. It has three terminals – Anode, Cathode and Gate. It is similar to that of a diode except



that it has an extra terminal called

Just like a Diode, an SCR is forward-biased when the Anode is connected to the positive terminal and the cathode is connected to the negative terminal of a voltage source. However, it can't conduct unless the gate terminal is supplied with a voltage source. Once the gate terminal is active, the switch (SCR) behaves ideally like a short circuit and allows the normal flow of electric current.

Thus, the gate terminal acts like a control terminal for the switching device i.e, the SCR. If the gate terminal voltage is low, the switch acts as an open circuit and stops the current to flow whereas if the gate voltage is high, it allows the normal flow of current through the connected circuit. Thus, instead of cutting off the power source to the motor, we can turn the gate supply ON/OFF to start and stop the motor respectively. Voltage drop across the rheostat, the power loss in SCR-controlled speed control is very low.

Application of Power Electronics

A whole lot of power electronics applications that we use in our daily life, such as a fan regulator, air-conditioning, induction cooking, light dimmer, emergency lights, vacuum cleaners, personal computers, UPS, battery charges, etc., are the major applications of power electronics.

Power electronics are also extensively used in automotive applications, like hybrid electric vehicles, trolleys, subways, forklifts, etc. A modern car itself is an example of power electronics that has some components like windshield wiper control, ignition switch, adaptive front lighting, electric power steering, interior lighting, etc. Apart from these, power electronics are widely used in ships and modern traction systems.

Power electronics are used in industries since the industries have a huge installation of high-power motors that are controlled by power electronic drives, for instance, cement mills, rolling mills, compressor pumps, fans, elevators, textile mills, blowers, elevators, rotary kilns, etc. Some other applications consist of arc furnaces, welding, heating applications, construction machinery, excavators, emergency power systems, etc.

Power electronics are used in defence and aerospace to supply power to aircraft, advance control in missiles, satellites, unmanned vehicles, space shuttles, and several other equipment of defence.

Power electronics are used in the generation of renewable energy, such as solar, wind etc., which needs storage systems and conversion systems, and power conditioning systems in order to become usable.

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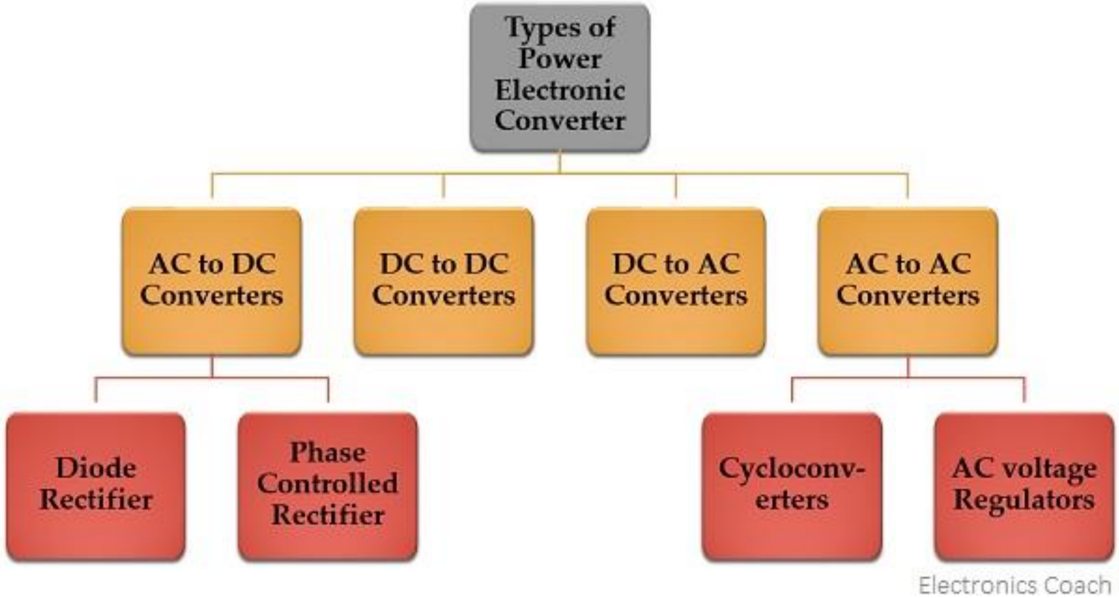
TYPES OF POWER CONVERTERS:-

Static Power converters execute power conversion quite efficiently. Power electronic switches have solid-state devices with components like inductors and capacitors. Generally, inductors and capacitors exhibit negligible power loss characteristics in comparison to resistors.

The classification of power converters are as follows:



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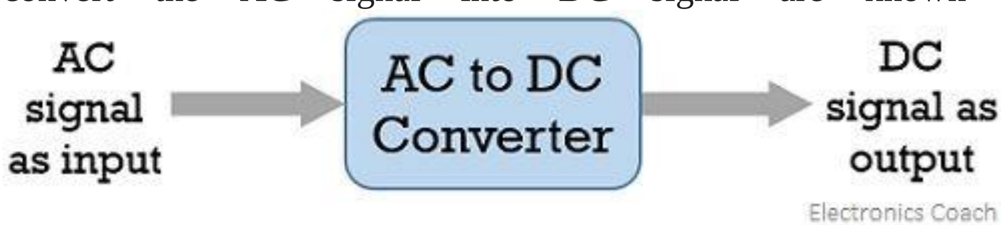
AC to DC Converters

A type of converter that changes input AC signal into a DC is known as AC to DC converter. We have already learned in basic electronics that the devices that convert the AC signal into DC signal are known as **rectifiers**.



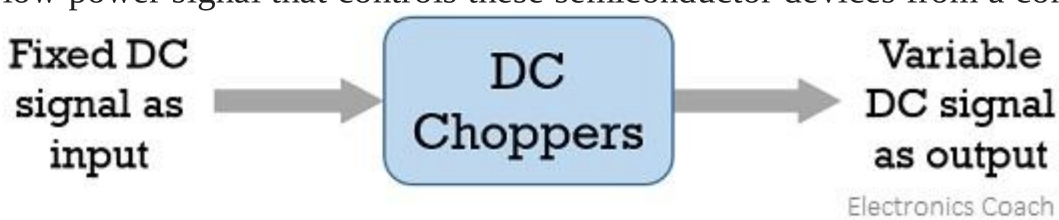
AC to DC Converter is further classified as:

Diode Rectifiers: This rectifier circuit changes applied ac input voltage into a fixed dc voltage. Either a single-phase or three-phase ac signal is applied at the input. These are mainly used in electric traction and in electrochemical processes like electroplating along with in battery charging and power supply. These are also used in welding and UPS related services.

Phase Controlled Rectifiers: Unlike diode rectifiers, phase-controlled rectifiers are designed to convert a fixed value of ac signal voltage into a variable dc voltage. Here line voltage operates the rectifier hence these are sometimes known as line commutated ac to dc converters. Similar to diode rectifiers, here also the applied ac signal can be a single-phase or three-phase ac signal. Its major applications are in dc drives, HVDC systems, compensators, metallurgical and chemical industries as well as in excitation systems for synchronous machines.

DC to DC Converters

The converters that convert the dc signal of fixed frequency present at the input into a variable dc signal at the output are also known as **choppers**. Here the achieved output dc voltage may have a different amplitude than the source voltage. Generally, power transistors, MOSFETs, and thyristors are the semiconductor devices used for their fabrication. The output is controlled by a low power signal that controls these semiconductor devices from a control unit.



Here forced commutation is required to turn off the semiconductor device. Generally, in low power circuits power transistors are used while in high power circuits thyristors are used.

Choppers are classified on the basis of the type of commutation applied to them and on the basis of the direction of power flow. Some major uses of choppers are in dc drives, SMPS, subway cars, electric traction, trolley trucks, vehicles powered by battery, etc.

DC to AC Converters

The devices that are designed to convert the dc signal into ac signal are known as **inverters**. The applied input is a fixed dc voltage that can be obtained from batteries but the output obtained is variable ac voltage. The voltage and frequency of the signal obtained are of variable nature. Here the semiconductor device i.e., the thyristor is turned off by using either line, load, or forced commutation.

Thus, it can be said that by the use of inverters, a fixed dc voltage is changed into an ac voltage of variable frequency. Generally, the semiconductor devices used for its fabrication are power transistors, MOSFETs, IGBT, GTO, thyristors, etc.

Inverters mainly find applications in induction motor and synchronous motor drives along with UPS, aircraft, and space power supplies. In high voltage dc transmission system, induction heating supplies as well as low power systems of mobile nature like flashlight discharge system in photography camera to very high power industrial system.

Like choppers, in inverters also conventional thyristors are used in high power applications and power transistors are used in low power applications.

<u>AC to AC Converters</u>

An ac to ac converter is designed to change the ac signal of fixed frequency into a variable ac output voltage .

There are two classifications of ac to ac converters which are as follows:

Cycloconverters: A cycloconverter is a device used for changing ac supply of fixed voltage and single frequency into an ac output voltage of variable voltage as well as different frequency. However, here the obtained variable ac signal frequency is lower than the frequency of the applied ac input signal. It adopts single-stage conversion. Generally, line commutation is mostly used in cycloconverters however forced or load commutated cycloconverters are also used in various applications.

These mainly find applications in slow-speed large AC traction drives such as a rotary kiln, multi MW ac motor drives, etc.

AC Voltage Controllers (AC voltage regulators): The converters designed to change the applied ac signal of fixed voltage into a variable ac voltage signal of the same frequency as that of input. For the operation of these controllers, two thyristors in an antiparallel arrangement are used. Line commutation is used for turning off both the devices. It offers the controlling of the output voltage by changing the firing angle delay.

The major applications of ac voltage controllers are in lighting control, electronic tap changers, speed control of large fans and pumps as well.

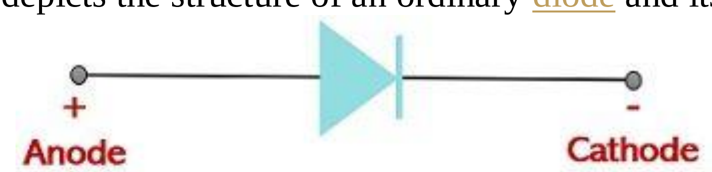
POWER SEMICONDUCTOR SWITCHES&THEIR V-I CHARACTERISTICS:-

POWER DIODE:-

A power diode is a type of diode that is commonly used in power electronics circuits. Just like a regular diode, a power diode has two-terminals and conducts current in one direction. A power diode varies in construction from a standard diode to enable this higher current rating.
To better understand how a power diode differs from a regular diode, let's revisit how a standard diode works.

Diodes are the simplest semiconductor device having only two layers, two terminals, and one junction.
The ordinary signal diodes have a junction formed by p type semiconductor and n type semiconductor, the lead joining p-type is called the anode and the other side lead joining the n-type is called the cathode.

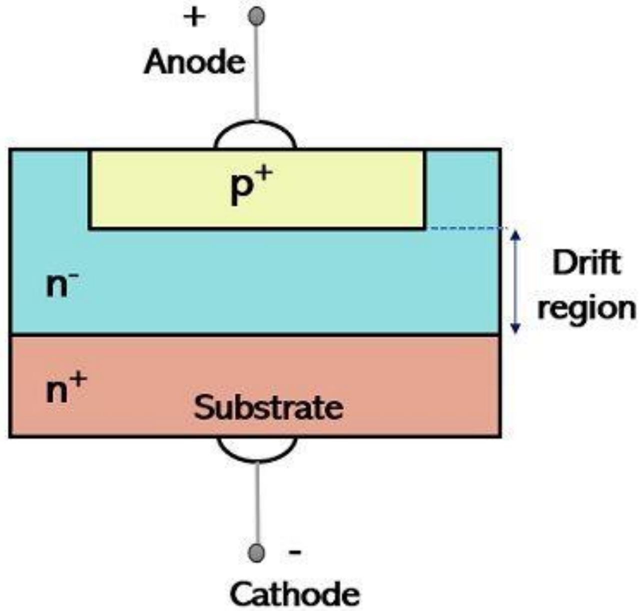
The figure below depicts the structure of an ordinary diode and its symbol.



Symbol of Power Diode

Power diodes are also similar to regular diodes, although they vary slightly in their construction.

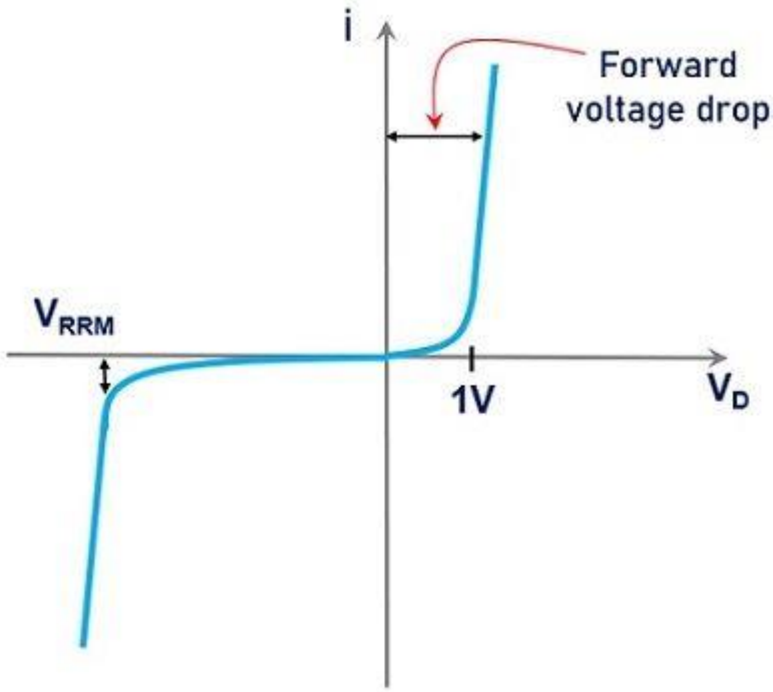
In regular diodes (also known as "signal diode"), the doping level of both P and N sides is the same and hence we get a PN junction, but in power diodes, we have a junction formed between a heavily doped P^+ and a lightly doped N^- the layer which is epitaxially grown on a heavily dopedN^+layer.



Structure of Power Diode

V-I Characteristics

Initially with no supply voltage forward current is 0 but as the supply input increases, and reaches the threshold value (of about 0.7 V), a small amount of forward current flows through the device. Once the threshold value is surpassed, a considerable increase in diode current (at 1V) is noticed as it starts conduction. Here linear rise in forward current is noticed when voltage increases beyond the threshold.



I-V characteristics of Power Diode

POWER BJT:-

Bipolar Junction Transistor (BJT) is a three terminal, three layer, two junction semiconductor device. Emitter(E), Base(B) and Collector(C) are the three terminals of the device.

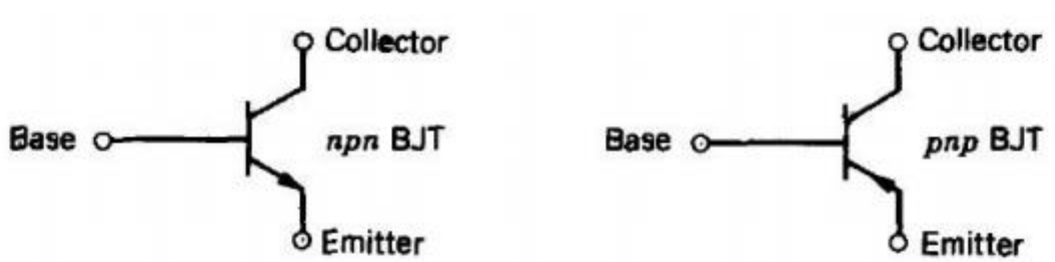


Figure 5.17 Symbol of power BJT

Symbol: The symbol of the Power BJT is same as signal level transistor.

Structure

The construction of the Power Transistor is different from the signal transistor as shown in the following figure. The n- layer is added in the power BJT which is known as drift region.

A Power BJT has a four layer structure of alternating P and N type doping as shown in above npn transistor.

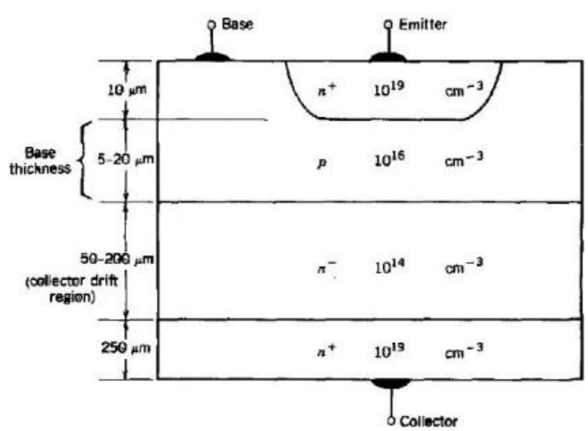
It has three terminals labeled as Collector, Base, Emitter.

In most of Power Electronic applications, the Power Transistor works in Common Emitter configuration.

ie, Base is the input terminal, the Collector is the output terminal and the Emitter is common between input and output.

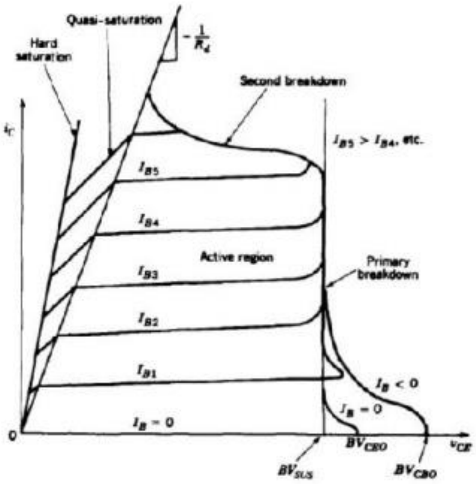
In power switches npn transistors are most widely used than pnp transistors.

The thickness of the dirft region determines the breakdown voltage of the Power transistor.s



The characteristics of the device is determined by the doping level in each of the layers and the thickness of the layers.

VI Characteristics

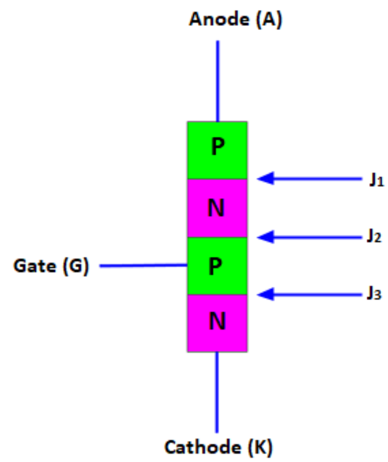


The VI characteristics of the Power BJT is different from signal level transistor.

- 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.

Silicon Controlled Rectifier

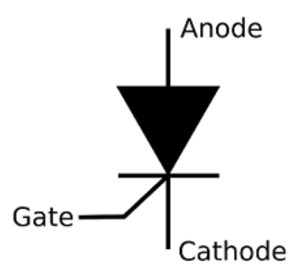
A Silicon Controlled Rectifier is a 3 terminal and 4 layer semiconductor current controlling device. It is mainly used in the devices for the control of high power. Silicon controlled rectifier is also sometimes referred to as SCR diode, 4-layer diode, 4-layer device, or Thyristor. It is made up of a silicon material which controls high power and converts high AC current into DC current (rectification). Hence, it is named as silicon controlled rectifier.



SCR Structure

Silicon Controlled Rectifier Symbol

The schematic symbol of a silicon controlled rectifier is shown in the below figure. A SCR diode consists of three terminals namely anode (A), cathode (K), Gate (G). The diode arrow represents the direction of conventional current.



Construction of Silicon Controlled Rectifier

A silicon controlled rectifier is made up of 4 semiconductor layers of alternating P and N type materials, which forms NPNP or PNPN structures. It has three P-N junctions namely J_1, J_2, J_3 with three terminals attached to the semiconductors materials namely anode (A), cathode (K), and gate (G). Anode is a positively charged electrode through which the conventional current enters into an electrical device, cathode is a negatively charged electrode through which the conventional current leaves an electrical device, gate is a terminal that controls the flow of current between anode and cathode. The gate terminal is also sometimes referred to as control terminal.

The anode terminal of SCR diode is connected to the first p-type material of a PNPN structure, cathode terminal is connected to the last n-type material, and gate terminal is connected to the second p-type material of a PNPN structure which is nearest to the cathode.

In silicon controlled rectifier, silicon is used as an intrinsic semiconductor. When pentavalent impurities are added to this intrinsic semiconductor, an N-type semiconductor is formed. When trivalent impurities are added to an intrinsic semiconductor, a p-type semiconductor is formed.

When 4 semiconductor layers of alternating P and N type materials are placed one over another, three junctions are formed in PNPN structure. In a PNPN structure, the junction J_1 is formed between the first P-N layer, the junction J_2 is formed between the N-P layer and the junction J_3 is formed between the last P-N layer. The doping of PNPN structure is depends on the application of SCR diode.

V-I Characteristics of SCR

The V-I characteristics of SCR is shown in the below figure. The horizontal line in the below figure represents the amount of voltage applied across the SCR whereas the vertical line represents the amount of current flows in the SCR.

V_A = Anode voltage, I_A = Anode current, $+V_A$ = Forward anode voltage,

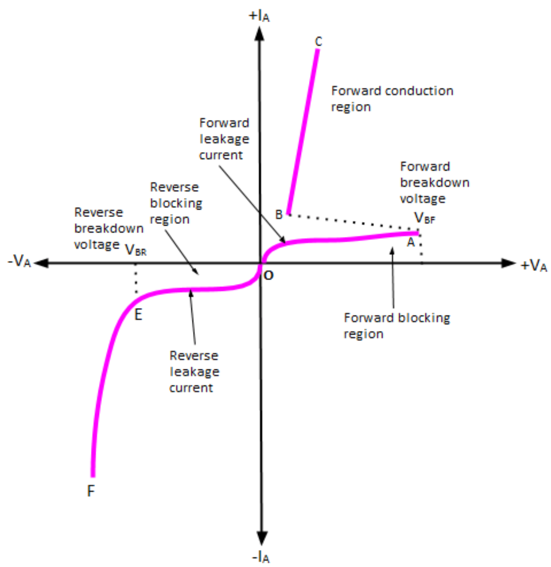
$+I_A$ = Forward anode current, $-V_A$ = Reverse anode voltage, $+I_A$ = Reverse anode current

The V-I characteristics of SCR is divided into three regions:

- Forward blocking region
- Forward conduction region
- Reverse blocking region

- Forward blocking region

In this region, the positive voltage (+) is given to anode (+), negative voltage (-) is given to cathode (-), and gate is open circuited. Due to this the junction J_1 and J_3 become forward biased while J_2 become reverse biased. Therefore, a small leakage current flows from anode to cathode terminals of the SCR. This small leakage current is known as forward leakage current.



V-I Characteristics of SCR

The region OA of V-I characteristics is known as forward blocking region in which the SCR does not conduct electric current.

- Forward Conduction region

If the forward bias voltage applied between anode and cathode is increased beyond the breakdown voltage, the minority carriers (free electrons in anode and holes in cathode) gains large amount of energy and accelerated to greater velocities. This high speed minority carriers collides with other atoms and generates more charge carriers. Likewise, many collisions happens with atoms. Due to this, millions of charge carriers are generated. As a result depletion region breakdown occurs at junction J_2 and current starts flowing through the SCR. So the SCR will be in On state. The current flow in the SCR increases rapidly after junction breakdown occurs.

The voltage at which the junction J_2 gets broken when the gate is open is called forward breakdown voltage (V_{BF}).

The region BC of the V-I characteristics is called conduction region. In this region, the current flowing from anode to cathode increases rapidly. The region

AB indicates that as soon as the device becomes on, the voltage across the SCR drops to some volts.

- Reverse Blocking Region

In this region, the negative voltage (-) is given to anode (+), positive voltage (+) is given to cathode (-), and gate is open circuited. In this case, the junction J_1 and junction J_3 are reverse biased whereas the junction J2 becomes forward biased.

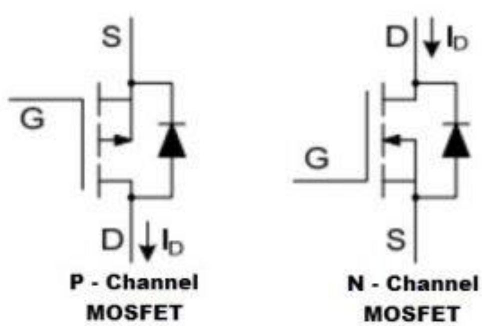
As the junctions J_1 and junction J_3 are reverse biased, no current flows through the SCR circuit. But a small leakage current flows due to drift of charge carriers in the forward biased junction J_2. This small leakage current is called reverse leakage current. This small leakage current is not sufficient to turn on the SCR.

If the reverse bias voltage applied between anode and cathode is increased beyond the reverse breakdown voltage (V_{BR}), an avalanche breakdown occurs. As a result, the current increases rapidly. The region EF is called reverse avalanche region. This rapid increase in current may damage the SCR device.

POWER MOSFET

One kind of MOSFET which handles high levels of power is known as Power MOSFET. As compared to normal MOSFETs in the less voltage range, these MOSFETS works much better by exhibiting high speed of switching. Its operating principle is the same as general MOSFETs.

The most widely used power MOSFETs are p-channel Enhancement-mode, n-channel Enhancement-mode or n-channel depletion mode & p-channel depletion mode. The power MOSFET frequency is high like up to 100 kiloHertz. The **power MOSFET symbol** is shown below.

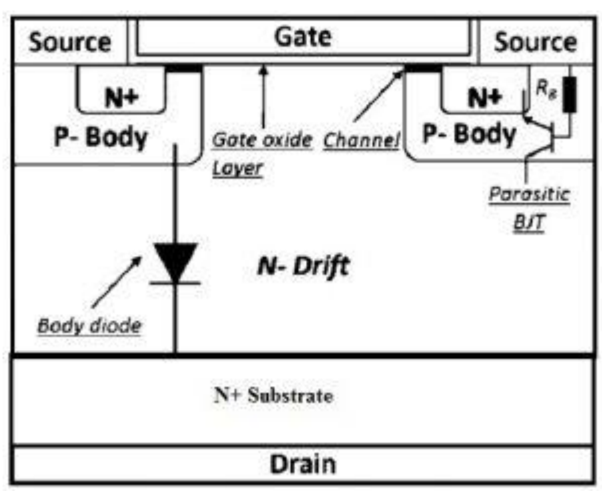


These are three-terminal silicon devices that work through applying a signal toward the gate terminal so that it controls current conduction among source & drain terminals. The current conduction capacities are equal to thousands of amperes including breakdown voltage ratings from 10Volts-1000Volts.
Further, power MOSFETs are available in different structures such as VDMOS (Vertical Diffused MOS or DMOS (Double-Diffused MOS), Trench-MOS (UMOS), or VMOS, etc.

In integrated circuits, the power MOSFET used is a lateral device including source, drain & gate terminals on the pinnacle of the device where the current flowing within a lane is parallel as compared to the exterior. The VDMOS (Vertical Double diffused MOSFET) utilizes the substrate of a device like a drain terminal.

Power MOSFET Construction

Generally, the power MOSFETs are enhancement types. A drift layer is used to enhance the voltage rating for enhancement MOSFET. The structure of the power MOSFET is the vertical shape and it includes four layers. This type of structure is mainly used to decrease the region of the flow of current. So this structure will decrease the on-state resistance & on-state loss.



In the MOSFET structure, the middle layer like p-type is called as body whereas n- layer is called as the drift region. This layer is doped lightly as evaluated to the other layers like source & drain. This drift region will decide the breakdown voltage for this MOSFET. In the power MOSFET construction, both the first &

last layers are n+ layers. Here the source layer is the primary layer whereas the drain layer is the last layer.

The structure of n+ p n- n+ is the n channel MOSFET in enhancement mode. But the structure of a p-channel MOSFET includes quite opposite doping shape. In this construction, the gate terminal is not connected directly to p-type as there is an oxide layer in between the metal & semiconductor which works as a dielectric layer.

It forms a metal oxide semiconductor capacitance on the MOSFET's input which is high like above 1000 pF. The oxide layer provides excellent insulating properties by offering the silicon dioxide layer to separate the terminal from the body to the gate.

Power MOSFET Characteristics

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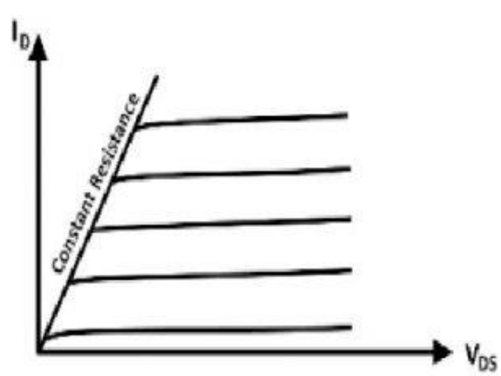
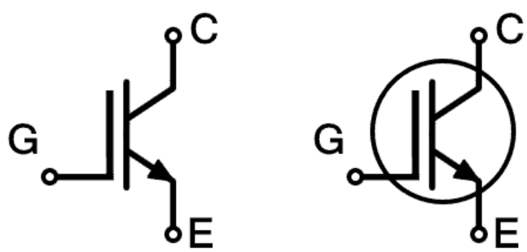


Once the voltage of the gate-source is low as compared to the threshold voltage, then power MOSFET will be in the cut-off region. To keep away from a breakdown, the breakdown voltage from the drain to the source must be larger as compared to the voltage applied. So avalanche breakdown will occur.

The power MOSFET moves into the ohmic state then the power dissipation is low in this region. In the saturation state, the drain current is approximately independent of the voltage of drain to source.
It is simply dependent on the voltage of the gate to source terminals. The voltage of the gate terminal is greater as compared to the threshold voltage. The drain current will increase when the voltage from gate to source increases.

POWER IGBT

The **IGBT or Insulated Gate Bipolar Transistor** is the combination of BJT and MOSFET. Its name also implies the fusion between them. "Insulated Gate" refers to the input part of MOSFET having very high input impedance. It does not draw any input current rather it operates on the voltage at its gate terminal. "Bipolar" refers to the output part of the BJT having bipolar nature where the current flow is due to both types of charge carriers. It allows it to handle very large currents and voltages using small voltage signals. This hybrid combination makes the IGBT a voltage-controlled device.

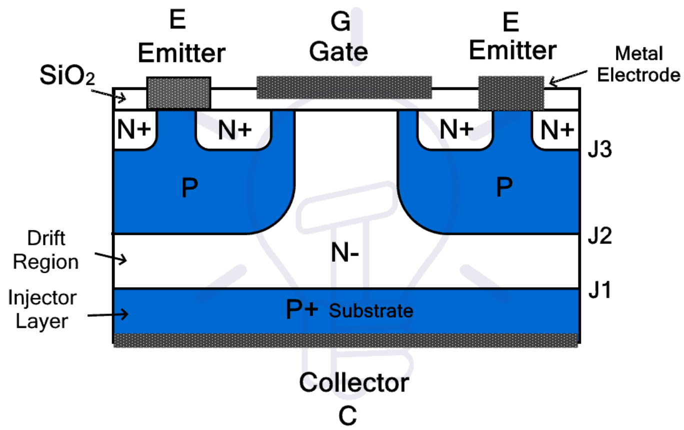


IGBT - Insulated-Gate Bipolar Transistor
Symbol

It is a four-layer PNPN device having three PN junctions. It has three terminals Gate (G), Collector(C) and Emitter (E). The terminal's name also implies being taken from both transistors. Gate terminal as it is the input part, taken from MOSFET while the collector and emitter as they are the output, taken from the BJT.

Construction of IGBT

IGBT is made of four layers of semiconductor to form a PNPN structure. The collector (C) electrode is attached to P layer while the emitter (E) is attached between the P and N layers. A P+ substrate is used for the construction of IGBT. An N- layer is placed on top of it to form PN junction J1. Two P regions are fabricated on top of N- layer to form PN junction J2. The P region is designed in such a way to leave a path in the middle for the gate (G) electrode. N+ regions are diffused over the P region as shown in the figure.



Structure of IGBT

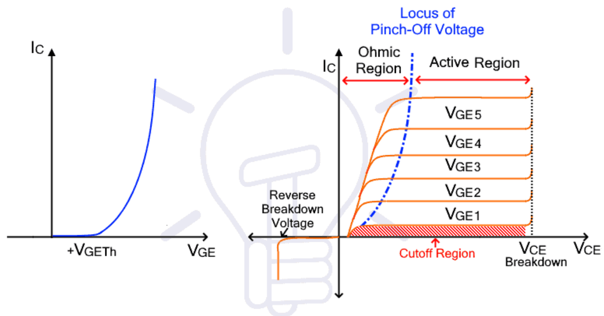
The emitter and gate are metal electrodes. The emitter is directly attached to the N+ region while the gate is insulated using a silicon dioxide layer. The base P+ layer inject holes into N- layer that is why it is called injector layer. While the N- layer is called the drift region. Its thickness is proportional to voltage blocking capacity. The P layer above is known as the body of IGBT.

The N- layer is designed to have a path for current flow between the emitter and collector through the junction using the channel that is created under the influence of the voltage at the gate electrode.

V-I Characteristics of IGBT

Unlike BJT, IGBT is a voltage-controlled device that requires only a small voltage at its gate to control the collector current. However, the gate-emitter voltage V_{GE} needs to be greater than the threshold voltage.

Transfer characteristics of the IGBT show the relation of input voltage V_{GE} to output collector current I_C. When the V_{GE} is 0v, there is no I_C and the device remains switched off. When the V_{GE} is slightly increased but remains below threshold voltage V_{GET}, the device remains switched off but there is a leakage current. When the V_{GE} exceeds the threshold limit, the I_C starts to increase and the device switches ON. Since it is a unidirectional device, the current only flows in one direction.



I-V Characteristics of IGBT

The given graph shows the relation between the collector current I_C and collector-emitter voltage V_{CE} at different levels of V_{GE}. At $V_{GE} < V_{GET}$ the IGBT is in **cutoff mode** and the $I_C = 0$ at any V_{CE}. At $V_{GE} > V_{GET}$, the IGBT goes into active mode, where the I_C increases with an increase in V_{CE}. Furthermore, for each V_{GE} where $V_{GE1} < V_{GE2} < V_{GE3}$, the I_C is different.

The reverse voltage should not exceed the reverse breakdown limit. So does the forward voltage. If they exceed their respective breakdown limit, uncontrolled current starts passing through it.

THYRISTOR RATINGS AND PROTECTION

Ratings of Thyristor

There are different ratings that are specified by the device manufacturers and they are available in SCR manuals.The designer must make use of this data in order to select a device which has adequate ratings.The specified ratings should not be exceeded in order to operate SCR reliably. In this section some of the important ratings have been discussed .

- **Latching Current (IL):** Latching current IL is the minimum anode current required to maintain thyristor in ON state immediately after thyristor has been Turn ON and the gate signal has been removed .
- **Holding Current (IH):** Minimum anode current below which device stop conducting and return to its off state usually this value is very small in mA.
- **Forward Breakdown Voltage (VBO):** If anode to cathode voltage VAK is increase to sufficient large value, the reverse bias junction J2 breaks this is known as Avalanche Breakdown and corresponding voltage is called as forward breakdown voltage VBO .

• **Reverse Breakdown Voltage (VBR):** If reverse voltage is increased During reverse blocking if Ig = 0 then only reverse saturation current (Is) flows until the reverse voltage reaches reverse break down voltage (VBR). At this point current starts rising sharply. Large reverse voltage and current generates excessive heat and destroys the device.

• **dv/dt:** dv/dt rating of thyristor indicates maximum rate of rise of anode voltage that will not trigger the device without any gate signal.

• **di/dt:** di/dt rating of thyristor indicates maximum rate of rise of anode to cathode current .

• **Surge Current:** It specifies the maximum allowable non repetitive current the device can withstand. The device is assumed to be operating under rated blocking voltage, forward current and junction temperature before the surge current occurs. Following the surge the device should be disconnected from the circuit and allowed to cool down. Surge currents are assumed to be sine waves of power frequency with a minimum duration of ½ cycles. Manufacturers provide at least three different surge current ratings for different durations.

• **Gate current to trigger (IGT):** Minimum value of the gate current below which reliable turn on of the thyristor cannot be guaranteed. Usually specified at a given forward break over voltage .

• **Gate voltage to trigger (VGT):** Minimum value of the gate cathode forward voltage below which reliable turn on of the thyristor cannot be guaranteed. It is specified at the same break over voltage as IGT.

THYRISTOR PROTECTION:-

There are different types of **thyristor protection** schemes available for satisfactory operation of the device like

1. Over voltage protection.
2. Over current protection.
3. High dv/dt protection.

4. High di/dt protection.
5. Thermal protection.

Over Voltage Protection

It is the most important protection scheme w. r. t. others as thyristors are very sensitive to over voltages. Maximum time thyristor failures happen due to over-voltage transients.

A thyristor may be subjected to internal or external over-voltages.

Internal Over-Voltages : After commutation of a thyristor reverse recovery current decays abruptly with high di/dt which causes a high reverse voltage [as, V = L(di/dt) so if di/dt is high then V will be large] that can exceed the rated break-over voltage and the device may be damaged.

External Over-Voltages : These are caused due to various reasons in the supply line like lightning, surge conditions (abnormal voltage spike) etc. External over voltage may cause different types of problem in thyristor operation like increase in leakage current, permanent breakdown of junctions, unwanted turn-on of devices etc. So, we have to suppress the over-voltages.

Protective Measure: The effect of over-voltages can be minimized by using non-linear resistors called voltage clamping devices like metal oxide varistors. At the time of normal operation, it offers high impedance and acts as it is not present in the circuit. But when the voltage exceeds the rated voltage then it serves as a low impedance path to protect SCR.

Over Current Protection

Overcurrent mainly occurs due to different types of faults in the circuit. Due to overcurrent i^2R loss will increase and high generation of heat may take place that can exceed the permissible limit and burn the device.

Protective Measure: SCR can be protected from overcurrent by using Circuit Breaker (CB) and fast acting current limiting fuses (FACLF). CBs are used for protection of thyristor against continuous overloads or against surge currents of long duration as a CB has long tripping time. But fast-acting fuses is used for protecting SCR against high surge current of very short duration.

High dv/dt Protection

When a thyristor is in forward blocking state then only J_2 junction is reverse biased which acts as a capacitor having constant capacitance value C_j (junction capacitance). As we know that current through capacitor follows the relation

$$i = C\frac{dv}{dt} \Rightarrow i \propto \frac{dv}{dt}(if\ C\ constant)$$

Hence leakage current through the J_2 junction which is nothing but the leakage current through the device will increase with the increase in dv_a/dt i.e. rate of change of applied voltage across the thyristor. This current can turn-on the device even when the gate signal is absent. This is called dv/dt triggering and must be avoided which can be achieved by using Snubber circuit in parallel with the device.

Protective Measure :

Snubber Circuit: It consists of a capacitor connected in series with a resistor which is applied parallel with the thyristor, when S is closed then voltage V_s is applied across the device as well as C_s suddenly. At first Snubber circuit behaves like a short circuit. Therefore voltage across the device is zero. Gradually voltage across C_s builds up at a slow rate. So dv/dt across the thyristor will stay in allowable range .

Before turning on of thyristor C_s is fully charged and after turning on of thyristor it discharges through the SCR. This discharging current can be limited with the help of a resistance (R_s) connected in series with the capacitor (C_s) to keep the value of current and rate of change of current in a safe limit.

High di/dt Protection

When a thyristor is turned on by gate pulse then charge carriers spread through its junction rapidly. But if rate of rise of anode current, i.e. di/dt is greater than the spreading of charge carriers then localized heat generation will take place which is known as local hot spots. This may damage the thyristor. Protective Measure: To avoid local hot spots we use an inductor in series with the device as it prevents high rate of change of current through it.

High Temperature Protection

With the increase in the temperature of the junction, insulation may get failed. So we have to take proper measures to limit the temperature rise. Protective Measure: We can achieve this by mounting the thyristor on heat sink which is mainly made by high thermal conductivity metals like aluminum (Al), Copper (Cu) etc. Mainly aluminum (Al) is used due to its low cost. There are several types of mounting techniques for SCR such as – Lead-mounting, stud-mounting, Bolt-down mounting, press-fit mounting, press-pack mounting etc.

Gate Protection of Thyristor

Like a thyristor, Gate circuit should also be protected from over voltages and over currents. Overvoltage's in the gate circuit can cause false triggering and overcurrent can cause high junction temperature .

Protective Measure: Over voltages **thyristor protection** is achieved by using a zener diode and a resistor can be used to protect the gate circuit from overcurrent. Noise in gate circuit can also cause false triggering which can be avoided by using a resistor and a capacitor in parallel. A diode (D) may be connected in series or in parallel with the gate to protect it from high reverse voltage.

Overall Protection of a Thyristor

Lead mounting: In such mounting technique housing of SCR itself is used as heat radiator. Hence no need of additional heat zink arrangement. Hence, this technique of thyristor Protection is generally used for low current application, normally less than one ampere .
Stud mounting: The anode of the thyristor is in the form of threaded stud which is screwed to a metalling heat sink block .
Bolt-down mounting: Here the device is connected to the heat sink with the help of nut-bolt mechanism. It is mainly used in small and medium rating circuit.
Press fit mounting: This kind of mounting is obtained by inserting the whole SCR into the metallic block. It is used in high rating circuit.
Press-Pack mounting: This kind of mounting for **thyristor protection** is obtained by sandwiching the thyristor between to heat sink with the help of clamps. It is used for very high rating circuit.

METHODS OF SCR COMMUTATION:-

To turn On a Thyristor, there are various triggering methods in which 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 by bringing 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 control a conducting Thyristor must be commutated properly.
There are mainly two techniques for Thyristor Commutation: Natural and Forced. The Forced commutation technique is further divided into five categories which are Class A, B, C, D, and E.

Below is the Classification:

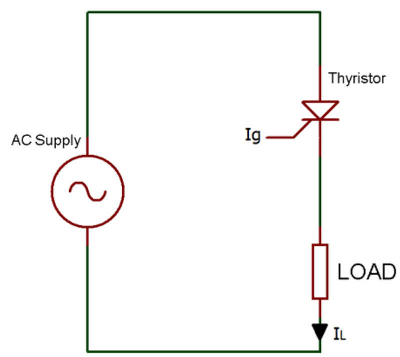
- Natural Commutation
- Forced Commutation
  - Class A: Self or Load Commutation
  - Class B: Resonant-Pulse Commutation
  - Class C: Complementary Commutation

- Class D: Impulse Commutation
- Class E: External Pulse Commutation

Natural Commutation

Natural Commutation occurs only in AC circuits, and it is named so because it 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.

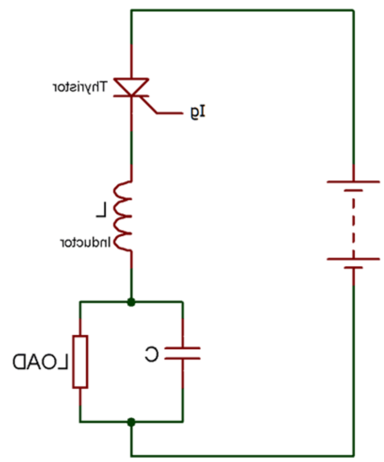


Forced Commutation

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:

1. Class A: Self or Load Commutation

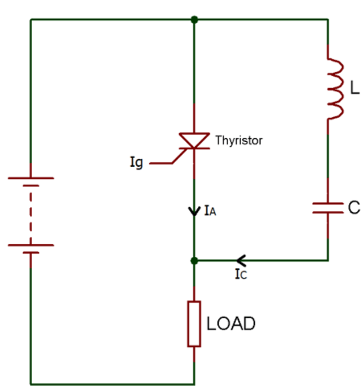
Class A is also called as "Self-Commutation" and it is one of the most used technique among all Thyristor commutation technique. In the below circuit, the inductor, capacitor and resistor form a second order under damp circuit.



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 charges the capacitor to its peak value or equal to the input 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.

2. 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.

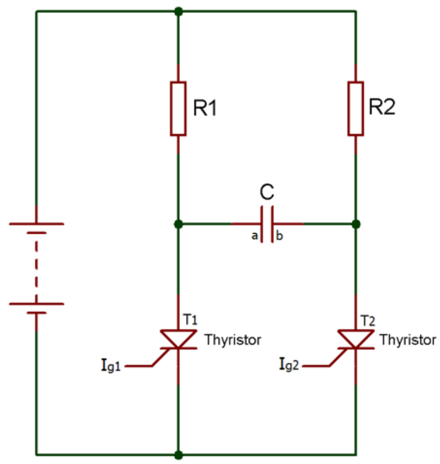


Now, as we apply the input voltage, the capacitor starts charging upto the input voltage (Vs) and Thyristor remains reversed biased until the gate pulse is applied. When we apply the gate pulse, the Thyristor turns ON and now the current start flowing from both the ways. But, then the constant load current 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 I_A. Therefore, due to this opposing commutating current, when the anode current is getting lesser than the holding current, Thyristor turns OFF.

3. Class C: Complementary Commutation

Class C commutation is also called as Complementary Commutation. As you can see the circuit below, there are two Thyristor in parallel, one is main and another is auxiliary.

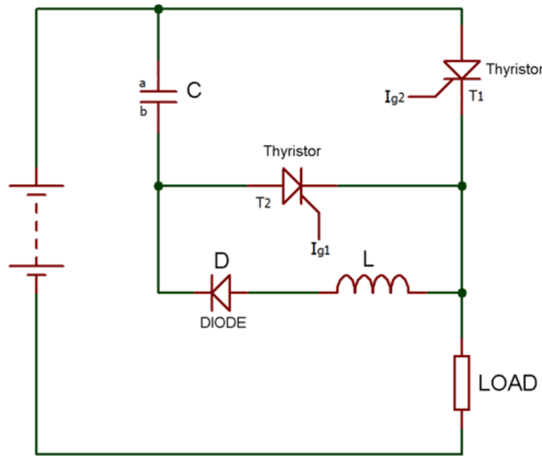


Initially, both the Thyristor are in OFF condition and the voltage across capacitor is also zero. Now, as the gate pulse is applied to the main Thyristor, the current will start flowing from two paths, one is from R1-T1 and second is R2-C-T1. Hence, the capacitor also starts charging to the peak value equal to the input voltage with the polarity of plate B positive and plate A negative.

Now, as the gate pulse is applied to the Thyristor T2, it turns ON and a negative polarity of current appear across the Thyristor T1 which cause T1 to get turn OFF. And, the capacitor starts charging with the reverse polarity. Simply we can say that when T1 turns ON it turns OFF T2 and as T2 turns ON it turns OFF T1.

4. Class D: Impulse Commutation

Class D commutation is also called as Impulse Commutation or Voltage Commutation. As Class C, Class D commutation circuit also consists of two Thyristor T1 and T2 and they are named as main and auxiliary respectively. Here, diode, inductor, and auxiliary Thyristor form the commutation circuit.



Initially, both the Thyristor are in OFF state and voltage across capacitor C is also zero. Now as we apply the input voltage and trigger the Thyristor T1 the load current starts flowing through it. And, the capacitor starts charging with polarity of plate A negative and plate B positive.

Now, as we trigger the auxiliary Thyristor T2, the main Thyristor T1 turns OFF and the capacitor starts charging with the opposite polarity. When it gets full-charged, it causes the auxiliary Thyristor T2 to turn OFF, because a capacitor does not allow the flow of current through it when it gets fully charged.

Therefore, the output current will also be zero because at this stage because of both the Thyristors are in OFF state.

5. Class E: External Pulse Commutation

Class E commutation is also called External Pulse Commutation. Now, you can see in the circuit diagram, the Thyristor is already in forward bias. So, as we trigger the Thyristor, the current will appear at the load.

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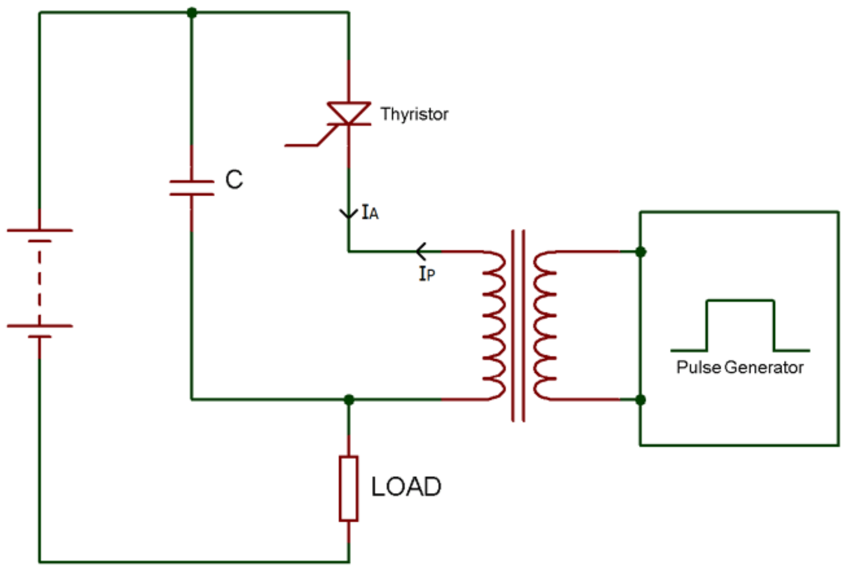

The capacitor in the circuit is used for the dv/dt protection of the Thyristor and the pulse transformer is used to turn OFF the Thyristor.

Now, when we give pulse through the pulse transformer an opposite current will flow in the direction of the cathode. This opposite current oppose the flow of the anode current and if $\mathbf{I_A - I_P < I_H}$ Thyristor will turn OFF.

Where $\mathbf{I_A}$ is Anode current, $\mathbf{I_P}$ is pulse current and $\mathbf{I_H}$ is holding current.

starts charging to the peak value equal to the input voltage with the polarity of plate B positive and plate A negative.

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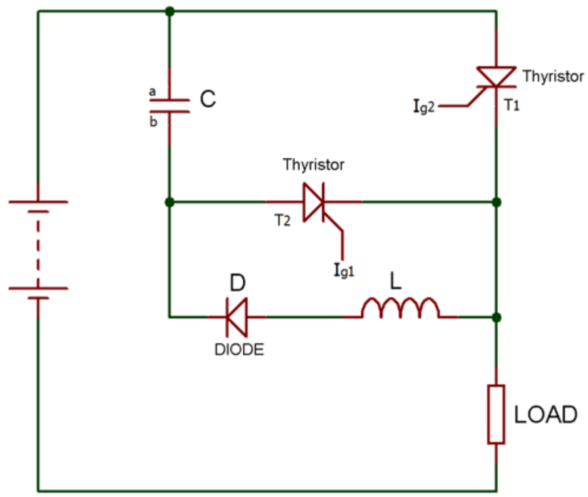

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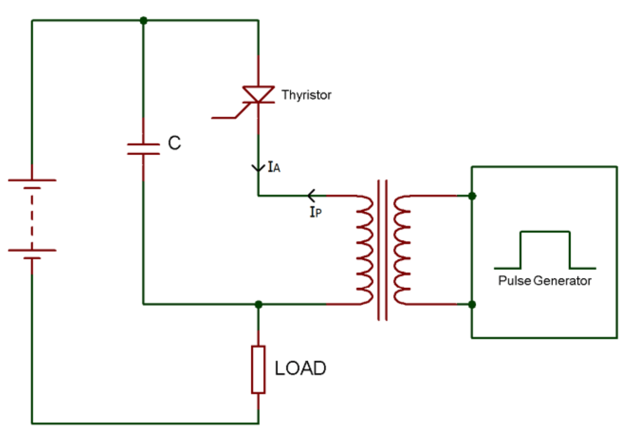

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Where $\mathbf{I_A}$ is Anode current, $\mathbf{I_P}$ is pulse current and $\mathbf{I_H}$ is holding current.

UJT AS A TRIGGER SOURCE:-

UJT Triggering of SCR Working Principle – One common application of the unijunction transistor is the triggering of the other devices such as the SCR, triac etc. The basic elements of such a triggering circuit are shown in Fig. 26.91. The resistor R_E is chosen so that the load line determined by R_E passes through the device characteristic in the negative resistance region i.e., to the right of the peak point but to the left of the valley point, as shown in Fig. 26.92. If the load line does not pass to the right of the peak point P, the device cannot turn on.

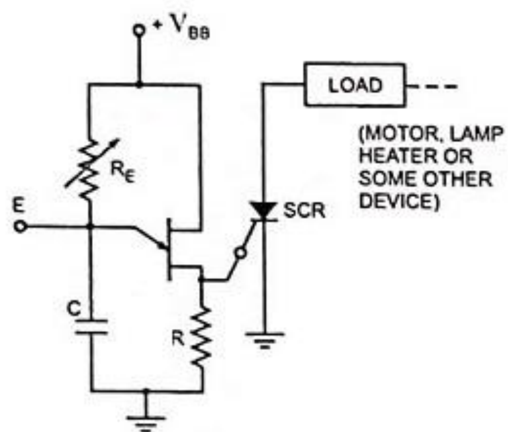


Fig. 26.91 *UJT Triggering of An SCR*

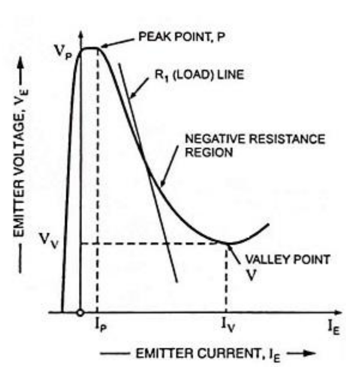


Fig. 26.92

$$R_E < \frac{V_{BB} - V_P}{I_P} \qquad \ldots(26.37)$$

This can be established as below :

Consider the peak point at which $I_{RE} = I_P$ and $V_E = V_P$ (the equality $I_{RE} = I_P$ is valid because the charging current of capacitor at this instant is zero i.e., the capacitor, at this particular instant, is changing from a charging state to a discharging state). Then $V_E = V_{BB} - I_{RE}R_E$.

So

$$R_{E\,(max)} = \frac{V_{BB} - V_E}{I_{R_E}} = \frac{V_{BB} - V_P}{I_P} \text{ at the peak point.}$$

$$\text{or } R_E < \frac{V_{BB} - V_P}{I_P}$$

At the valley point, V

$I_E = I_V$ and $V_E = V_V$ so that

$V_E = V_{BB} - I_{RE}R_E$

So

$$R_{E\,(min)} = \frac{V_{BB} - V_E}{I_{R_E}} = \frac{V_{BB} - V_V}{I_V}$$

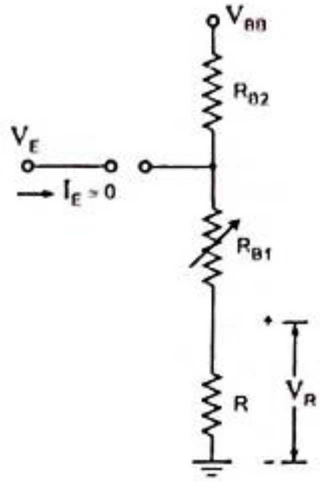
or for ensuring turn-off

$$R_E > \frac{V_{BB} - V_V}{I_V} \qquad \ldots(26.38)$$

So the range of resistor R_E is given as

$$\frac{V_{BB} - V_P}{I_P} > R_E > \frac{V_{BB} - V_V}{I_V}$$

The resistor R is chosen small enough so as to ensure that SCR is not turned on by voltage V_R when emitter terminal E is open or $I_E = 0$ (Fig. 26.93). The Voltage $V_R = RV_{BB}/R + R_{BB}$ for open-emitter terminal.

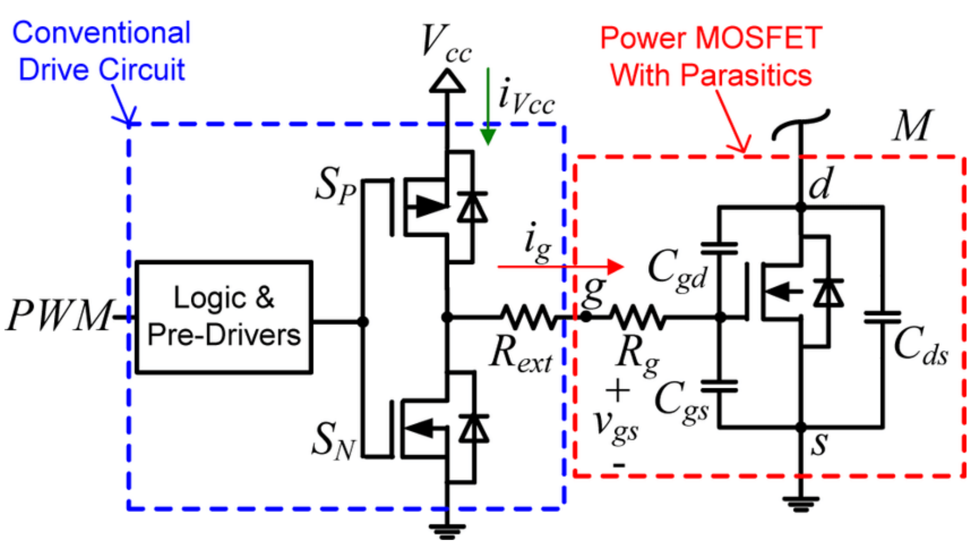


The capacitor C determines the time interval between triggering pulses and the time duration of each pulse.

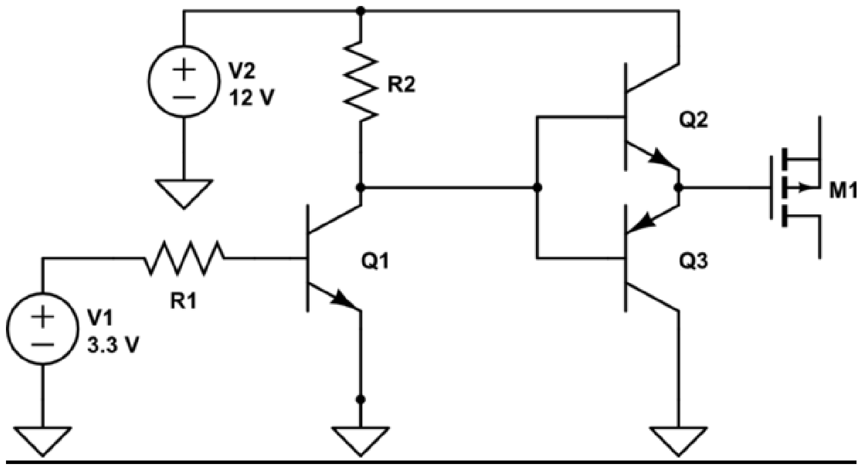
By varying R_E, we can change the time constant R_EC and alter the point at which the UJT fires. This allows us to control the conduction angle of the SCR, which means the control of load current.

GATE DRIVE CIRCUITS FOR BJT AND MOSFETs

A gate driver is **a power amplifier that accepts a low-power input from a controller IC and produces a high-current drive input for the gate of a high-power transistor** such as an BJT and MOSFET. Gate drivers can be provided either on-chip or as a discrete module.



BJT



UNIT – II

Single phase and three phase controlled rectifiers

Phase control technique – Single phase Line commutated converters

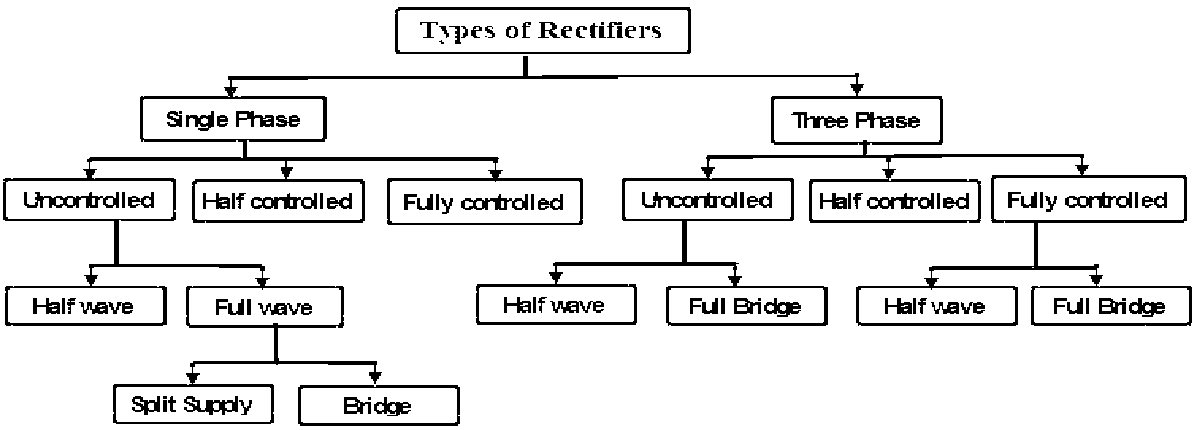
Unlike diode rectifiers, PCRs or phase controlled rectifiers has an advantage of regulating the output voltage. The diode rectifiers are termed as uncontrolled rectifiers. When these diodes are switched with Thyristors, then it becomes phase control rectifier. The o/p voltage can be regulated by changing the firing angle of theThyristors. The main application of these rectifiers is involved in speed control of DC motor.

What is a Phase Controlled Rectifier?

The term PCR or Phase controlled rectifier is a one type of rectifier circuit in which the diodes are switched by Thyristors or SCRs (Silicon Controlled Rectifiers). Whereas the diodes offer no control over the o/p voltage, the Thyristors can be used to differ the output voltage by adjusting the firing angle or delay. A phase control Thyristor is activated by applying a short pulse to its gate terminal and it is deactivated due to line communication or natural. In case of heavy inductive load, it is deactivated by firing another Thyristor of the rectifier during the negative half cycle of i/p voltage.

Types of Phase Controlled Rectifier

The phase controlled rectifier is classified into two types based on the type of i/p power supply. And each kind includes a semi, full and dual converter.



Single-phase Controlled Rectifier

This type of rectifier which works from single phase AC i/p power supply Single

Phase Controlled Rectifiers are classified into different types

Half wave Controlled Rectifier: This type of rectifier uses a single Thyristor device to provide o/p control only in one half cycle of input AC supply, and it offers low DC output.

Full wave Controlled Rectifier: This type of rectifier provides higher DC output

Full wave controlled rectifier with a center tapped transformer requires two

Thyristors.

Full wave bridge controlled rectifiers do not need a center tapped transformer

Three-phase Controlled Rectifier

This type of rectifier which works from three phase AC i/p power supply

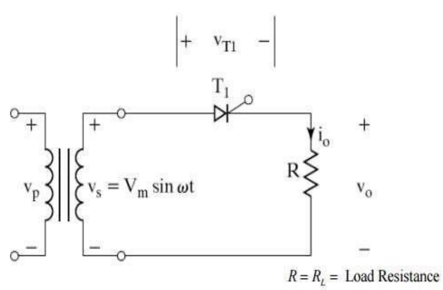
A semi converter is a one quadrant converter that has one polarity of o/p voltage and current.
A full converter is a a two quadrants converter that has polarity of o/p voltage can be either +ve or –vebut, the current can have only one polarity that is either +ve or -ve.

Dual converter works in four quadrants – both o/p voltage and o/p current can have both the polarities.

Operation of Phase Controlled Rectifier

The basic working principle of a PCR circuit is explained using a single phase half wave PCR circuit witha RL load resistive shown in the following circuit.

A single phase half wave Thyristor converter circuit is used to convert AC to DC power conversion. The i/p AC supply is attained from a transformer to offer the required AC supply voltage to the Thyristor converter based on the o/p DC voltage required. In the above circuit, the primary and secondary AC supply voltages are denoted with VP and VS.



During the +ve half cycle of i/p supply when the upper end of the transformer secondary winding is at a + ve potential with respect to the lower end, the Thyristor is in a forward biased state.

The thyristor is activated at a delay angle of ωt =α, by applying an appropriate gate trigger pulse to the gate terminal of thyristor. When the thyristor is activated at a delay angle of ωt =α, the thyristor behaviors and assuming a perfect thyristor. The thyristor acts as a closed switch and the i/p supply voltage acts across the load when it conducts from ωt =α to π radians For a purely resistive load, the load current io that flows when the thyristor T1 is on, is given by the expression.

Applications of Phase Controlled Rectifier

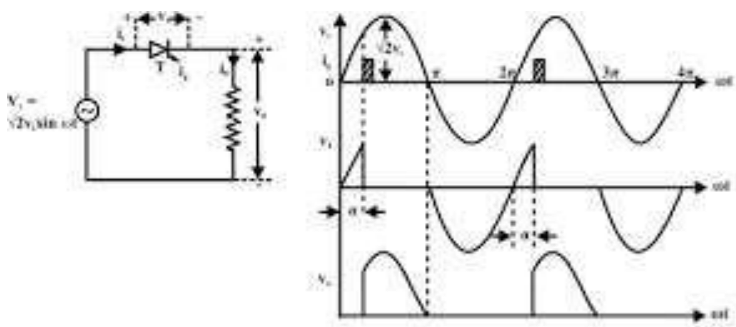
Phase controlled rectifier applications include paper mills, textile mills using DC motor drives and DC motor control in steel mills.

- AC fed traction system using a DC traction motor.
- Electro-metallurgical and Electrochemical processes.
- Reactor controls.
- Magnet power supplies.
- Portable hand instrument drives.
- Flexible speed industrial drives.
- Battery charges.
- High voltage DC transmission.
- UPS (Uninterruptible power supply systems).

Operation of half converter with R and RL loads

Single Phase Half Wave Controlled Rectifier with 'R' load:

As shown in figure below primary of transformer is connected to ac mains supply with which SCR becomes forward bias in positive half cycle. T1 is triggered at an angle α, T1 conducts and voltage is applied across R.



The load current i_0 flows through 'R'

the waveforms for voltage & current are as shown above. As load is resistive, Output current is given as,

$$I_o = \frac{V_o}{R}$$

Hence shape of output current is same as output voltage

As T1 conducts only in positive half cycle as it is reversed bias in negative cycle, the ripple frequency of output voltage is-

fripple= 50 Hz (supply frequency) Average output voltage is given as,

$$V_0(Avg) = \frac{1}{T}\int_0^T V_0(wt)\,dwt$$

i.e Area under one cycle.

Therefore T=2π&Vo(ωt) = Vm sinωt from α to π& for rest of the period Vo(ωt)=0

$$\therefore V_0(Avg) = \frac{1}{2\pi}\int_0^{2\pi} V_m sin(wt)\, dwt$$
$$= \frac{V_m}{2\pi}[-coswt]_\alpha^\pi$$
$$= \frac{V_m}{2\pi}(1 + cos\alpha)$$

Power transferred to load,

$$P_0(Avg) = \frac{V_0^2(Avg)}{R}$$

Thus, power & voltage can be controlled by firing angle.

Single Phase Half Wave Controlled Rectifier with 'RL' load

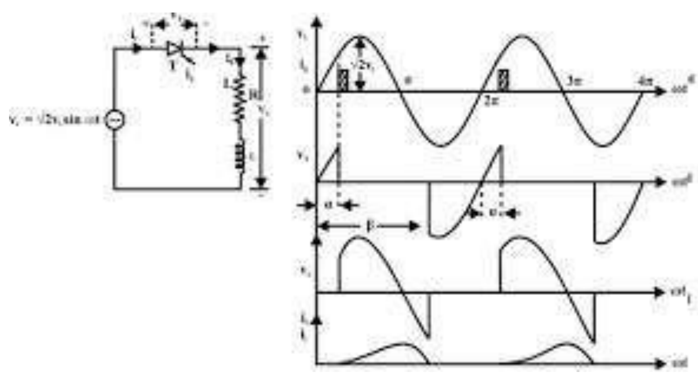


Figure above shows the single phase half wave rectifier with RL Load.

Normally motors are inductive loads L= armature of field coil inductance

R= Resistance of coil.

In positive half cycle, SCR starts conduction at firing angle "α".

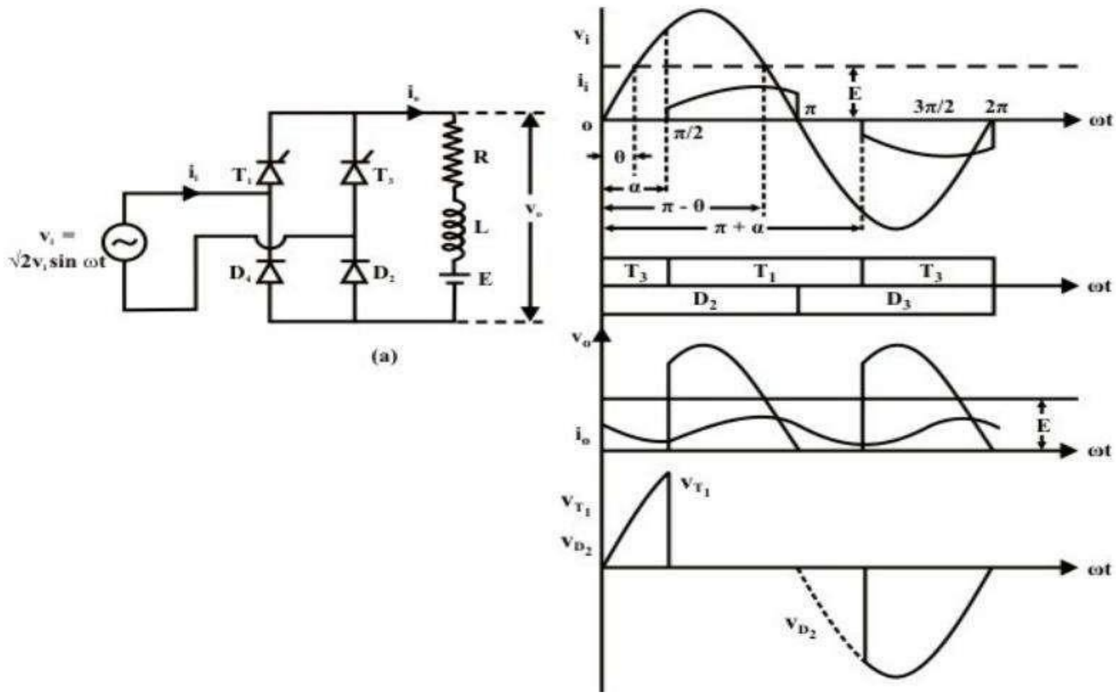
Drop across SCR is small & neglected so output voltage is equal to supply voltage.

- Due to ‘R_L’ load, current through SCR increases slowly.
- At ‘π’, supply voltage is at zero where load current is at its max value.
- In positive half cycle, inductor stores energy & that generates the voltage.
- In negative half cycle, the voltage developed across inductor, forward biases SCR & maintains its conduction.
- Basically with the property of inductance it opposes change in current.
- Output current & supply current flows in same loop, so all the time $i_o = i_s$.
- After π the energy of inductor is given to mains & there is flow of ‘io’. The energy reduces as if gets consumed by circuit so current also reduces.
- At ‘β’ energy stored in inductance is finished, hence ‘i_o’ becomes zero & ‘T1’ turns off.
- ‘i_o’ becomes zero from ‘β’ to ‘2π+α’ hence it is discontinuous conduction.

Single phase half controlled converter with RLE load

The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveform respectively. On the other hand T1 starts conduction when it is fired in the positive half cycle of the input voltage waveform and continuous conduction till T3 is fired in the negative half cycle. Fig. shows the circuit diagram and the waveforms of a single phase half controlled converter supplying an R – L – E load.

Referring to Fig T1 D2 starts conduction at ωt = α. Output voltage during this period becomes equal to

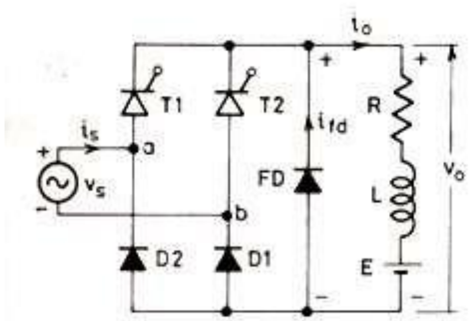


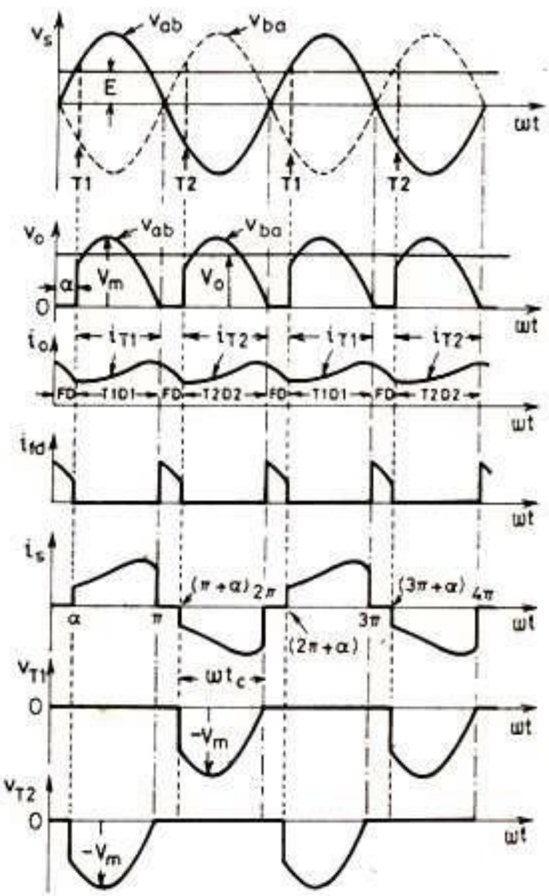
At ωt = π as vi tends to go negative D4 is forward biased and the load current commutates from D2 to D4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at ωt = π + α. The T3 D4 conduction mode continues upto ωt = 2π. Where upon load current again free wheels through T3 and D2 while the load voltage is clamped to zero. From the discussion in the previous paragraph it can be concluded that the output voltage (hence the output current) is periodic over half the input cycle. Hence

$$V_{oav} = \frac{1}{\pi}\int_{o}^{\pi} v_o \, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2} V_i \sin \omega t \, d\omega t = \frac{\sqrt{2} V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2} V_i}{\pi R}(1+\cos\alpha - \pi \sin\theta)$$

Single phase half controlled converter with RLE load and freewheeling diode

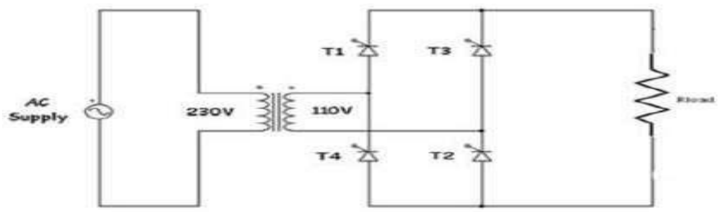


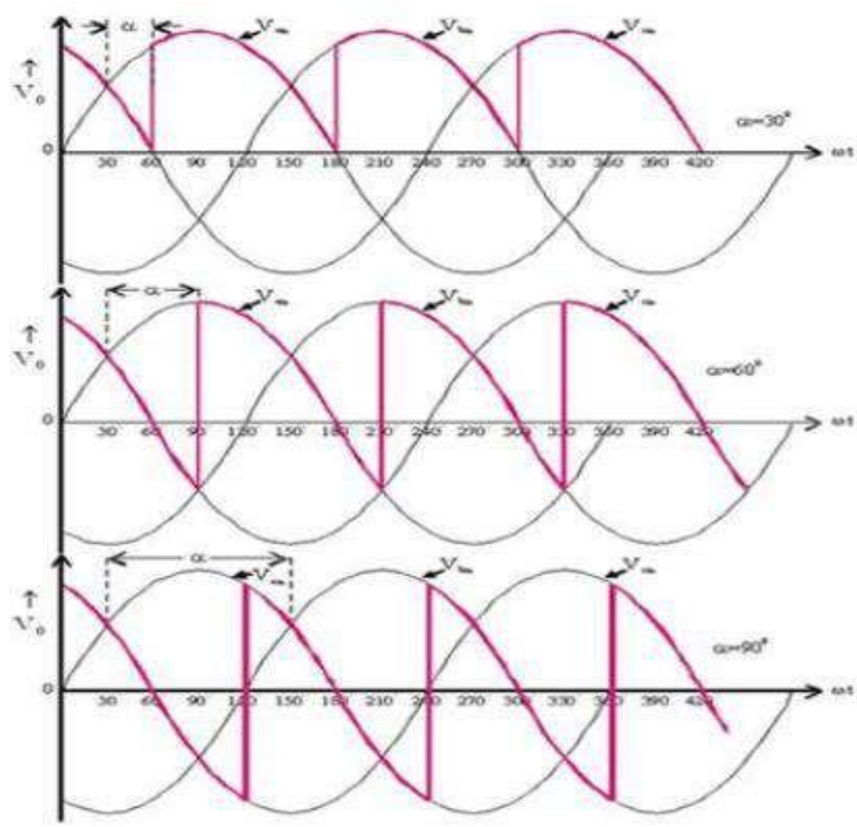


Single phase full wave controlled rectifier

Single Phase Full Wave Controlled Rectifier with 'R' load:

Figure below shows the Single phase Full Wave Controlled Rectifiers with R load





The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS(Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply).

•All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for

•duration equal to the turn-off time of the device specified in the data sheet.

•In positive half cycle Thyristors T1 & T2 are fired at an angle α .

•When T1 & T2 conducts Vo=Vs IO=is=Vo/R=Vs/R

•In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)

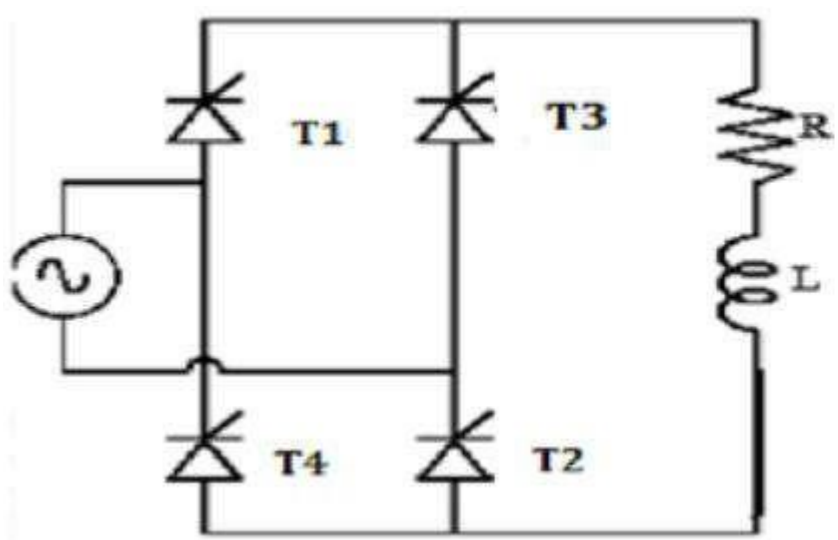
•Here output current & supply current are in opposite direction

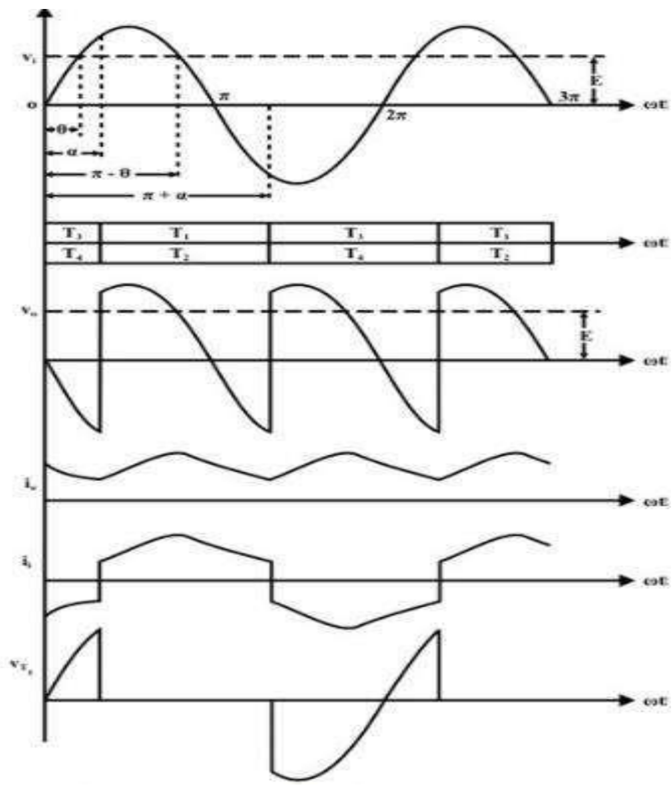
∴ is=-io

T3 & T4 becomes off at 2π.

single Phase Full Wave Controlled Rectifier with 'RL' load:

Figure below shows Single phase Full Wave Controlled Rectifiers with RL load.





Operation of this mode can be divided between four modes

Mode 1 (α toπ)

• In positive half cycle of applied ac signal, SCR's T1 & T2 are forward bias

& can be turned on at anangle α.

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

free, constant and equal to Io.

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

Mode 2 (π toπ+α)

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

change through it.

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

‘L’ as shown.

- Due to this induced voltage, SCR’s T1 & T2 are forward bais in spite the negative supply voltage.
- The load voltage is negative & equal to instantaneous ac supply voltage whereas load current is positive.
- Thus, load acts as source & stored energy in inductance is returned back to the ac supply.

Mode 3 (π+α to 2π)

- At wt=π+α SCR’s T3 & T4 are turned on & T1, T2 are reversed bias.
- Thus , process of conduction is transferred from T1,T2 to T3,T4.
- Load voltage again becomes positive & energy is stored in inductor
- T3, T4 conduct in negative half cycle from (π+α) to 2π
- With positive load voltage & load current energy gets stored

Mode 4 (2π to 2π+α)

- At wt=2π, input voltage passes through zero.
- Inductive load will try to oppose any change in current if in order to maintain load current constant & in

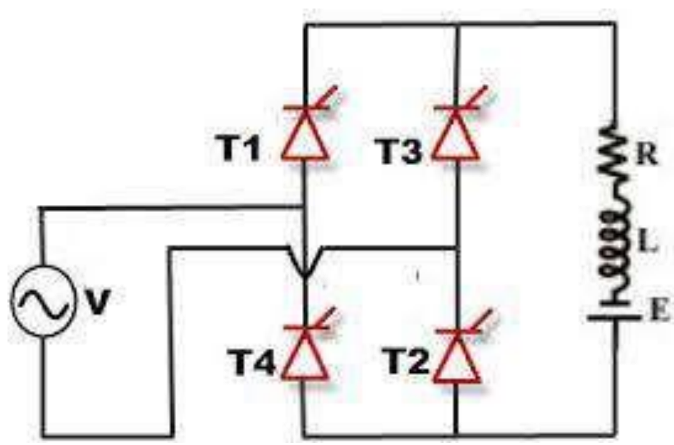
  the same direction.
- Induced emf is positive & maintains conducting SCR’s T3 & T4 with reverse polarity also.
- Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to be

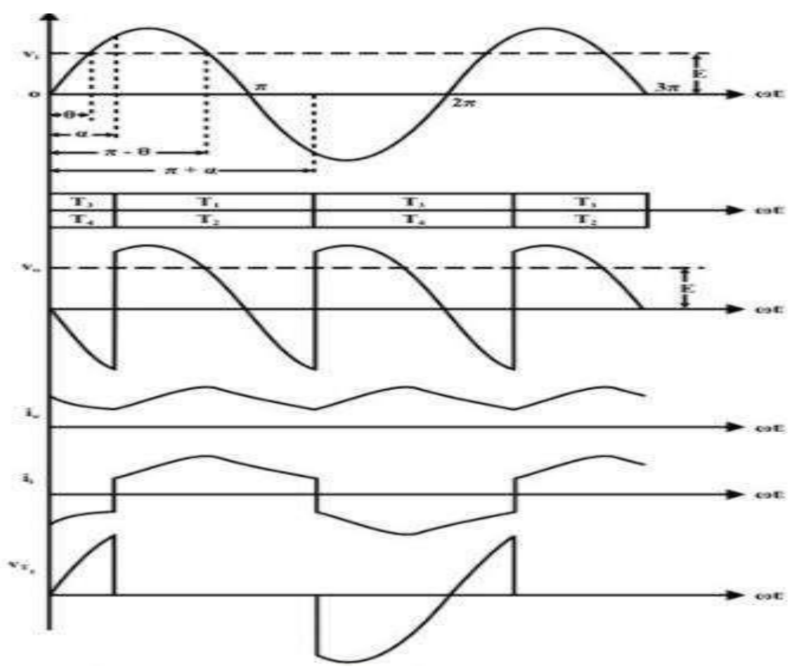
  positive.
- Thus load acts as source & stored energy in inductance is returned back to ac supply
- At wt=α or 2π+α, T3 & T4 are commutated and T1,T2 are turned on.

Single phase fully controlled converters with RLE load

The circuit diagram of a full wave bridge rectifier using thyristors in shown in figure below. It consists offour SCRs which are connected between single phase AC supply and a load.

This rectifier produces controllable DC by varying conduction of all SCRs.





In positive half-cycle of the input, Thyristors T1 and T2 are forward biased while

T3 and T4 are reverse biased. Thyristors T1 and T2 are triggered simultaneously at some firing angle in the positive half cycle, and T3 and T4 are triggered in the negative half cycle.

The load current starts flowing through them when they are in conduction state. The load for this converter can be RL or RLE depending on the application.

By varying the conduction of each thyristor in the bridge, the average output of this converter gets controlled. The average value of the output voltage is twice that of half-wave rectifier.

1. Input volt amperes = (RMS source voltage)(RMS line current)

$= V_S I_{rms}$

$$= V_s \frac{\sqrt{2}Vs}{R2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}sin2\alpha\right]^{1/2}$$

$$= \frac{Vs^2}{\sqrt{2\pi}XR}\left[(\pi-\alpha)+\frac{1}{2}sin2\alpha\right]^{1/2}$$

2. Input power factor: It is defined as the ratio of total mean input power to the total rms input voltamperes

3. form factor: Form factor is defined as the ratio of RMS voltage to the average DC voltage Form Factor = Vrms/Vavg

4. Effective value of the AC component of the output voltage

$V_{ac} = [Vrms^2 - Vavg^2]^{1/2}$

5. Ripple factor (R_f)

It is defined as the ratio of AC component to the DC. Where ripple is the amount of AC component present in DC component

$$R_f = \frac{Vac}{Vavg} = \frac{[Vrms^2 - Vavg^2]^{1/2}}{Vavg} = \left[\left(\frac{Vrms}{Vavg}\right)^2 - 1\right]^{1/2} = \sqrt{FF^2 - 1}$$

Effect of source inductance in single phase rectifier

Fig. below shows a single phase fully controlled converter with source inductance. For simplicity it has been assumed that the converter operates in the continuous conduction mode. Further, it has been assumed that the load current ripple is negligible and the load can be replaced by a dc current source the magnitude of which equals the average load current. Fig. shows the corresponding waveforms

It is assumed that the Thyristors T3 and T4 were conducting at t = 0. T1 and T2 are fired at $\omega t = \alpha$.

If there were no source inductance T3 and T4 would have commutated as soon as T1 and T2 are turned ON.

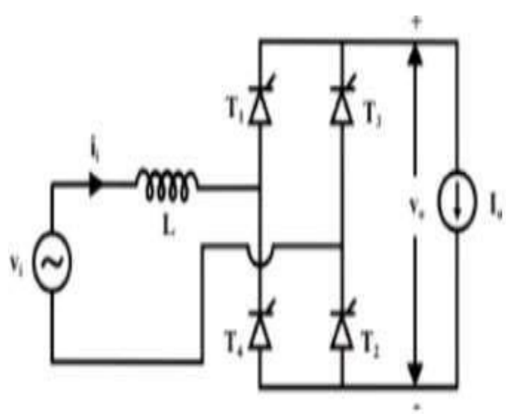
Effect of source inductance in single phase rectifier

Fig. below shows a single phase fully controlled converter with source inductance. For simplicity it has been assumed that the converter operates in the continuous conduction mode. Further, it has beenassumed that the load current ripple is negligible and the load can be replaced by a dc current source the magnitude of which equals the average load current. Fig. shows the corresponding waveforms

It is assumed that the Thyristors T3 and T4 were conducting at t = 0. T1 and T2 are fired at ωt = α. If

there were no source inductance T3 and T4 would have commutated as soon as T1 and T2 are turned ON.

The input current polarity would have changed instantaneously. However, if a source inductance is present the commutation and change of input current polarity cannot be instantaneous. s. Therefore, whenT1 and T2 are turned ON T3 T4 does not commutate immediately. Instead, for some interval all four Thyristors continue to conduct as shown in Fig. 2.14. This interval is called "overlap" interval.



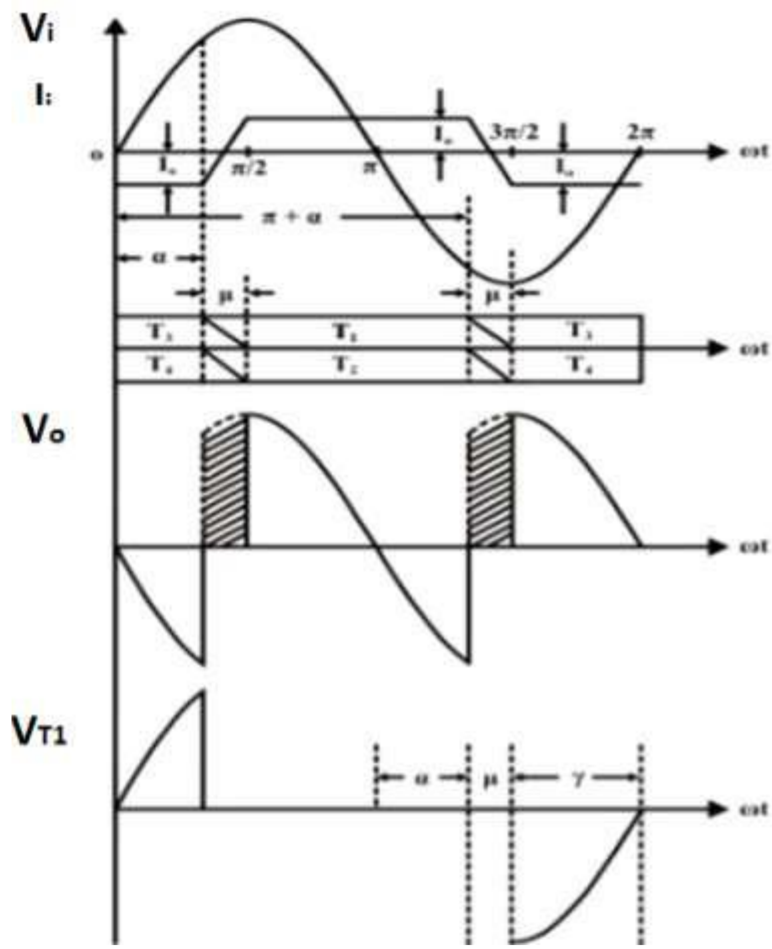


Figure: 2.14 single phase full converter output waveforms with source inductance

1. During overlap interval the load current freewheels through the thyristors and the output voltage is clamped to zero. On the other hand, the input current starts changing polarity as the current through T1 and T2 increases and T3 T4 current decreases. At the end of the overlap interval the current through T3 and T4 becomes zero and they commutate, T1 and T2 starts conducting the full load current

2. The same process repeats during commutation from T1 T2 to T3T4 at ωt = π + α . From Fig. 2.14 it is clear that, commutation overlap not only reduces average output dc voltage but also reduces the extinction angle γ which may

cause commutation failure in the inverting mode of operation if α is very close to 180°.

3. In the following analysis an expression of the overlap angle "μ" will be determined. From the

equivalent circuit of the converter during overlap period.

$$L\frac{di_i}{dt} = v_i \;\; for \;\; \alpha \leq \omega t + \mu$$

$$i_i(\omega t = \alpha) = -I_0$$

$$i_i = I - \frac{\sqrt{2}V_i}{\omega L} cos\omega t$$

$$\therefore i_i|_{\omega t - \alpha} = I - \frac{\sqrt{2}V_i}{\omega L} cos\alpha = -I_0$$

$$I = \frac{\sqrt{2}V_i}{\omega L}\cos\alpha - I_0$$

$$\therefore \quad i_i = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu \quad i_i = I_0$

$$I_0 = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos(\alpha + \mu)) - I_0$$

$$\therefore \quad \cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_0} I_0$$

$$V_0 = \frac{I}{\pi}\int_{\alpha}^{\alpha+\pi} V_i d\,\omega t$$

or $$V_0 = \frac{I}{\pi}\int_{\alpha+\mu}^{\alpha+\pi} \sqrt{2}v_i \sin\omega t d\,\omega t$$

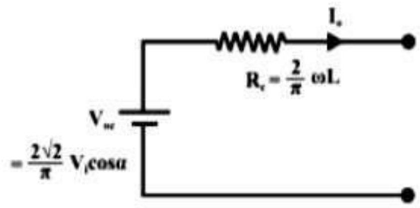
$$= \frac{\sqrt{2}v_i}{\pi}[\cos(\alpha + \mu) - \cos(\pi + \alpha)]$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos\alpha + \cos(\alpha + \mu)]$$

$$\therefore V_0 = 2\sqrt{2}\frac{v_i}{\pi}[cos\alpha - cos(\alpha + \mu)]$$

$$\therefore V_0 = \frac{2\sqrt{2}}{\pi}v_i cos\alpha - \frac{2}{\pi}\omega L I_0$$

The Equation can be represented by the following equivalent circuit



Equivalent circuit representation of the single phase fully controlled rectifier with source inductance

The simple equivalent circuit of Fig. represents the single phase fully controlled converter with source inductance as a practical dc source as far as its average behavior is concerned. The open circuit voltage of this practical source equals the average dc output voltage of an ideal converter (without source inductance) operating at a firing angle of α. The voltage drop across the internal resistance "RC"represents the voltage lost due to overlap shown in Fig. 2.14 by the hatched portion of the Vo waveform. Therefore, this is called the "Commutation resistance". Although this resistance accounts for the voltage drop correctly there is no power loss associated with this resistance since the physical process of overlap does not involve any power loss. Therefore this resistance should be used carefully where power calculation is involved.

Operation of three phase half wave rectifier with R and RL loads

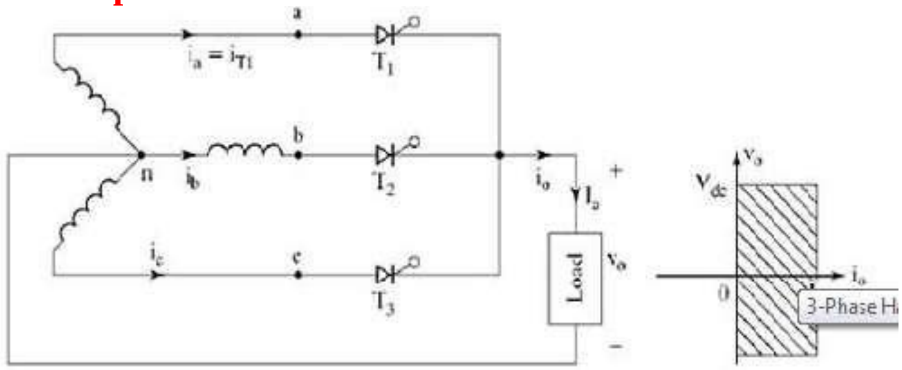
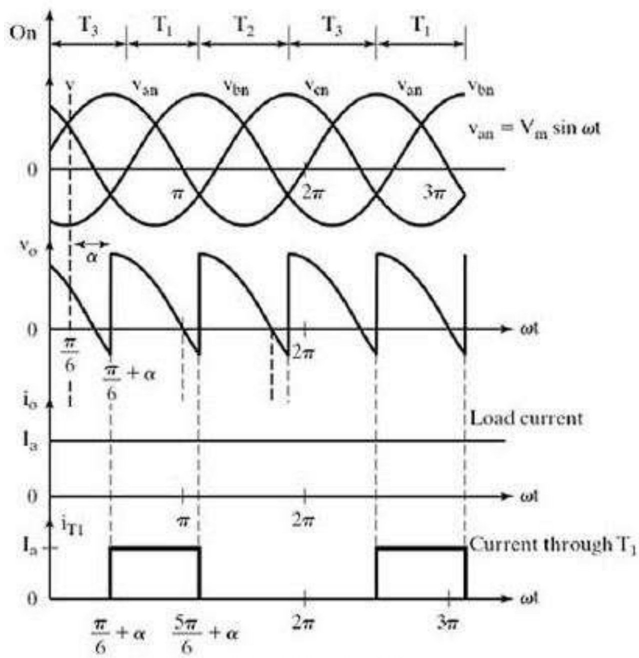


Figure: circuit diagram three phase half wave rectifier



Three phase supply voltage equations

We define three line neutral voltages (3 phase voltages) as follows $V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$$V_{YN} = V_{bn} = V_m \sin\left(wt - \frac{2\pi}{3}\right)$$

$$V_{BN} = V_{cn} = V_m \sin\left(wt - \frac{4\pi}{3}\right)$$

The **3-phase half wave converter** combines three **single phase half wave controlled rectifiers in one** single circuit feeding a common load. The thyristor T_1 in series with one of the supply phase windings *'a-n'* acts as one half wave controlled rectifier The second thyristor T_2 in series with the supply phase winding *'b-n'* acts as the second half wave controlled rectifier. The third thyristor T_3in series with the supply phase winding acts as the third half wave controlled rectifier.

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 at $\omega t=(\prod/6 + \alpha)=(30° + \alpha)$, the phase voltage V_{an} appears across the load when T_1 conducts. The load current flows through the supply phase winding *'a- n'* and through thyristor T_1 as long as T_1 conducts.

When thyristor T_2 is triggered at $\omega t=(5\prod/6\alpha)$, T_1 becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding *'b-n'* . WhenT_2 conducts the phase voltage v_{bn} appears across the load until the thyristor T_3 is triggered .

When the thyristor T_3 is triggered at $\omega t=(3\prod/2 + \alpha)=(270°+\alpha)$, T_2 is reversed biased and hence T_2turns-off. The phase voltage V_{an} appears across the load when T_3 conducts.

When T_1 is triggered again at the beginning of the next input cycle the thyristor T_3 turns off as it is reverse biased naturally as soon as T_1 is triggered. The figure shows the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristor T_1.

For a purely resistive load where the load inductance 'L = 0' and the trigger angle $\alpha > (\prod/6)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output

ripple frequency for a **3-phase half wave converter** is f_s, where f_s is the input supply frequency.3

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 (i.e., the supply current waveforms have an average or dc value).

The reference phase voltage is $v_{RN}=v_{an}=V_m sin\omega t$. The trigger angle is measured from the cross over points of the 3-phase supply voltage waveforms. When the phase supply voltage V_{an} begins its positive half cycle at $\omega t=0$, the first cross over point appears at $\omega t=(\prod/6)$*radians* 30°.

The trigger angle α for the thyristor T_1 is measured from the cross over point at . The thyristor T_1 is forward biased during the period ωt=30° to 150° , when the phase supply voltage v_{an} has higher amplitude than the other phase supply voltages. Hence T_1 can be triggered between 30° to 150°. When the thyristor T_1 is triggered at a trigger angle α, the average or dc output voltage for continuous load current is calculated using the equation

$$V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} Vmsinwt\, d(wt)$$

$$= \frac{3Vm}{2\pi}\left[(-cos\alpha)_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\right]$$

$$= \frac{3\sqrt{3}Vm}{2\pi}\ cos\alpha$$

$$= \frac{3Vml}{2\pi}\ cos\alpha$$

Operation of three phase half controlled rectifier with R and RL loads

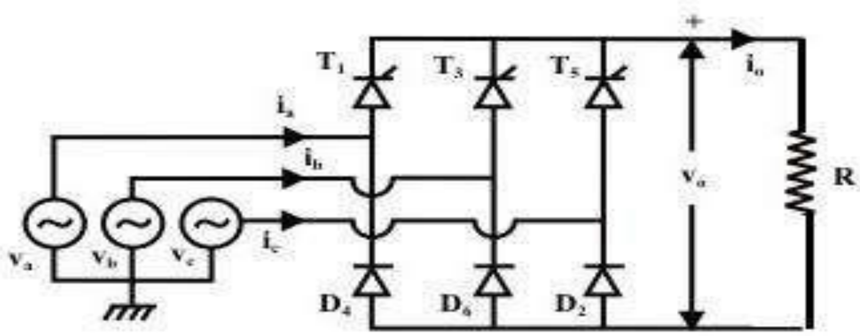
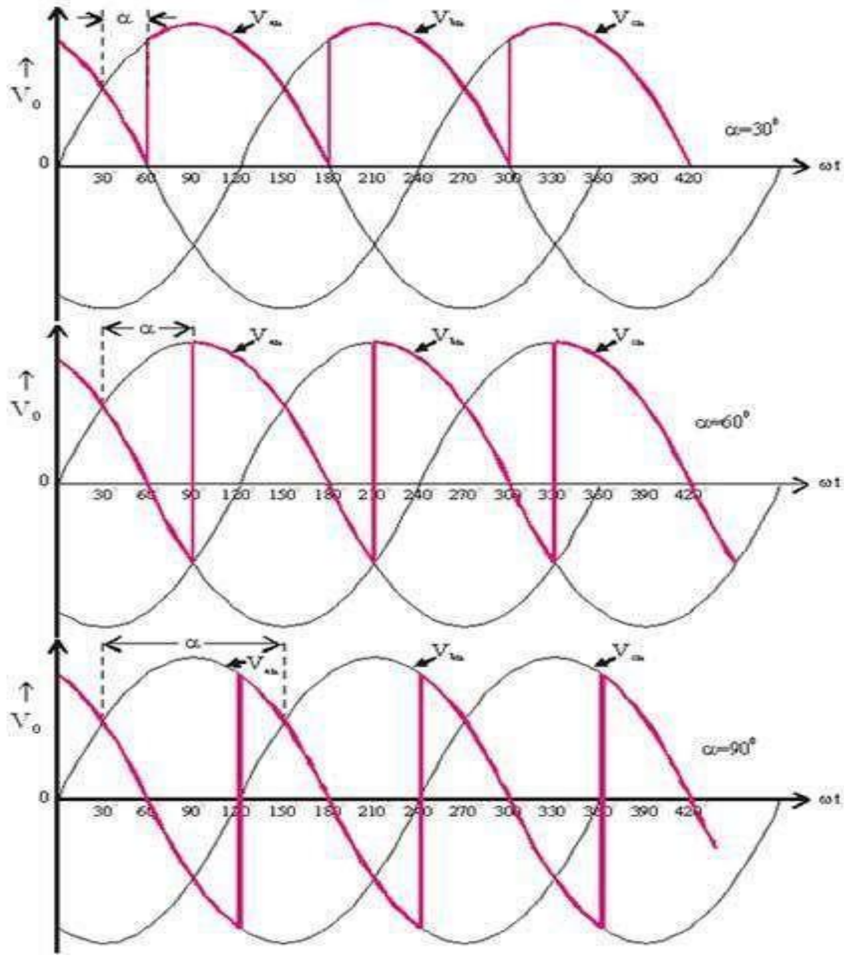


Figure:circuit diagram three phase half controlled rectifier

Three phase half wave controlled rectifier output voltage waveforms



Three single phase half wave converters can be connected to form a three phase half wave converter. Similarly three phase semi converter uses 3 SCRs T1, T3 & T5 and 3 diodes D2, D4&D6 In the circuit shown above when any device conducts, line voltage is applied across load. so line voltage are necessary to draw Phase shift between two line voltages is 60 degree & between two phase voltages it is 120 degree Each phase & line voltage is sine wave with the frequency of 50 Hz. R,Y,B are phase voltages with respect to 'N'.

In the case of a **three-phase half wave controlled** rectifier with resistive load, the thyristor T_1 is triggered at $\omega t=(30°+\alpha)$ and T_1 conducts up to *ωt=180°=&pron;* radians. When the phase supply voltage decreases to zero at , the load current falls to zero and the thyristor T_1 turns off. Thus T_1 conducts from *ωt=(30° + α) to (180°).*

Operation of three phase fully controlled rectifier with R and RL loads

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.

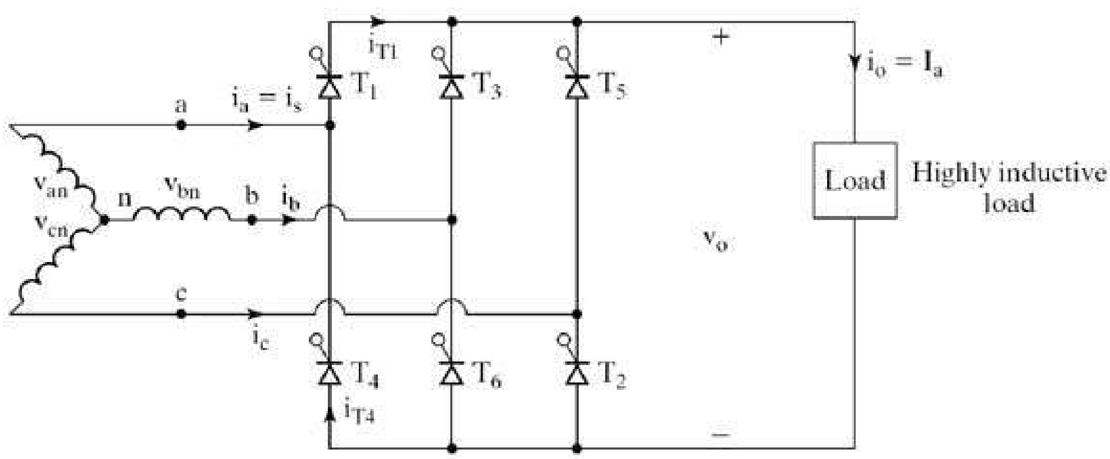


Figure: circuit diagram three phase fully controlled rectifier with R and RL load

At ω*t=(∏/6 +α)* , thyristor is already conducting when the thyristor is turned on by applying the gating signal to the gate of . During the time period ω *t=(∏/6 +α)* to (∏/2 +α), thyristors and conduct together and the line to line

supply voltage appears across the load.

At $\omega t=(\prod/2 \ +\alpha)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period $\omega\, t=(\prod/ \ +\alpha)$ *to* $(5\prod/6 \ +\alpha)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage appears across the load.

The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4, the supply current through the line ‘a’.

We define three line neutral voltages (3 phase voltages) as follows

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$V_{YN} = V_{bn} = V_m \sin(wt - \frac{2\pi}{3})$

$V_{BN} = V_{cn} = V_m \sin(wt - \frac{4\pi}{3})$

The corresponding line to line voltages are

$V_{RY} = V_{ab} = V_{an} - V_{bn} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right)$

$V_{YB} = V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\,Vm \sin\left(wt - \frac{\pi}{2}\right)$

$V_{BR} = V_{ca} = V_{cn} - V_{an} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{2}\right)$

To derive an expression for the average output voltage of **three phase full converter** with highly inductive load assuming continuous and constant load current

The output load voltage consists of 6 voltage pulses over a period of 2∏ radians, hence the average output voltage is calculated as

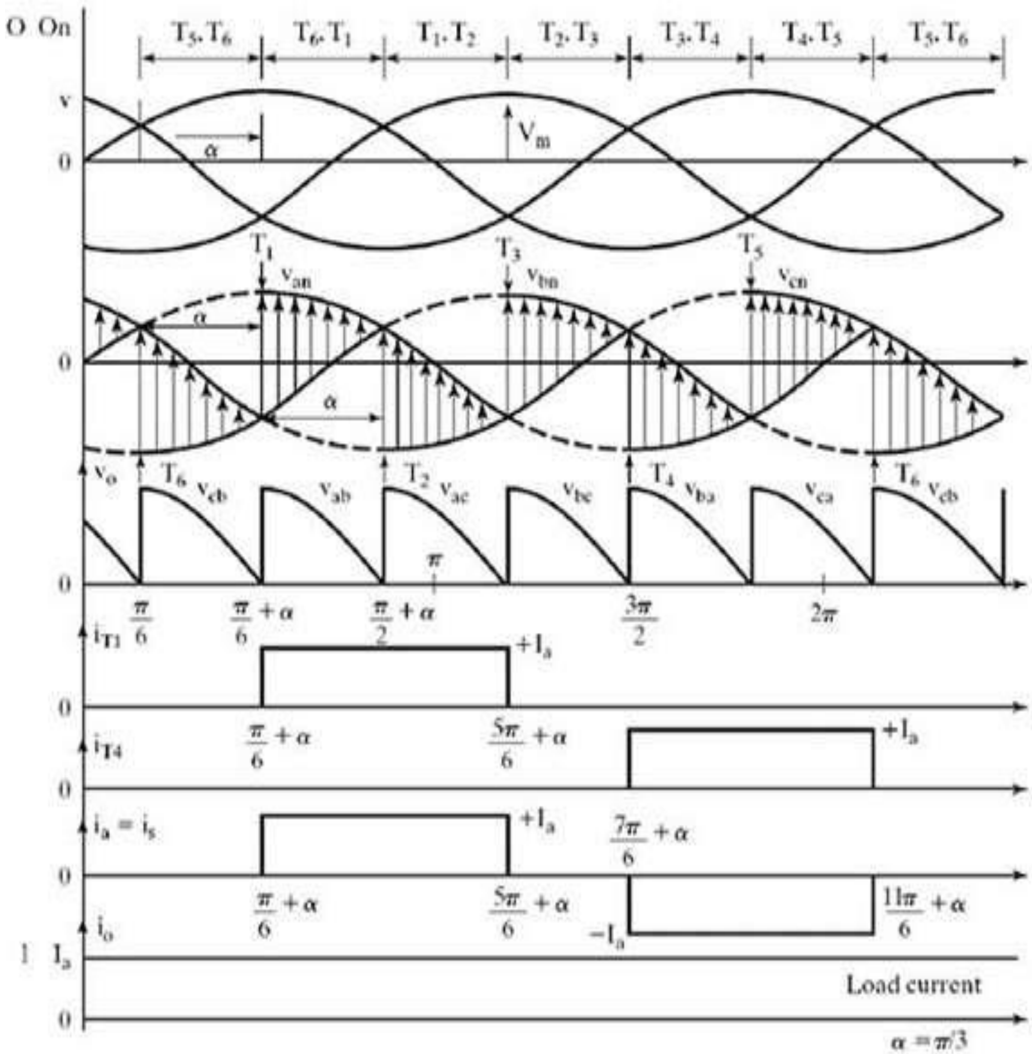
$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vo\,d(wt)$$

$$V_o = V_{ab} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right) d(wt)$$

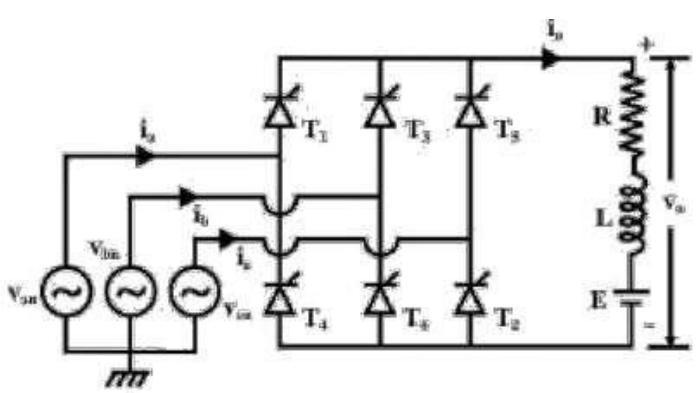
$$= \frac{3\sqrt{3}Vm}{\pi}\cos\alpha$$

$$= \frac{3Vml}{\pi}\cos\alpha$$



Operation of three phase half wave rectifier with RLE loads

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



For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter onlyone device from these two groups will conduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180°and hence can not conduct simultaneously. This leaves only six possible conduction mode for theconverter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Each conduction mode is of 60° duration and appears in the sequence mentioned. Each of theseline voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T1 is fired at the end

of T5 T6 conduction interval. During this period the voltage across T1 was vac. Therefore T1 is fired α

angle after the positive going zero crossing of vac. similar observation can be made about other thyristors.

Fig. 2.23 shows the waveforms of different variables. To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 2.22. If the converter firing angle is α each thyristor is fired "α"

angle after the positive going zero crossing of the line voltage with which it's firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 2.22. Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called

the “six pulse” converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.

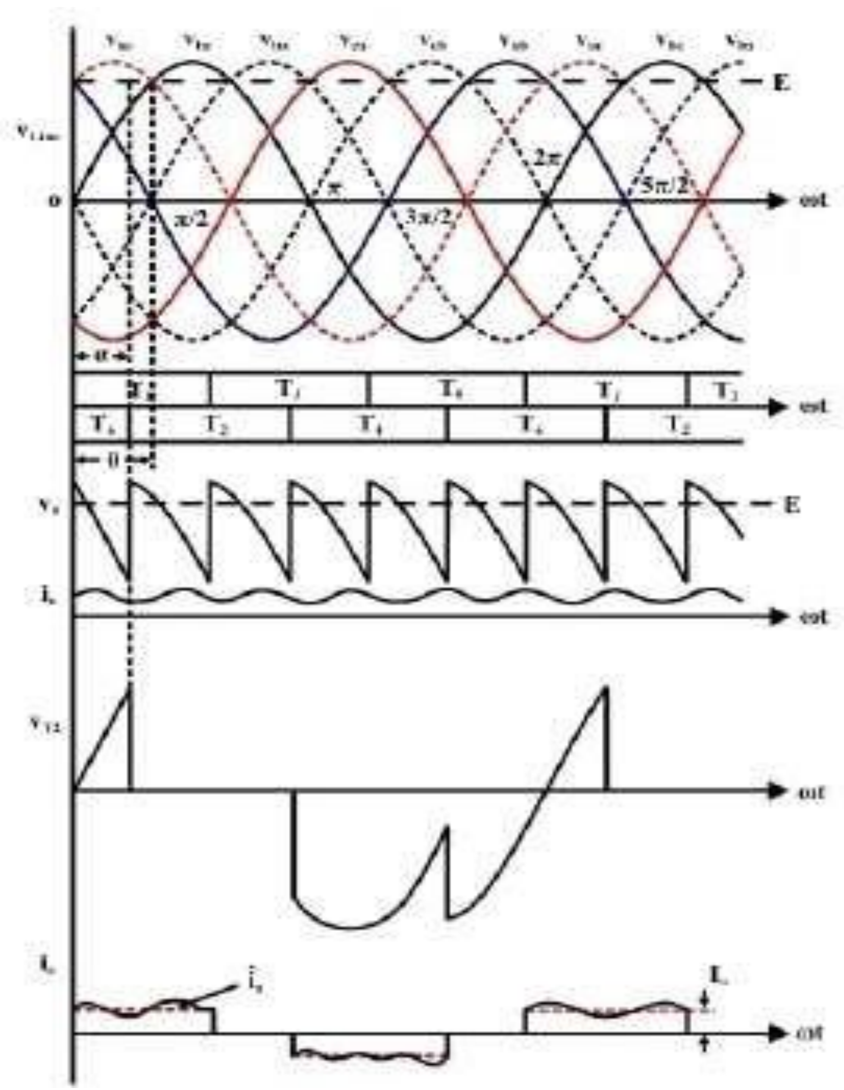
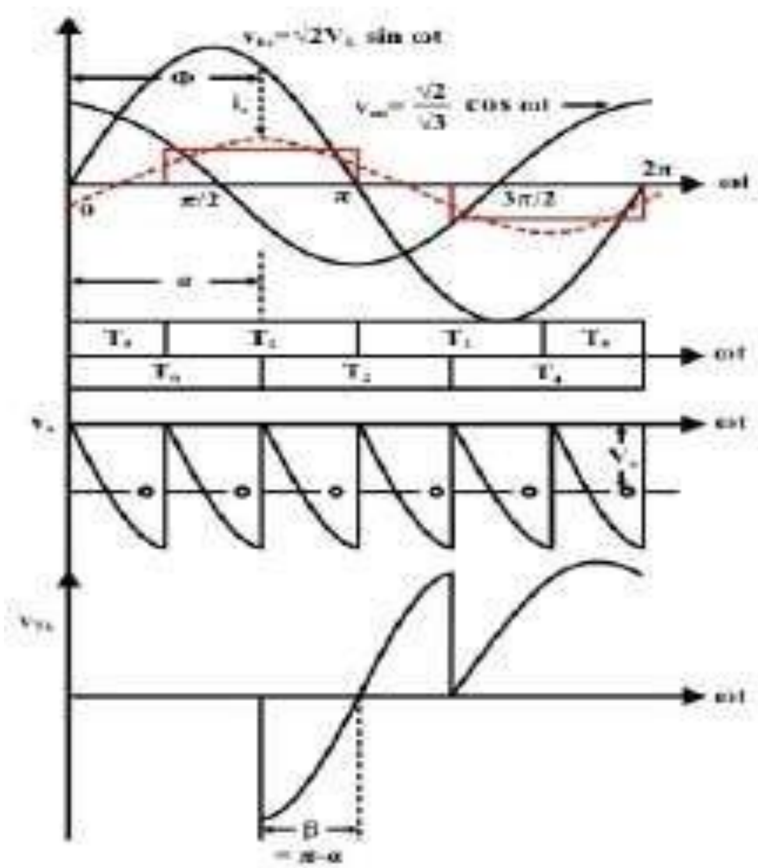
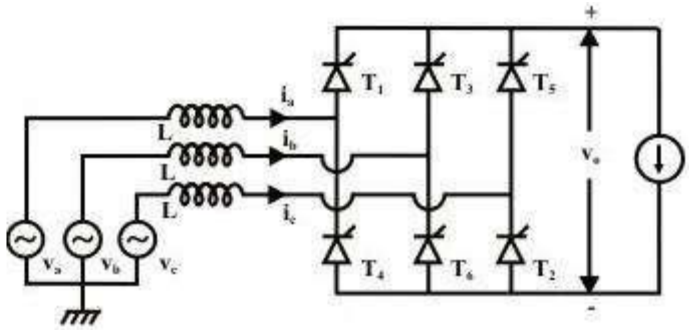


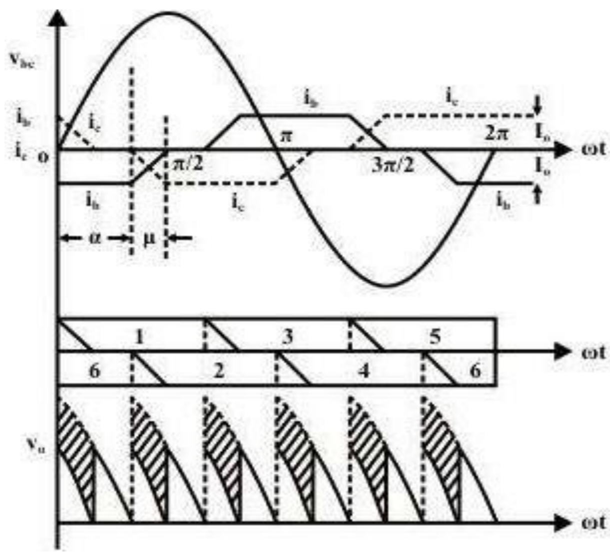
Figure: Input and output waveforms of three phase fully controlled rectifier in rectifier mode



Effect of source inductance in three phase rectifiers

The three phase fully controlled converter was analyzed with ideal source with no internal impedance. When the source inductance is taken into account, the qualitative effects on the performance of the converter is similar to that in the case of a single phase converter. Fig. 2.25 shows such a converter. As inthe case of a single phase converter the load is assumed to be highly inductive such that the load can be replaced by a current source.





As in the case of a single phase converter, commutations are not instantaneous due to the presence of source inductances. It takes place over an overlap period of "μ_1" instead. During the overlap period three thyristors instead of two conducts. Current in the outgoing thyristor gradually decreases to zero while the incoming thyristor current increases and equals the total load current at the end of the overlap period. If the duration of the overlap period is greater than 60° four thyristors may also conduct clamping the output voltage to zero for some time. However, this situation is not very common and will not be discussed any further in this lesson. Due to the conduction of two devices during commutation either from the top group or the bottom group the instantaneous output voltage during the overlap period drops (shown by the

hatched portion of Fig. 2.26 resulting in reduced average voltage. The exact amount of this reduction can be calculated as follows.

In the time interval $\alpha < \omega t \leq \alpha + \mu$, T and T from the bottom group and T from the top group conducts.

The equivalent circuit of the converter during this period is given by the circuit diagram of Fig.

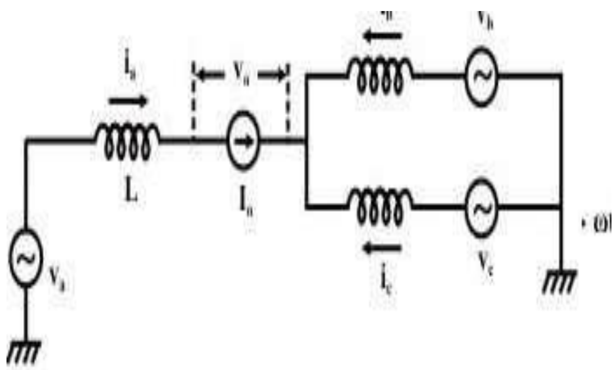


Figure: Equivalent circuit of waveforms with source inductance

Therefore, in the interval $\alpha < \omega t \leq \alpha + \mu$

$$v_b = L\frac{di_b}{dt} - L\frac{di_c}{dt} + v_c$$

or, $$v_{bc} = L\frac{d}{dt}(i_b - i_c)$$

but $i_b + i_c + I_o = 0$ $\quad \therefore \quad \frac{di_b}{dt} = -\frac{di_c}{dt}$

$$\therefore \quad 2L\frac{d}{dt}i_b = v_{bc} = \sqrt{2}V_L \sin\omega t$$

$$\therefore \quad i_b = C - \frac{\sqrt{2}V_L}{2\omega L}\cos\omega t$$

at $\omega t = \alpha$, $\quad i_b = -I_0 \quad \therefore \quad C = \frac{\sqrt{2}V_L}{2\omega L}\cos\alpha - I_0$

$$\therefore \quad i_b = \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu$, $\quad i_b = 0$

$$\therefore \quad \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos(\alpha + \mu)) = I_0$$

Or, $$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_L}I_0$$

Therefore, in the interval $\alpha < \omega t \le \alpha + \mu$

$$v_b = L\frac{di_b}{dt} - L\frac{di_c}{dt} + v_c$$

or, $$v_{bc} = L\frac{d}{dt}(i_b - i_c)$$

but $i_b + i_c + I_o = 0$ $\therefore$ $\frac{di_b}{dt} = -\frac{di_c}{dt}$

$\therefore$ $$2L\frac{d}{dt}i_b = v_{bc} = \sqrt{2}V_L \sin\omega t$$

$\therefore$ $$i_b = C - \frac{\sqrt{2}V_L}{2\omega L}\cos\omega t$$

at $\omega t = \alpha$, $i_b = -I_0$ $\therefore$ $C = \frac{\sqrt{2}V_L}{2\omega L}\cos\alpha - I_0$

$\therefore$ $$i_b = \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu$, $i_b = 0$

$\therefore$ $$\frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos(\alpha + \mu)) = I_0$$

Or, $$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_L}I_0$$

for $\mu \le 60°$. It can be shown that for this condition to be satisfied

$$I_0 \le \frac{V_L}{\sqrt{2}\omega L}\cos\left(\alpha - \frac{\pi}{3}\right)$$

To calculate the dc voltage

For $\alpha \le \omega t \le \alpha + \mu$

$$v_0 = v_a - v_b + L\frac{di_b}{d_t} = \frac{3}{2}v_a$$

for $\alpha + \mu \le \omega t \le \alpha + \frac{\pi}{3}$ $v_0 = v_{ac}$

$\therefore$ $$V_0 = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\frac{3}{2}v_a\, d\omega t + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}v_{ac}\, d\omega t\right]$$

$$=\frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\left(v_{ac}+\frac{3}{2}v_{a}-v_{ac}\right)+\int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}v_{ac}\,d\omega t\right]$$

$$=\frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\frac{\pi}{3}}v_{ac}\,d\omega t+\int_{\alpha}^{\alpha+\mu}\left(\frac{v_{a}}{2}+v_{c}\right)d\omega t\right]$$

$$=\frac{3\sqrt{2}}{\pi}V_{L}\cos\alpha-\frac{3}{2\pi}\int_{\alpha}^{\alpha+\mu}v_{bc}\,d\omega t$$

or

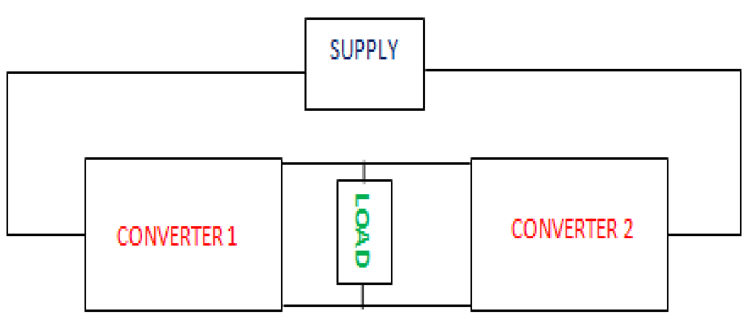
$$V_{o}=\frac{3\sqrt{2}}{\pi}V_{L}\cos\alpha-\frac{3\sqrt{2}V_{L}}{2\pi}\int_{\alpha}^{\alpha+\mu}\sin\omega t\,d\omega t$$

$$=\frac{3\sqrt{2}}{\pi}V_{L}\cos\alpha-\frac{3\sqrt{2}V_{L}}{2\pi}\left[\cos\alpha-\cos(\alpha+\mu)\right]$$

$$V_{o}=\frac{3\sqrt{2}}{\pi}V_{L}\cos\alpha-\frac{3}{\pi}\omega L\,I_{o}$$

Introduction to dual converters

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 rectifier and the other will perform as 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. The basic block diagram is shown below



Modes of Operation of Dual Converter

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

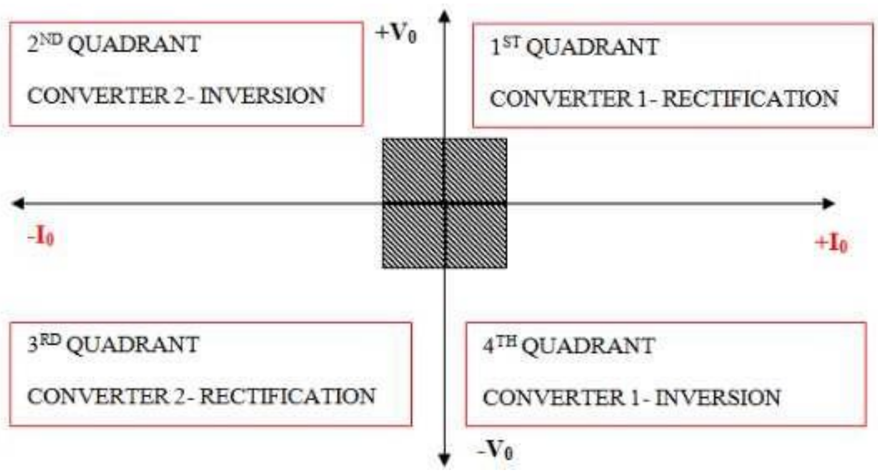
Non Circulating Current Mode

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

Circulating Current Mode

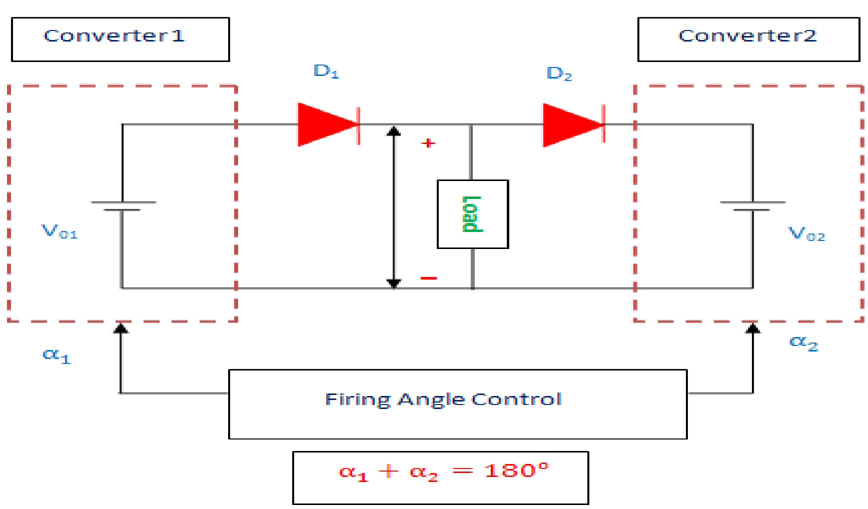
- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α_1) + firing angle of converter 2

  (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, Vdc and Idc 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, Vdc and Idc are negative.
- The four quadrant operation is shown below



Ideal Dual Converter

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D_1 and D_2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V_{01} and converter 2 is V_{02}. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the Thyristors have to be controlled.



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. The circuit diagram is shown below.

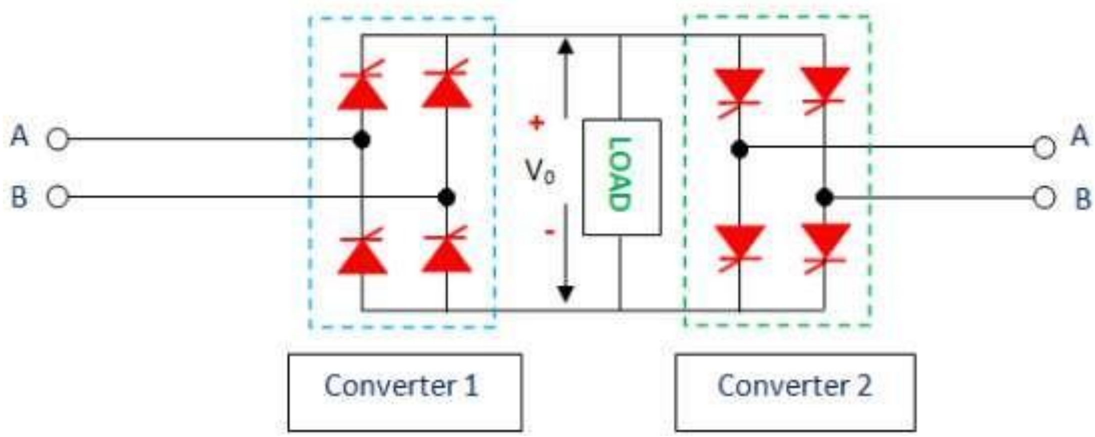


Figure: 2.31 Single phase Dual converter

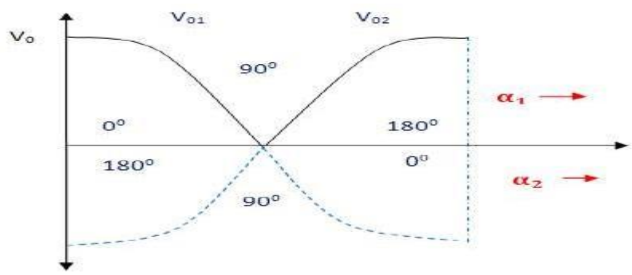
Average output voltage of Single-phase converter= $\frac{2V_m Cos\ \alpha}{\pi}$ Average output voltage of Three-phase converter = $\frac{3V_{ml} Cos\ \alpha}{\pi}$

For converter 1, the average output voltage, $V_{01} = V_{max}Cos\alpha_1$ For converter 2, the average output voltage, $V_{02} = V_{max}Cos\alpha_2$

$$V_0 = V_{01} = -V_{02}$$
$$V_{max}Cos\alpha_1 = -V_{max}Cos\alpha_2$$
$$Cos\alpha_1 = Cos(180^o - \alpha_2)\ or\ Cos\alpha_2 = Cos(180^o + \alpha_2)$$
$$\alpha_1 + \alpha_2 = 180^o\ \ And\ \alpha_1 - \alpha_2 = 180^o$$

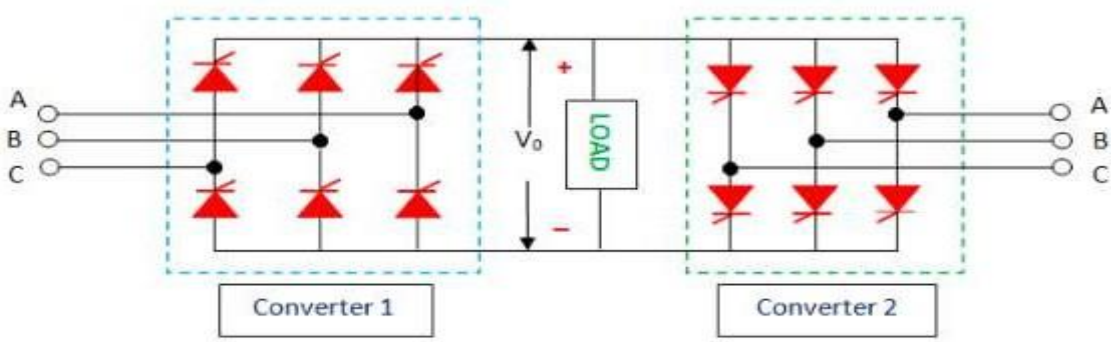
Output voltage,

The firing angle can never be greater than 180°. So, $\alpha_1 + \alpha_2 = 180^o$



Three Phase Dual Converter

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 converter. It will 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.



Application of Dual Converter

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

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UNIT-III

DC-DC CONVERTERS (CHOPPER/SMPS)

INTRODUCTION:

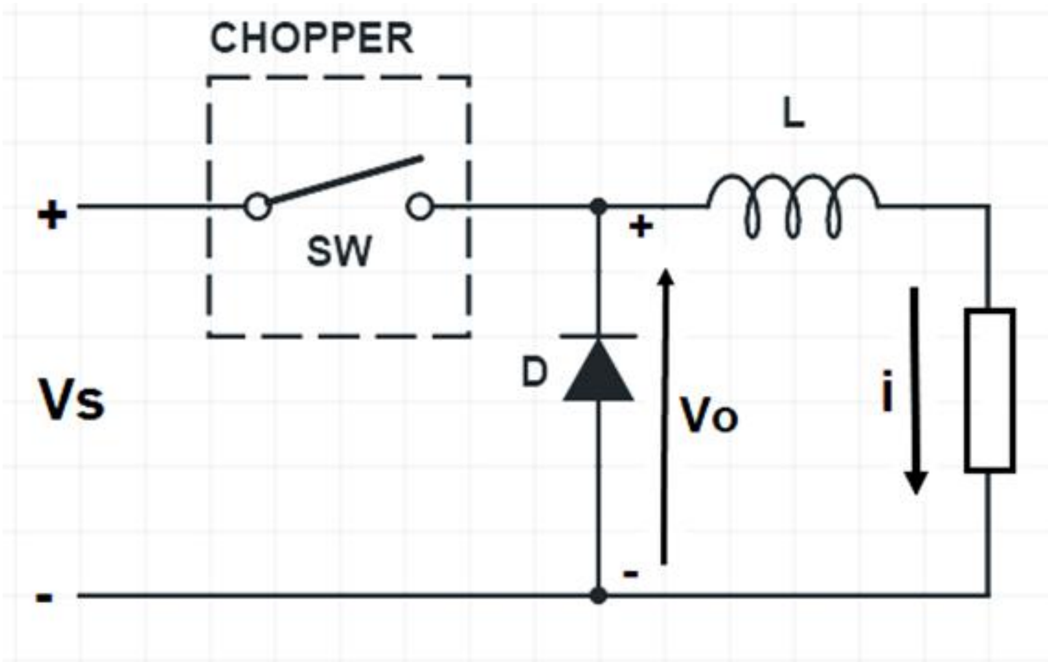
A chopper is a device that converts fixed DC input to a variable DC output voltage directly. Essentially, a chopper is an electronic switch that is used to interrupt one signal under the control of another .

Chopper is fed through a constant DC voltage source and its output is variable DC voltage. The average value of output DC voltage may be less than or higher than the input DC voltage source. A simple diagram defining the chopper is shown below.

A chopper is a DC equivalent to an AC transformer having continuously variable turn ratio. Like a transformer, a it can be used to step-up or step-down the fixed DC input voltage. On this basis, there are two types of chopper: Step-up and Step-down Chopper. A chopper whose average value of DC output voltage is more than the fixed DC input voltage is called Step-up Chopper. While, a chopper whose average value of DC output voltage is less than the DC input voltage is called Step-down chopper.

Working Principle of Chopper:

A chopper is a high speed ON/OFF switch. It connected source to load and disconnects the load from the source at a fast speed. Figure below represents the simple circuit to show its working principle.



In this circuit, the switch SW is chopper. This switch can be made ON

ELEMENTARY CHOPPER WITH AN ACTIVE SWITCH AND DIODE:

Elementary chopper with an active switch and diode. A chopper is a DC equivalent to an AC transformer having continuously variable turn ratio. Like a transformer, a it can be used to step up or step down the fixed DC input voltage. On this basis, there are two types of chopper: Step-up and Step-down Chopper.

CONCEPT OF DUTY RATIO:-

The duty cycle is between 0 and 1. It can be 0 if the chopper switch is never on and it can be 1 when the chopper switch is always on. f = 1/T = α/Ton.

AVERAGE INDUCTOR VOLTAGE:

The average voltage output (Vo) in a step up chopper is **greater than the voltage input (Vs)**. The figure below shows a configuration of a step up chopper.

Classification of Choppers

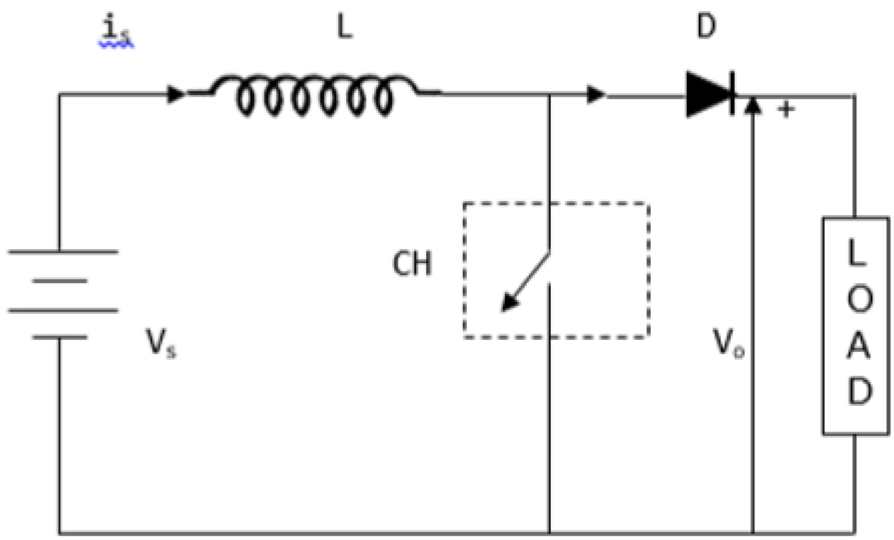
Depending on the voltage output, choppers are classified as −

- Step Up chopper boost converter

- Step Down Chopper Buck converter Step Up/Down Chopper Buck–boost converter

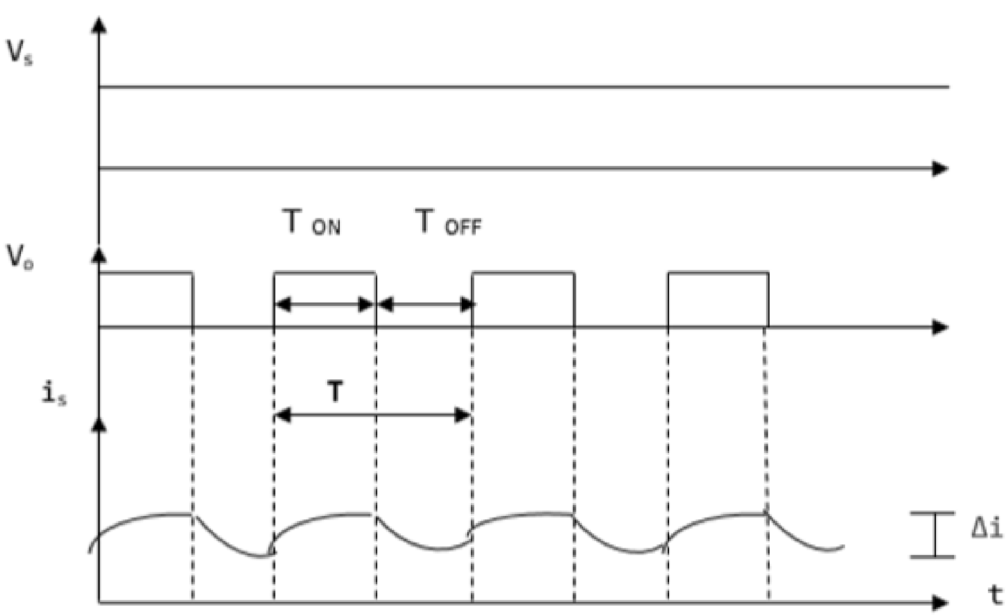
<u>Step Up Chopper :</u>

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



Current and Voltage Waveforms

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



Where

T_{ON} – time interval when chopper is ON

T_{OFF} – time interval when chopper is OFF

V_L – Load voltage

V_s – Source voltage

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

V_o is given by –

V0=1/T∫TON0VSdt

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

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

Δi = is the inductor peak to peak current. When the chopper CHis OFF, discharge occurs through the inductor L. Therefore, the summation of the V_s and V_L is given as follows –

$$V_0 = V_S + V_L, \quad V_L = V_0 - V_S$$

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

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

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

V0=1T∫TON0VSdt

Equating Δi from ON state to Δi from OFF state gives –

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

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

This give the average voltage output as,

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

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

This give the average voltage output as,

V0=VS1−D

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

Step Down Chopper

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

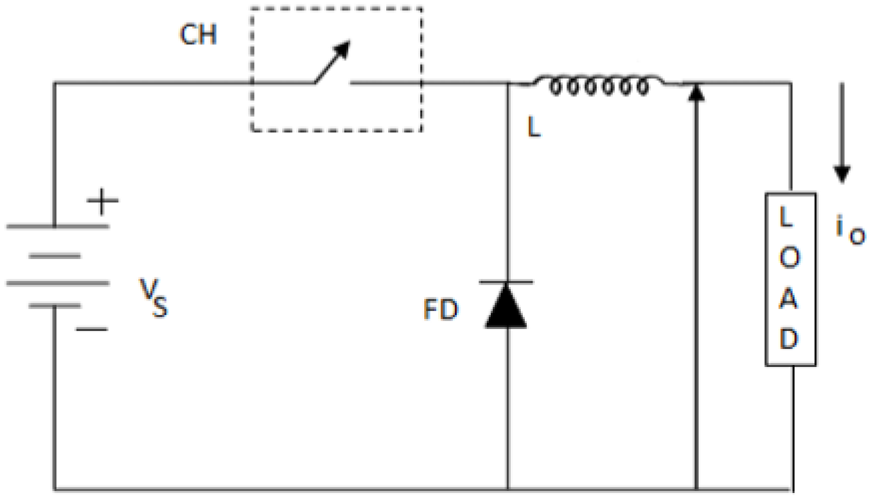
When the chopper is ON –

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

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

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

Circuit Diagram



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

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

Rewritten as −

Ldidt=V0......................................(i)

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

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

Equating equations i and ii gives;

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

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

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

The above equation gives;

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

Equation i gives −

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

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

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

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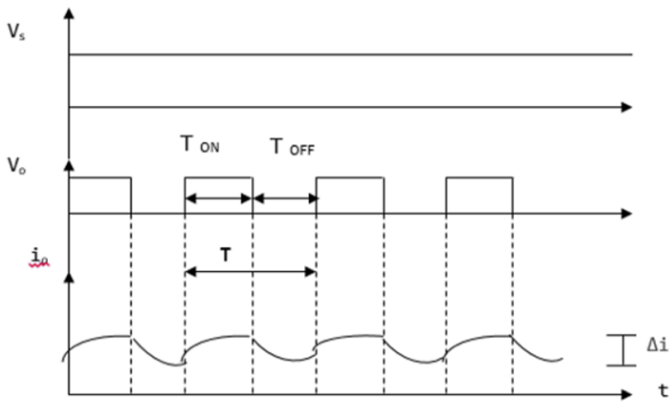
Current and Voltage Waveforms

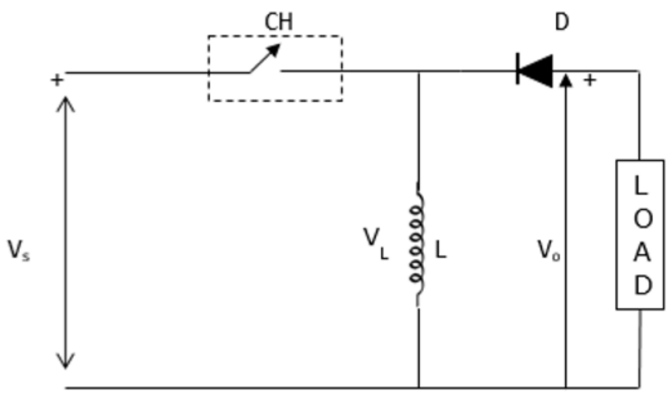
The current and voltage waveforms are given below −

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



Step Up/ Step Down Chopper

This is also known as a buck-boost converter. It makes it possible to increase or reduce the voltage input level. The diagram below shows a buck-boost chopper.



When the chopper is switched ON, the inductor L becomes charged by the source voltage V_s. Therefore, V_s =

$$L\frac{di}{dt} = V_S$$

$$\Delta i = \frac{V_S}{L}T_{ON} = \frac{V_S}{L}T\frac{T_{ON}}{T} = \frac{DV_S}{Lf}$$

Because –

$D = \frac{T_{ON}}{T}$ and

$$f = \frac{1}{T} \ldots\ldots (iii)$$

When the chopper is switched OFF, the inductor's polarity reverses and this causes it to discharge through the diode and the load.

Hence,

$$V_0 = -V_L$$

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

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

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

Evaluating equation iii and iv gives –

$$\frac{DV_S}{Lf} = -\frac{V_0}{L}T_{OFF} ,$$

$$DV_S = -DV_S = -V_0 T_{OFF} f$$

$$DV_S = -V_0\frac{T-T_{ON}}{T} = -V_0\left(1 - \frac{T_{ON}}{T}\right) ,$$

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

Because $D = \frac{T_{ON}}{T} = \frac{T-T_{OFF}}{1-D}$

This gives,

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

D can be varied from 0 to 1. When, D = 0; $V_O = 0$

When D = 0.5, $V_O = V_S$

When, D = 1, $V_O = \infty$.

Hence, in the interval $0 \leq D \leq 0.5$, output voltage varies in the range $0 \leq V_O < V_S$ and we get step down or Buck operation. Whereas, in the interval $0.5 \leq D \leq 1$, output voltage varies in the range $V_S \leq V_O \leq \infty$ and we get step up or Boost operation.

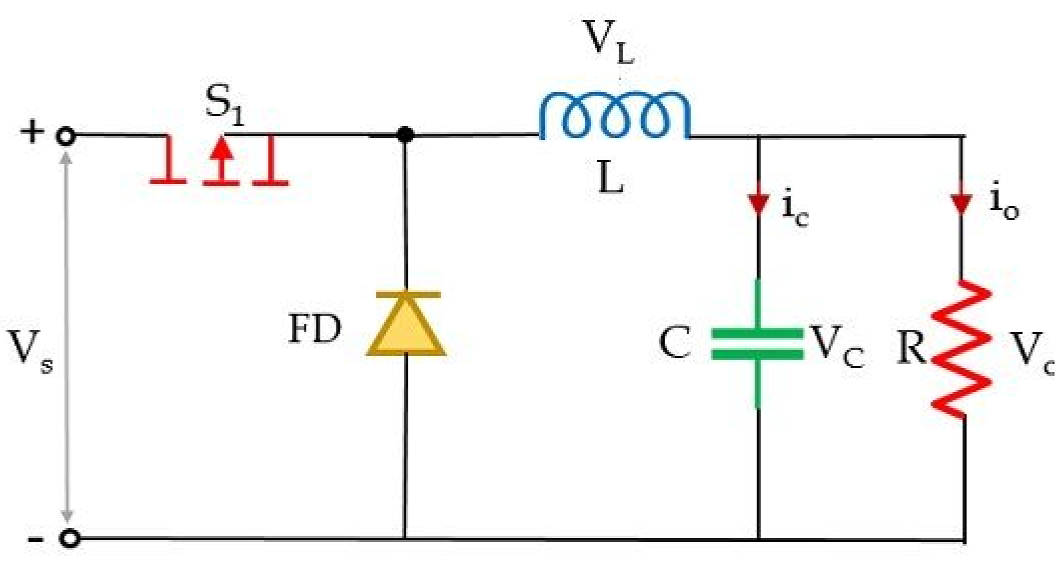
BUCK CONVERTER:-

Buck Converter is a type of chopper circuit that is designed to perform step-down conversion of the applied dc input signal. In the case of buck converters, the fixed dc input signal is changed into another dc signal at the output which is of lower value. This means it is designed to produce a dc signal as its output that possesses a lower magnitude than the applied input.

It is sometimes called **Step-down DC to DC Converter** or **Step-down Chopper** or **Buck Regulator**.

Operating Principle of Buck Converter

The figure given below shows the circuit representation of Buck Converter:

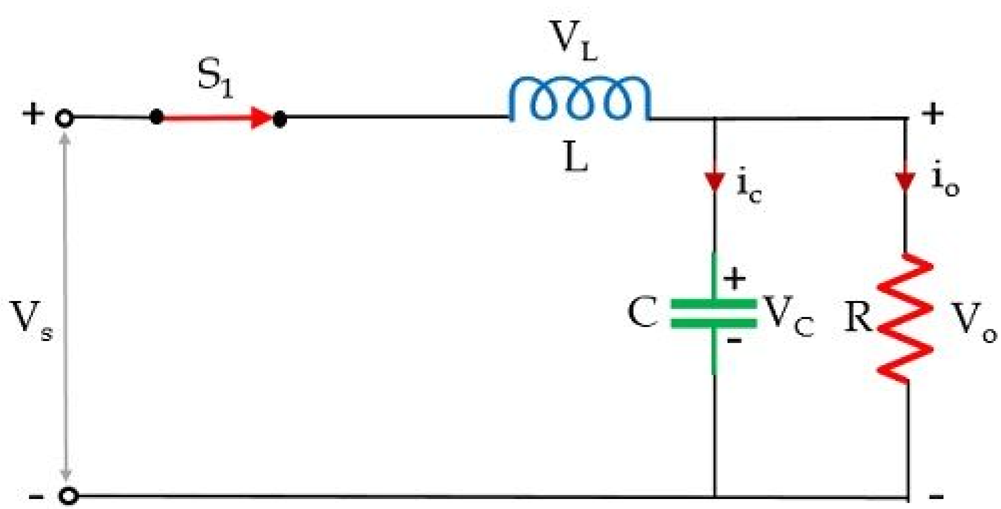


Buck Converter

In the above figure, it is clearly shown that along with the power electronics solid-state device which acts as a switch for the circuit, there is another switch in the circuit which is a freewheeling diode. The combination of these two switches forms a connection with a low-pass LC filter in order to reduce current or voltage ripples. This helps in generating regulated dc output. A pure resistor is connected across this whole arrangement that acts as a load of the circuit.

The whole operation of the circuit takes place in two modes. The first mode is the one when the power MOSFET i.e., switch S_1 is closed.

In this mode of operation, switch S_1 is in closed condition thus allows the flow of current to take place through it.



When S_1 is closed

Initially when a fixed dc voltage is applied across the input terminal of the circuit then in the closed condition of switch S_1 current flows in the circuit in the manner shown above. Due to this flowing current, the inductor in the path stores energy in the form of a magnetic field. Also, there is a capacitor in the circuit and current flows through it also, therefore, it will store the charge and the voltage across it will appear across the load.

However, due to Lenz's law, the energy stored within the inductor will oppose the cause which has produced it and so an induced current will get generated and the polarity across the inductor will get reversed.

Here the total time period is a combination of T_{on} and T_{off} time.

When S1 is in closed condition then T_{on} = DT thus Δt = DT. Therefore, we can write,

$$\frac{\Delta i_L}{\Delta t} = \frac{V_s - V_{out}}{L}$$

$$\frac{\Delta i_L}{DT} = \frac{V_s - V_{out}}{L}$$

Hence,

$$\Delta i_t = (\frac{V_s - V_{out}}{L})DT$$

$$T = T_{on} + T_{off}$$

The duty cycle is written as:

$$D = \frac{T_{on}}{T}$$

On applying KVL, in the above-given circuit,

$$V_s = V_L + V_{out}$$

$$V_L = V_s - V_{out}$$

Also,

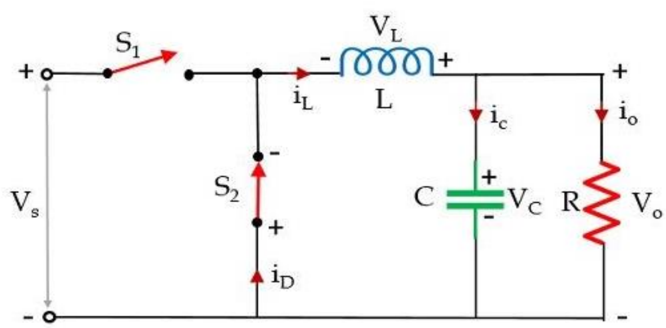
$$V_L = L\frac{di_L}{dt} = V_s - V_{out}$$

$$\frac{di_L}{dt} = \frac{V_s - V_{out}}{L}$$

The above equation represents the change in current through the circuit when switch S1 is closed.

Now, the second mode of operation takes place when switch S_2 is closed and S_1 gets open. However, you must be thinking about how automatically, the switch S_2 will be closed. So, as we have discussed that the inductor in the circuit will store the energy so, once S_1 will get open the inductor in the circuit will start acting as the source.
In this mode, the inductor releases the energy which is stored in the previous mode of operation. As we have discussed that the polarity of the inductor will get reversed therefore this causes the freewheeling diode to come in a forward-biased state which was earlier present in a reverse-biased state due to the applied dc input.

Due to this, the flow of current takes place in a way as shown below:



When S_2 is closed

This flow of current will take place till the time the stored energy within the inductor gets completely collapsed. As once the inductor gets completely discharged, the diode comes in reverse biased condition leading to cause opening of switch S2, and instantly switch S1 will get closed and the cycle continues.

Now, let us apply KVL, in the above circuit,

$$0 = V_L + V_{out}$$

$$V_L = L\frac{di_L}{dt} = -V_{out}$$

$$T = T_{on} + T_{off}$$

$$T = DT + T_{off}$$

$$T_{off} = T - DT$$

$$T_{off} = (1 - D)T$$

This equation represents the rate of change in current through the inductor when the switch S1 is open.

As we know that the net change of current through the inductor in one complete cycle is zero. Thus,

$$\Delta i_L = -\frac{V_{out}}{L}(1 - D)T$$

$$\Delta i_{L(S1-closed)} + \Delta i_{L(S1-open)} = 0$$

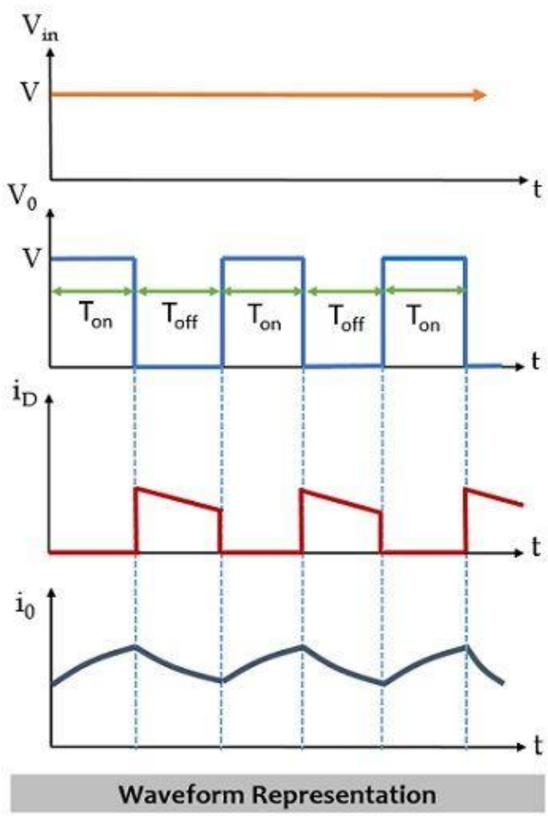
$$\frac{V_s - V_{out}}{L} DT + \left\{ -\frac{V_{out}}{L}(1-D)T \right\} = 0$$

$$\frac{V_s DT}{L} - \frac{V_{out} DT}{L} - \frac{V_{out} T}{L} + \frac{V_{out} DT}{L} = 0$$

$$\left(\frac{V_s DT}{L}\right) = \frac{V_{out} T}{L}$$

$$V_{out} = DV_s$$

The figure given below represents the waveform representation of Buck Converter:



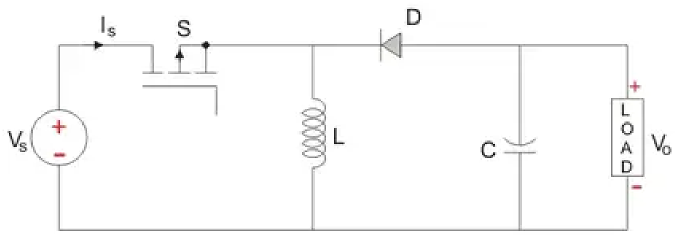
Hence, we can say, buck converters are used to provide a lower value of dc signal from a fixed dc input.

Buck-Boost Converter:

The buck–boost converter is a type of DC-to-DC converter (also knowns' as chopper) that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is used to "step up" the DC voltage, similar to a transformer for AC circuits.

It is equivalent to a fly back converter using a single inductor instead of a transformer. Two different topologies are called buck–boost converter.

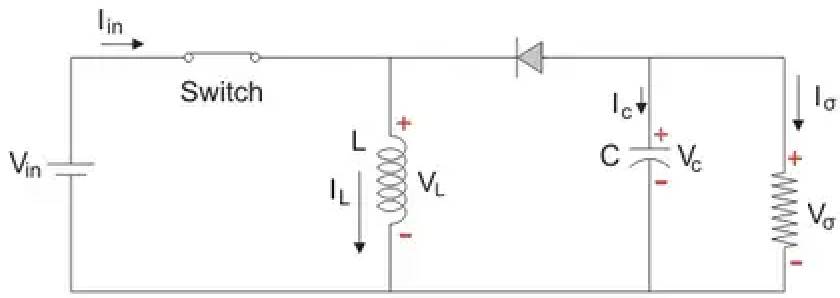
DC-DC converters are also known as choppers. Here we will have a look at **Buck Boost converter** which can operate as a DC-DC Step-Down converter or a DC-DC Step-Up converter depending upon the duty cycle, D.
A typical Buck-Boost converter is shown below.



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.

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

Mode I : Switch is ON, Diode is OFF:-



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.
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

and the switching frequency,

$$T = T_{ON} + T_{OFF}$$

and the switching frequency,

$$f_{switching} = \frac{1}{T}$$

Let us now define another term, the duty cycle,

$$D = \frac{T_{ON}}{T}$$

Let us analyse the **Buck Boost converter** in steady state operation for this mode using KVL.

$$\therefore V_{in} = V_L$$

$$\therefore V_L = L\frac{di_L}{dt} = V_{in}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{in}}{L}$$

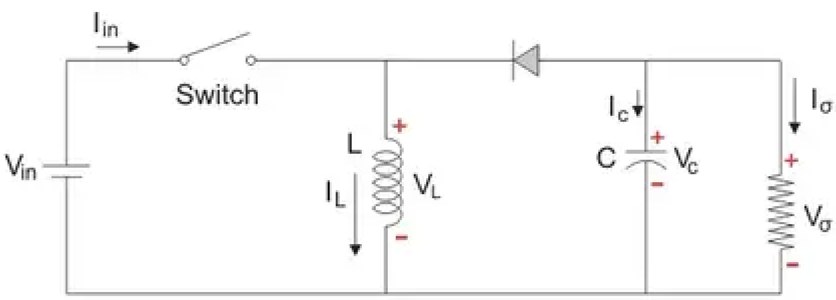
Since the switch is closed for a time $T_{ON} = DT$ we can say that $\Delta t = DT$.

$$(\Delta i_L)_{closed} = \left(\frac{V_{in}}{L}\right) DT$$

While performing the analysis of the Buck-Boost converter we have to keep in mind that

1. The inductor current is continuous and this is made possible by selecting an appropriate value of L.
2. The inductor current in steady state rises from a value with a positive slope to a maximum value during the ON state and then drops back down to the initial value with a negative slope. Therefore the net change of the inductor current over any one complete cycle is zero.

Mode II : Switch is OFF, Diode is ON:-



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. But for analysis we keep the original conventions to analyse the circuit using KVL.

Let us now analyse the **Buck Boost converter** in steady state operation for Mode II using KVL.

$$\therefore V_L = V_o$$

$$\therefore V_L = L\frac{di_L}{dt} = V_o$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L}$$

Since the switch is open for a time

$T_{OFF} = T - T_{ON} = T - DT = (1 - D)T$

we can say that

$\Delta t = (1 - D)T$

.

$$(\Delta i_L)_{open} = \left(\frac{V_o}{L}\right)(1 - D)T$$

It is already established that the net change of the inductor current over any one complete cycle is zero.

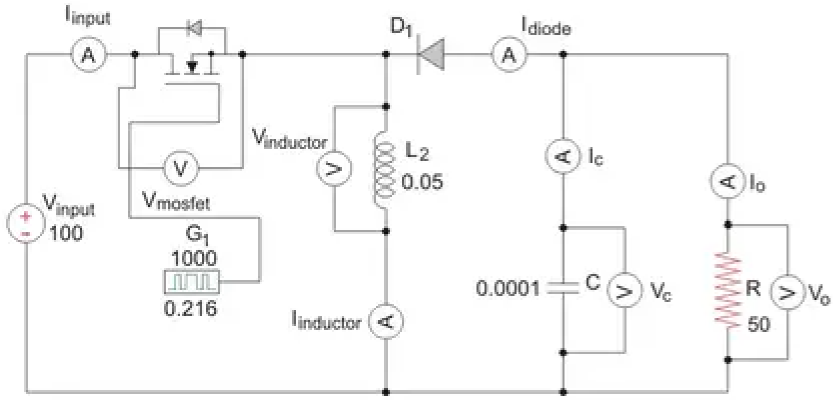
$$\therefore (\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\left(\frac{V_o}{L}\right)(1 - D)T + \left(\frac{V_{in}}{L}\right)DT = 0$$

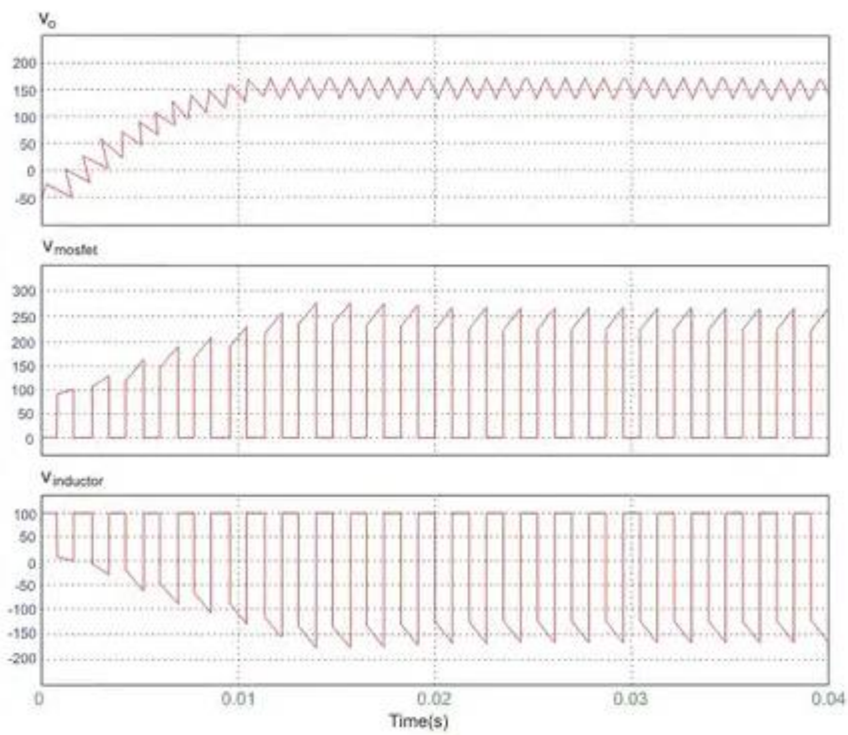
$$\frac{V_o}{V_{in}} = \frac{-D}{1 - D}$$

We know that D varies between 0 and 1. If D > 0.5, the output voltage is larger than the input; and if D < 0.5, the output is smaller than the input. But if D = 0.5 the output voltage is equal to the input voltage.

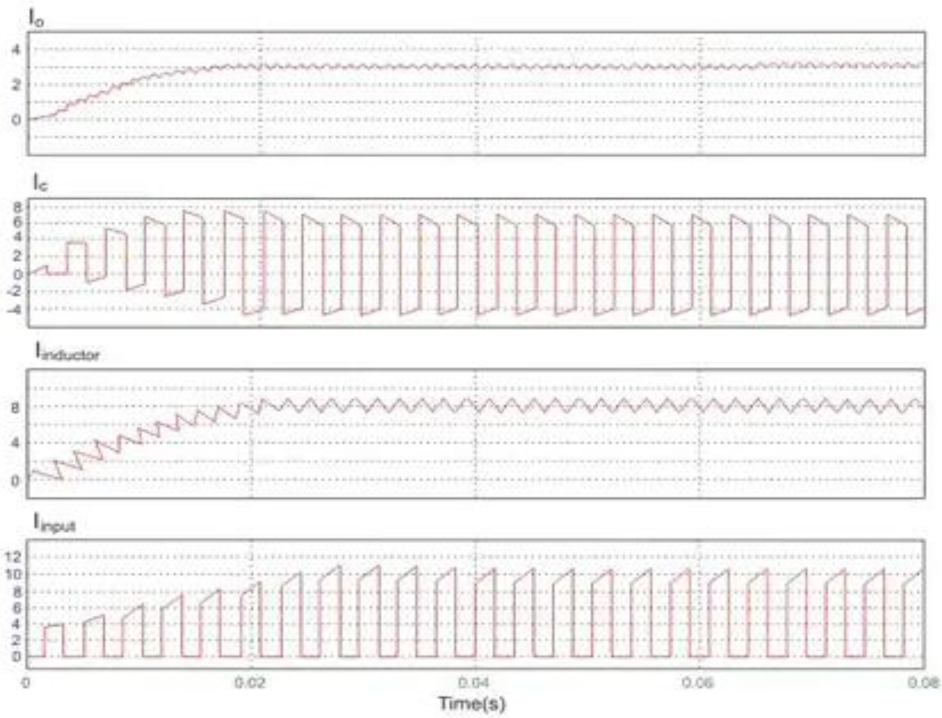
A circuit of a Buck-Boost converter and its waveforms is shown below.



The inductance, L, is 50mH and the C is 100µF and the resistive load is 50Ω. The switching frequency is 1 kHz. The input voltage is 100 V DC and the duty cycle is 0.5.



The voltage waveforms are as shown above and the current waveforms are as shown in the figure below.



UNIT-IV

AC-DC CONVERTERS(INVERERS)

Introduction to Inverters

The word 'inverter' in the context of power-electronics denotes a class of power conversion (or power conditioning) circuits that operates from a dc voltage source or a dc current source and converts it into ac voltage or current. The inverter does reverse of what ac-to-dc converter does (refer to ac to dc converters). Even though input to an inverter circuit is a dc source, it is not uncommon to have this dc derived from an ac source such as utility ac supply. Thus, for example, the primary source of input power may be utility ac voltage supply that is converted to dc by an ac to dc converter and then 'inverted' back to ac using an inverter. Here, the final ac output may be of a different frequency and magnitude than the input ac of the utility supply

A single phase Half Bridge DC-AC inverter is shown in Figure below

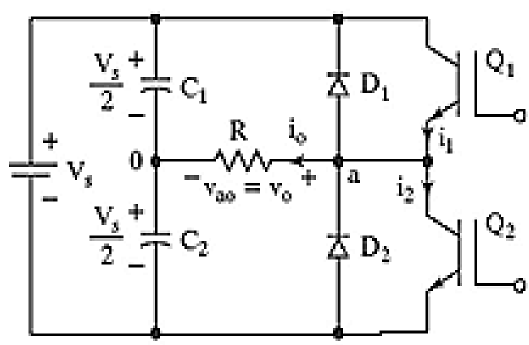


Figure: Single phase Half Bridge DC-AC inverter with R load

The analysis of the DC-AC inverters is done taking into accounts the following assumptions and conventions.

1) The current entering node a is considered to be positive.

2) The switches S1 and S2 are unidirectional, i.e. they conduct current in one direction.

3) The current through S1 is denoted as i1 and the current through S2 is i2.

The switching sequence is so design is shown in Figure below. Here, switch S1 is on for the time duration $0 \leq t \leq T1$ and the switch S2 is on for the time duration $T1 \leq t \leq T2$. When switch S1 is turned on, the instantaneous voltage across the load is v o = Vin/ 2

When the switch S2 is only turned on, the voltage across the load is
v o = Vin/ 2.

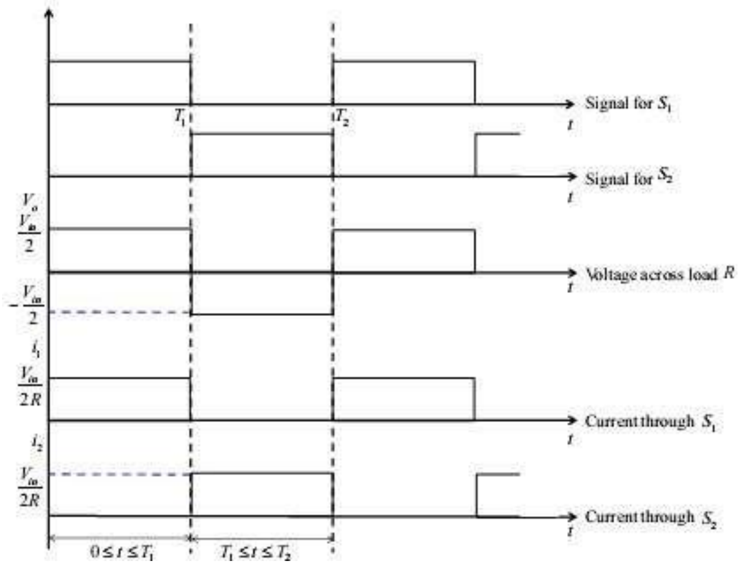


Figure: Single phase Half Bridge DC-AC inverter output waveforms

The r.m.s value of output voltage v o is given by,

$$V_{o,rms} = \left(\frac{1}{T_1} \int_0^{T_1} \frac{V_{in}^2}{4} dt \right) = \frac{V_{in}}{2}$$

The instantaneous output voltage v o is rectangular in shape. The instantaneous value of v o can be

expressed in Fourier series as,

$$v_o = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$$

Due to the quarter wave symmetry along the time axis , the values of a0 and an are zero. The value of bnis given by,

$$b_n = \frac{1}{\pi}\left[\int_{-\frac{\pi}{2}}^{0} \frac{-V_{in}}{2} d(\omega t) + \int_{0}^{\frac{\pi}{2}} \frac{V_{in}}{2} d(\omega t)\right] = \frac{2V_{in}}{n\pi}$$

Substituting the value of bn from above equation , we get

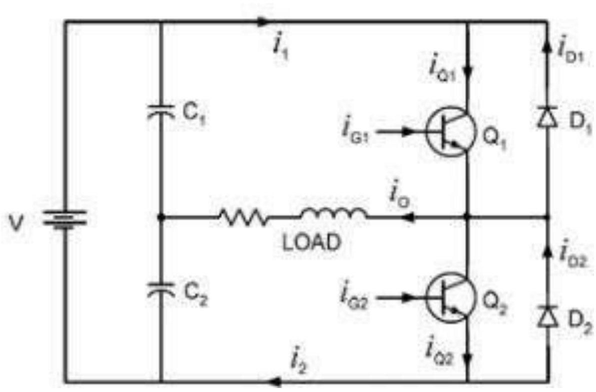
$$v_o = \sum_{n=1,3,5,...}^{\infty} \frac{2V_{in}}{n\pi} \sin(n\omega t)$$

The current through the resistor (iL) is given by,

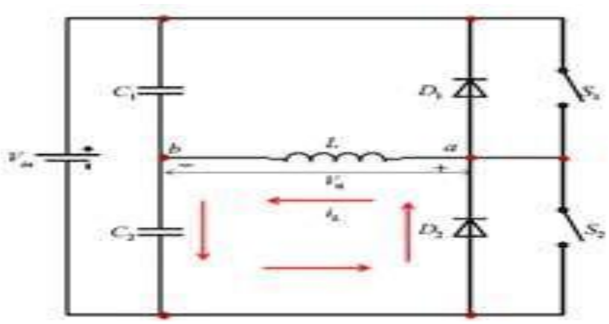
$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{1}{R} \frac{2V_{in}}{n\pi} \sin(n\omega t)$$

Half Bridge DC-AC Inverter with L Load and R-L Load

The DC-AC converter with inductive load is shown in Figure below. For an inductive load, the load current cannot change immediately with the output voltage.



The working of the DC-AC inverter with inductive load is as follow is:Case 1: In the time interval 0<=t<= T1 the switch S1 is on and the current flows through the inductor from points a to b. When the switch S1 is turned off (case 1) at t-T1, the load current would continue to flow through the capacitor C2 and diode D2 until the current falls to zero, as shown in Figure below.



Case 2: Similarly, when S2 is turned off at t = T1 , the load current flows through the diode D1 and capacitor C1until the current falls to zero, as shown in Figure below.

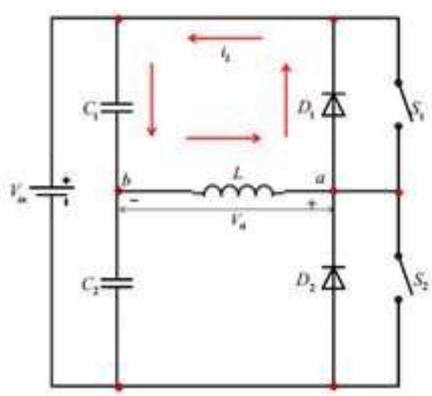


Figure: Single phase Half Bridge DC-AC inverter with L load

When the diodes D1 and D2 conduct, energy is feedback to the dc source and these diodes are known as feedback diodes. These diodes are also known as freewheeling diodes. The current for purely inductive load is given by,

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{1}{\omega nL} \frac{2V_{in}}{n\pi} \sin\left(n\omega t - \frac{\pi}{2}\right)$$

Similarly, for the R – L load. The instantaneous load current is obtained as,

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{2V_{in}}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin(n\omega t - \theta_n)$$

Where,

$$\theta_n = \tan^{-1}\left(\frac{n\omega L}{R}\right)$$

Operation of single phase full bridge inverter

A single phase bridge DC-AC inverter is shown in Figure below. The analysis of the single phase DC-AC inverters is done taking into account following assumptions and conventions.

1) The current entering node a in Figure 8 is considered to be positive.

2) The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.

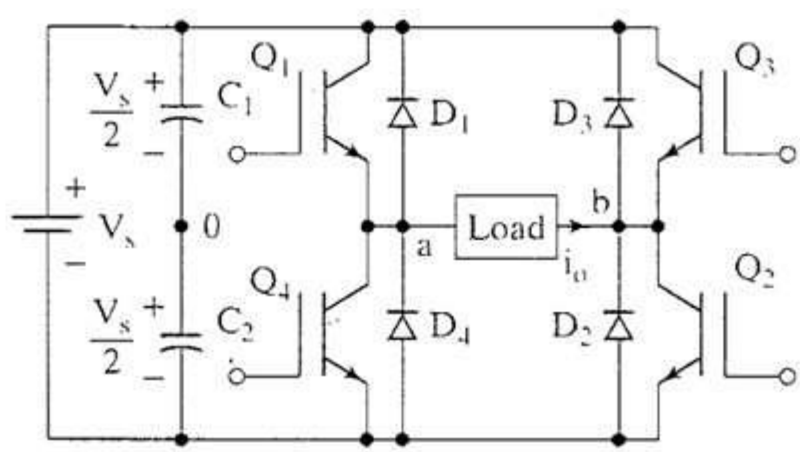


Figure: Single phase Full Bridge DC-AC inverter with R load

When the switches S1 and S2 are turned on simultaneously for a duration 0 ≤ t ≤ T1 , the the input

voltage Vin appears across the load and the current flows from point a to b.

Q1 – Q2 ON, Q3 – Q4 OFF ==> ν o = Vs

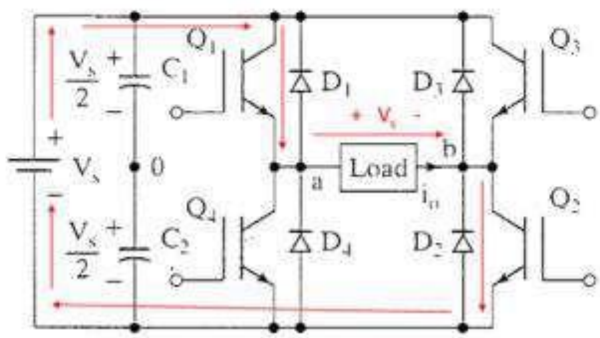


Figure: Single phase Full Bridge DC-AC inverter with R load

If the switches S3 and S4 turned on duration T1 ≤ t ≤ T2, the voltage across the load the load is reversed

and the current through the load flows from point b to a. Q1 – Q2 OFF, Q3 – Q4 ON ==> ν o = -Vs

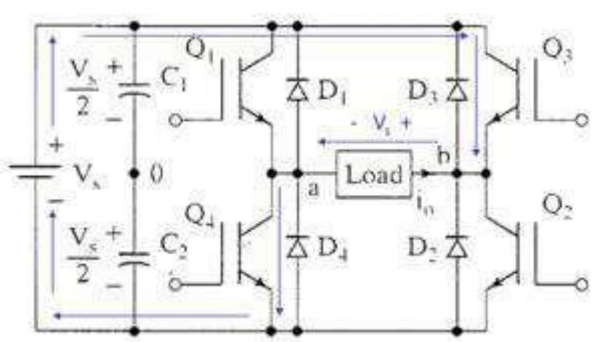


Figure: Single phase Full Bridge DC-AC inverter with R load current directions

The voltage and current waveforms across the resistive load are shown in Figure below

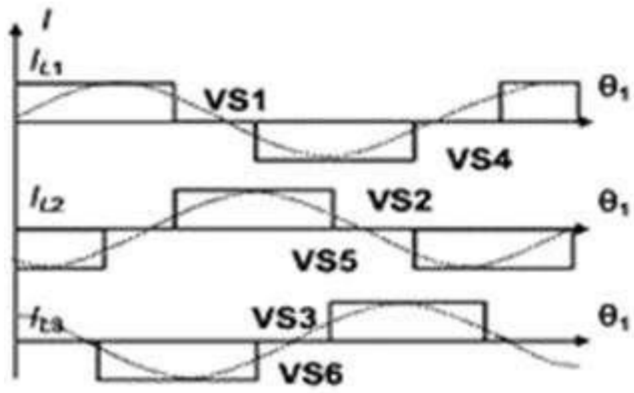
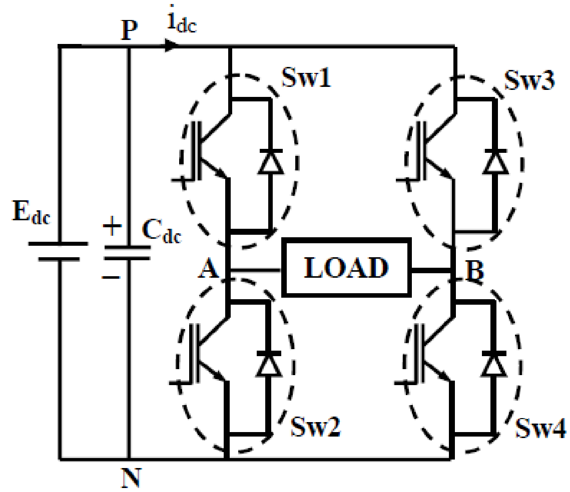


Figure: Single phase Full Bridge DC-AC inverter waveforms

Single Phase Full Bridge Inverter for R-L load:

A single-phase square wave type voltage source inverter produces square shaped output voltage for a single-phase load. Such inverters have very simple control logic and the power switches need to operate at much lower frequencies compared to switches in some other types of inverters. The first generation inverters, using thyristor switches, were almost invariably square wave inverters because thyristor switches could be switched on and off only a few hundred times in a second. In contrast, the present day switches like IGBTs are much faster and used at switching frequencies of several kilohertz. Single-phase inverters mostly use half bridge or full bridge topologies. Power circuits of these topologies are shown inin Figure below.



The above topology is analyzed under the assumption of ideal circuit conditions. Accordingly, it is assumed that the input dc voltage (Edc) is constant and the switches are lossless. In full bridge topology has two such legs. Each leg of the inverter consists of two series connected electronic switches shown within dotted lines in the figures. Each of these switches consists of an IGBT type controlled switchacross which an uncontrolled diode is put in anti-parallel manner. These switches are capable of conducting bi-directional current but they need to block only one polarity of voltage. The junction pointof the switches in each leg of the inverter serves as one output point for the load.

Three phase bridge Inverters:

Three phase inverters are normally used for high power applications. The advantages of a three phaseinverter are:

- The frequency of the output voltage waveform depends on the switching rate of the swtiches and hence
can be varied over a wide range.

• T

he direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.

• The ac output voltage can be controlled by varying the dc link voltage.

The general configuration of a three phase DC-AC inverter is shown in **Figure** Two types of control signals can be applied to the switches:

• 180° conduction

• 120° conduction

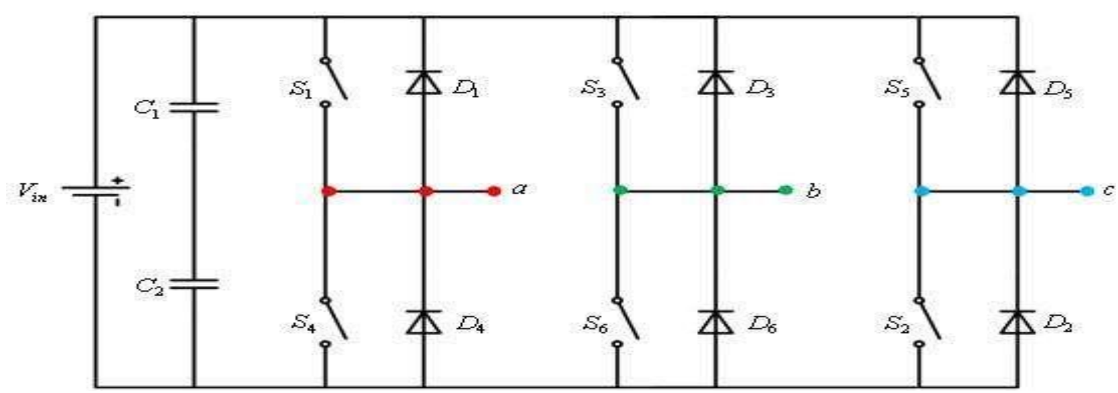


Figure: Circuit diagram of three phase bridge inverter

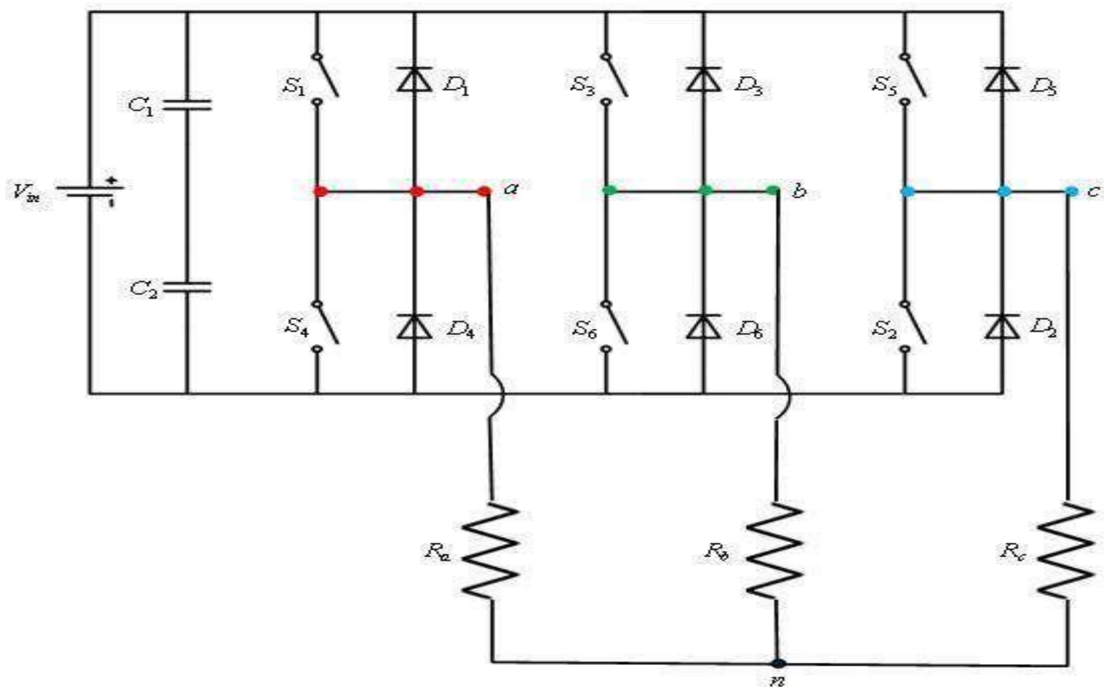
180 degree mode of operation:

The configuration of the three phase inverter with star connected resistive load is shown in **Figure.** The following convention is followed:

• A current leaving a node point ***a***, ***b*** or ***c*** and entering the neutral point ***n*** is assumed to be positive.

• All the three resistances are equal, $R_a = R_b = R_c = R$.

In this mode of operation each switch conducts for 180°. Hence, at any instant of time ***three switches*** remain ***on*** . When S_1 is ***on*** , the terminal ***a*** gets connected to the positive terminal of input DC source. Similarly, when S_4 is ***on*** , terminal ***a*** gets connected to the negative terminal of input DC source. There are six possible modes of operation in a cycle and each mode is of 60° duration and the explanationof each mode is as follows:



Mode 1 **:** In this mode the switches S_5 , S_6 and S_1 are turned ***on*** for time interval $0 \le \omega t \le \frac{\pi}{3}$. As a resultof this the terminals ***a*** and ***c*** are connected to the positive terminal of the input DC source and the

terminal ***b*** is connected to the negative terminal of the DC source. The current flow through R_a, R_b and R_c is shown in Figure and the equivalent circuit is shown in Figure**.** The equivalent resistance of the circuit shown in ***Figure*** is

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2} \tag{1}$$

The current *i* delivered by the DC input source is

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R} \tag{2}$$

The currents i_a and i_b are

$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R} \tag{3}$$

Keeping the current convention in mind, the current i_b is

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R} \tag{4}$$

Having determined the currents through each branch, the voltage across each branch is

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3} \tag{5}$$

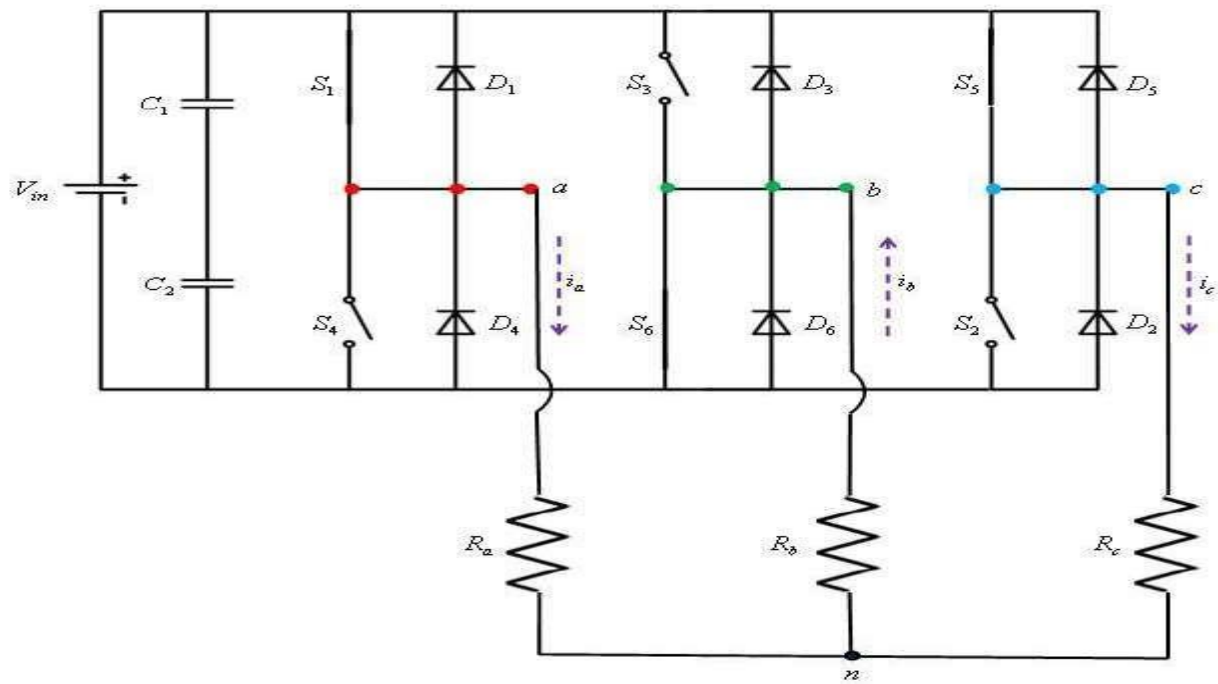
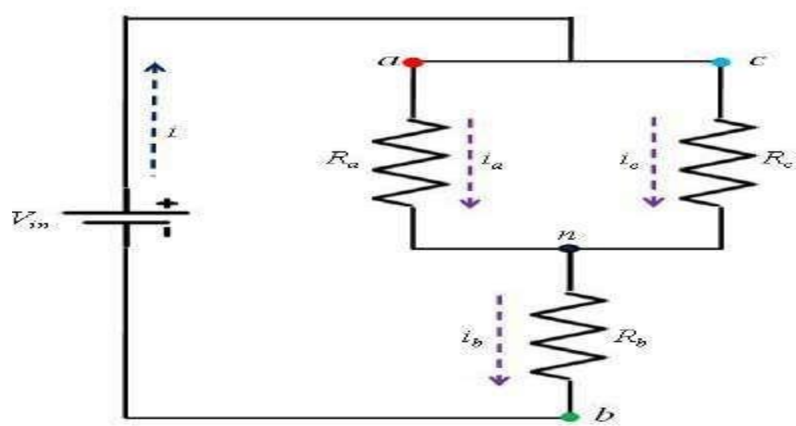


Figure: Mode 1 operation of three phase bridge inverter with star connected load



Mode 2 **:** In this mode the switches S_6 , S_1 and S_2 are turned ***on*** for time interval .

The current flow and the equivalent circuits are shown in **Figure** and **Figure** respectively. Following the reasoning given for ***mode 1*** , the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R} \quad (6)$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3} \quad (7)$$

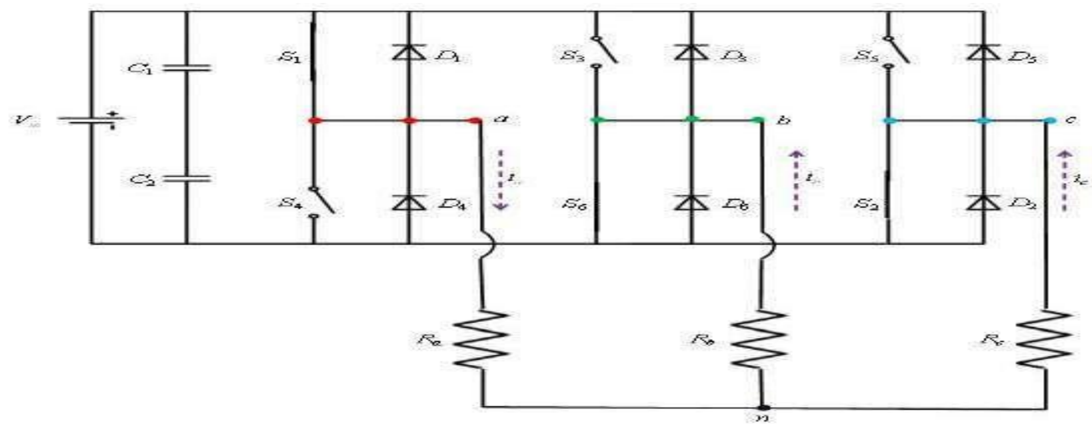


Figure: Mode 2 operation of three phase bridge inverter with star connected load

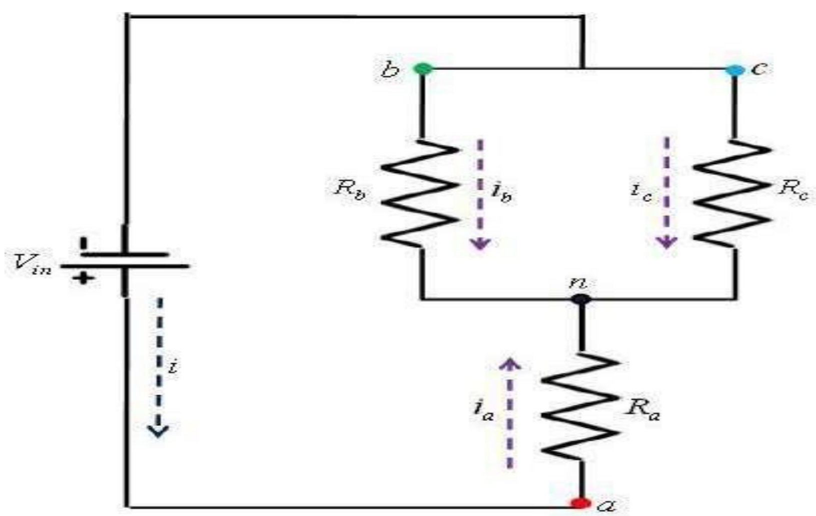


Figure: Current flow in Mode 2 operation

$$\frac{2\pi}{3} \le \omega t \le \pi$$

Mode 3* :** In this mode the switches S_1 , S_2 and S_3 are ***on for .
The current flow and the equivalent circuits are shown in **Figure** and **figure** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R} \qquad (8)$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3} \qquad (9)$$

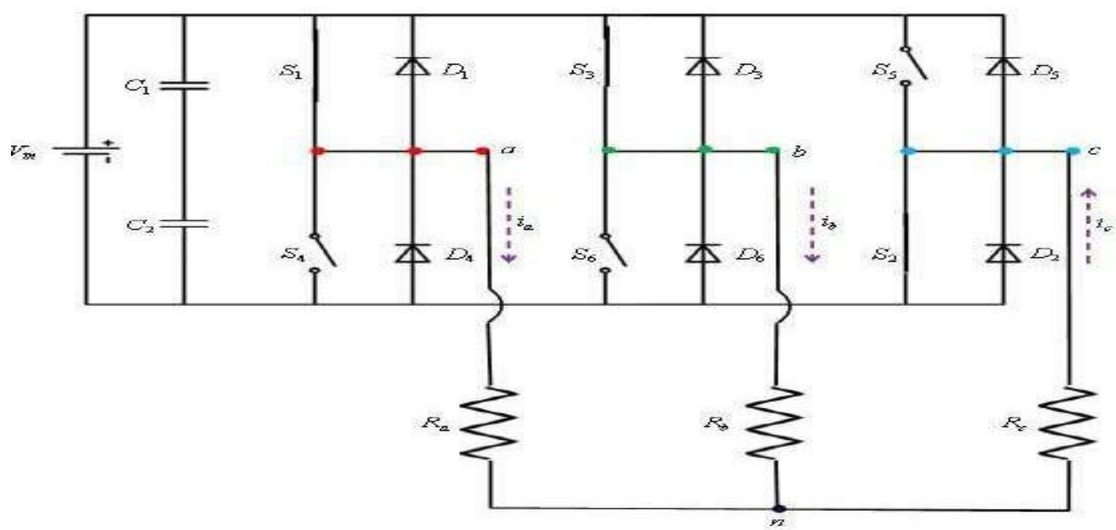


Figure: Mode 3 operation of three phase bridge inverter with star connected load

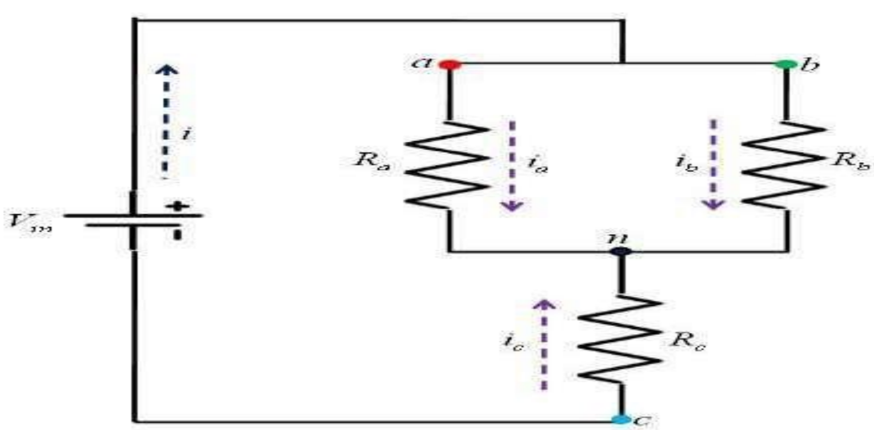


Figure: Current flow in Mode 3 operation

For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} = -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode 4*** (10)

$$\left.\begin{aligned} i_b = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} = -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode5*** (11)

$$\left.\begin{aligned} i_a = i_b = -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} = -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\}$$ for ***mode 6*** (12)

The plots of the phase voltages (v_{an}, v_{bn} and v_{cn}) and the currents (i_a, i_b and i_c) are shown in **Figure**

Having known the phase voltages, the line voltages can also be determined as:

$$\begin{aligned} v_{ab} &= v_{an} - v_{bn} \\ v_{bc} &= v_{bn} - v_{cn} \\ v_{ca} &= v_{cn} - v_{an} \end{aligned}$$ (13)

The plots of line voltages are also shown in **Figure** and the phase and line voltages can be expressed interms of Fourier series as:

Mode 2 **:** In this mode the switches S_6 , S_1 and S_2 are turned ***on*** for time interval $\frac{\pi}{3} \le \omega t \le \frac{2\pi}{3}$.

The current flow and the equivalent circuits are shown in **Figure** and **Figure** respectively. Following the reasoning given for ***mode 1*** , the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R} \qquad (6)$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3} \qquad (7)$$

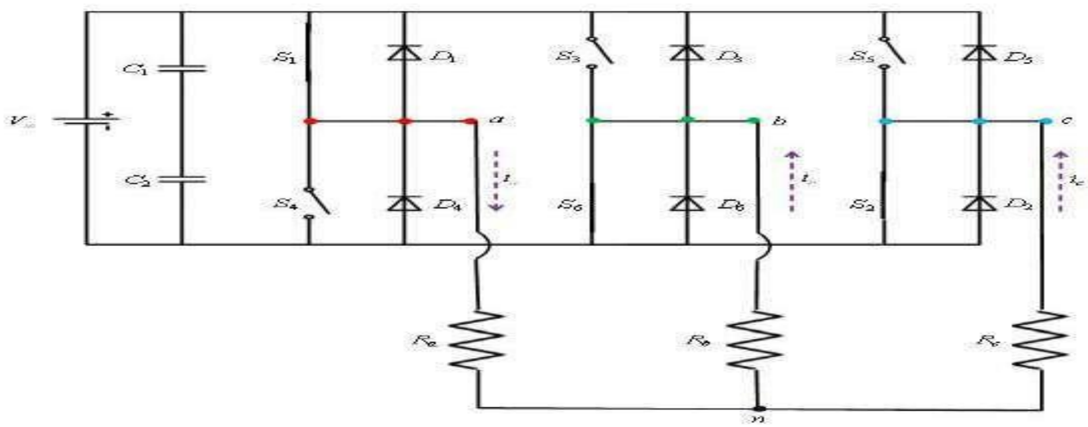


Figure: Mode 2 operation of three phase bridge inverter with star connected load

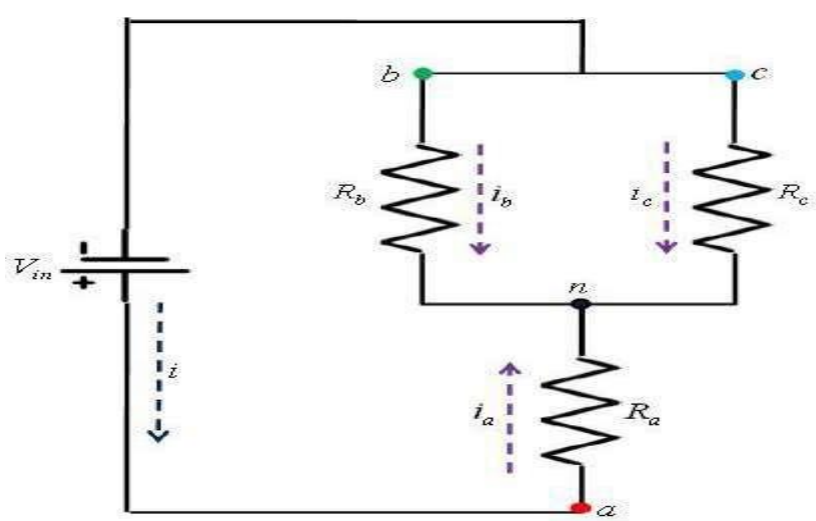


Figure: Current flow in Mode 2 operation

Mode 3 **:** In this mode the switches S_1 , S_2 and S_3 are ***on*** for .
The current flow and the equivalent circuits are shown in **Figure** and **figure** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R} \tag{8}$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3} \tag{9}$$

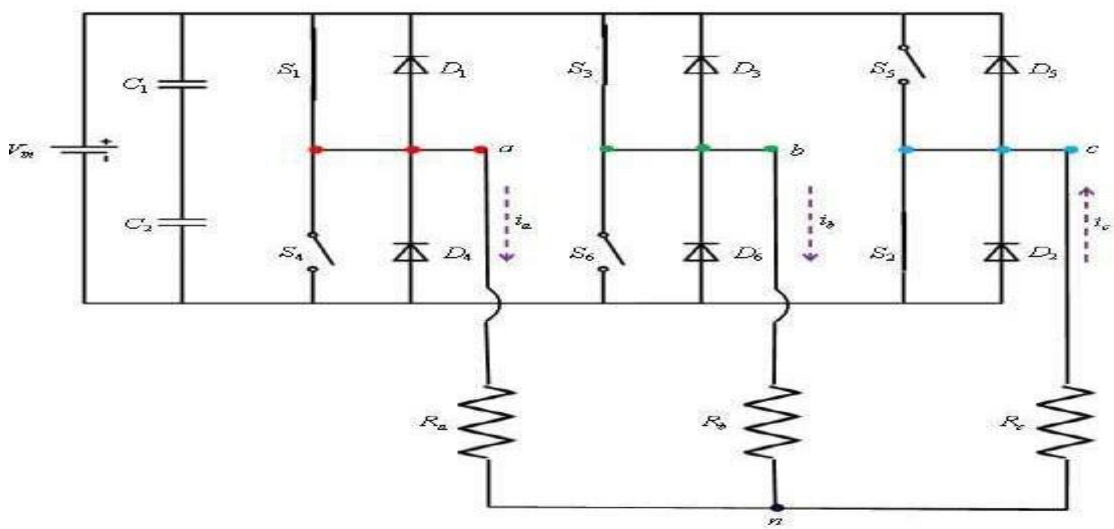


Figure: Mode 3 operation of three phase bridge inverter with star connected load

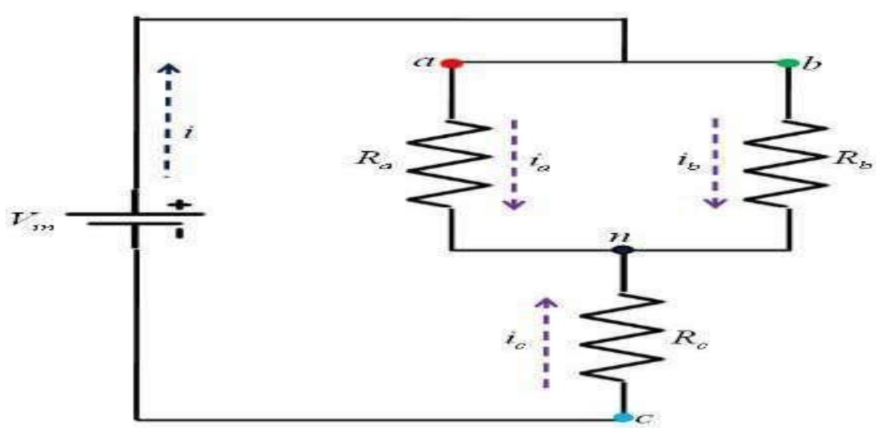


Figure: Current flow in Mode 3 operation

For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} = -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode 4}} \qquad (10)$$

$$\left.\begin{aligned} i_b = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} = -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode5}} \qquad (11)$$

$$\left.\begin{aligned} i_a = i_b = -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} = -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode 6}} \qquad (12)$$

The plots of the phase voltages (v_{an}, v_{bn} and v_{cn}) and the currents (i_a, i_b and i_c) are shown in **Figure**

Having known the phase voltages, the line voltages can also be determined as:

$$\begin{aligned} v_{ab} &= v_{an} - v_{bn} \\ v_{bc} &= v_{bn} - v_{cn} \\ v_{ca} &= v_{cn} - v_{an} \end{aligned} \qquad (13)$$

The plots of line voltages are also shown in **Figure** and the phase and line voltages can be expressed interms of Fourier series as:

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$

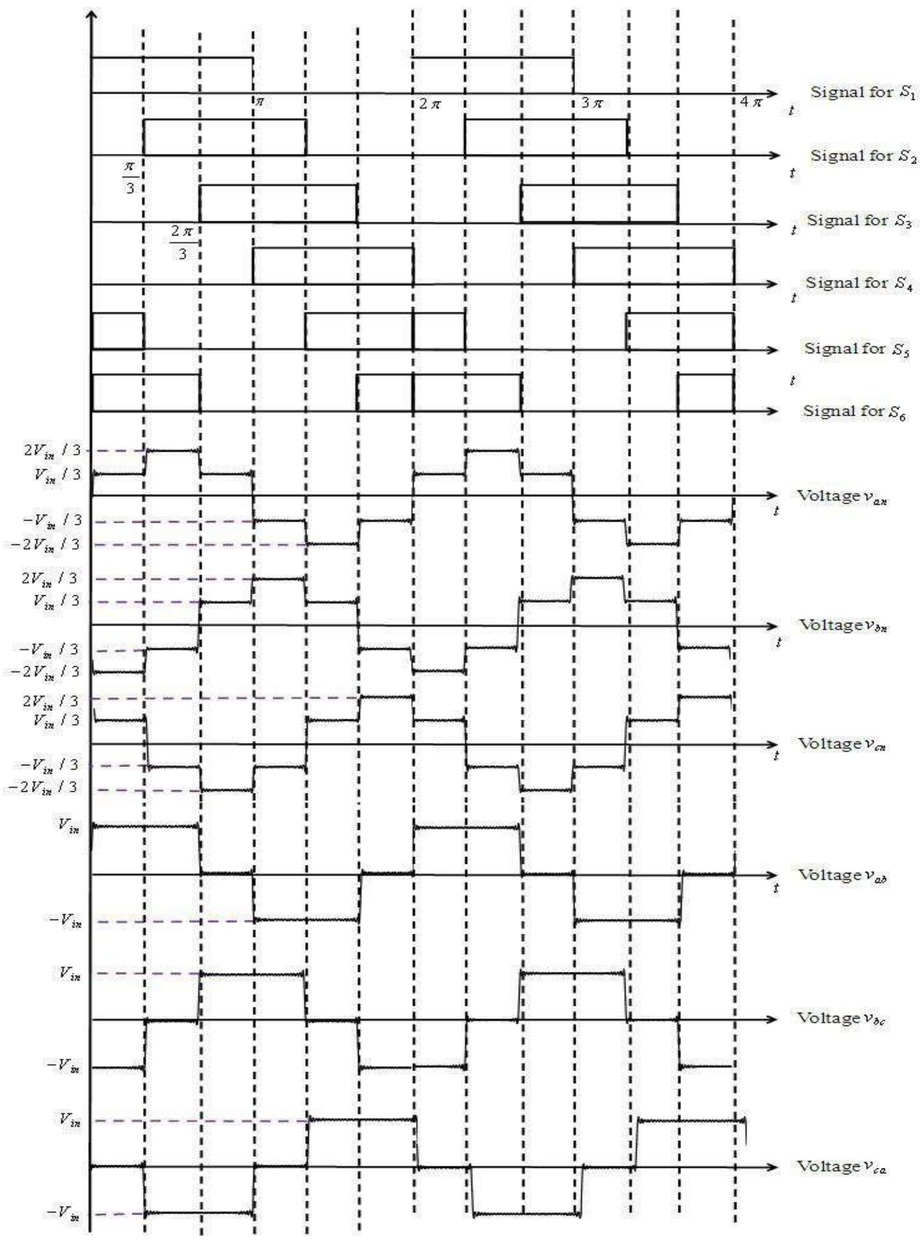
$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{2n\pi}{3}\right)$$

$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{4n\pi}{3}\right)$$

$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left(n\omega t + \frac{n\pi}{6}\right)$$

$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left(n\omega t - \frac{n\pi}{2}\right)$$

$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\left(n\omega t - \frac{7n\pi}{6}\right)$$



Three Phase DC-AC Converters with 120 degree conduction mode

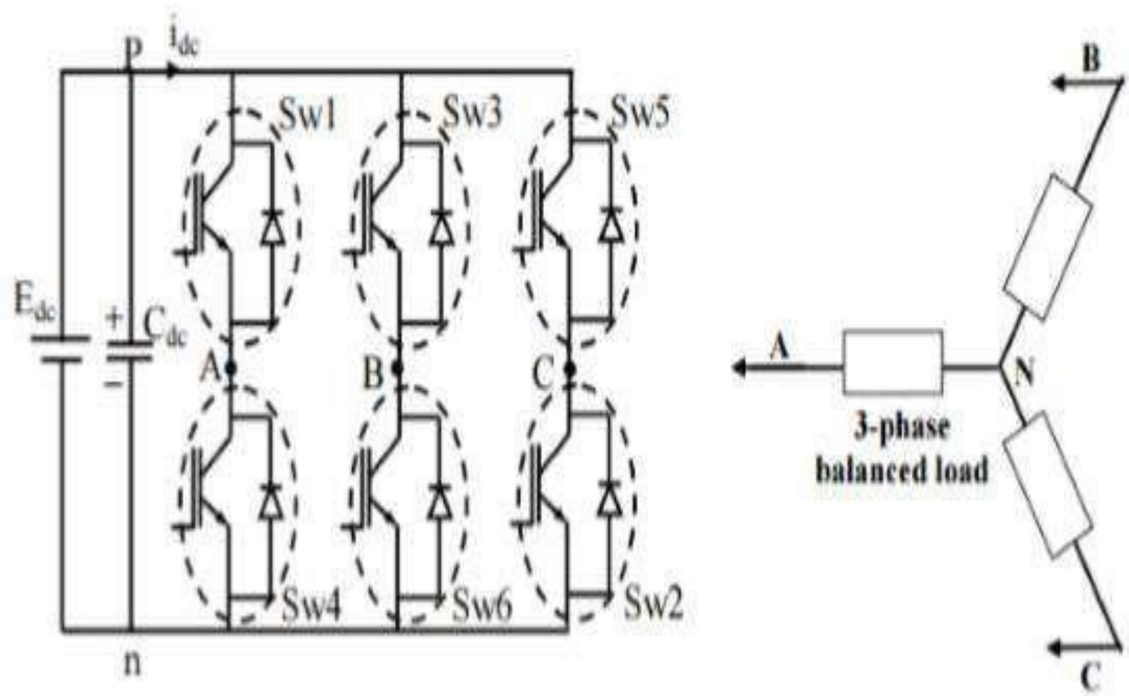


Figure: Circuit diagram of three phase bridge inverter

120° mode of conduction

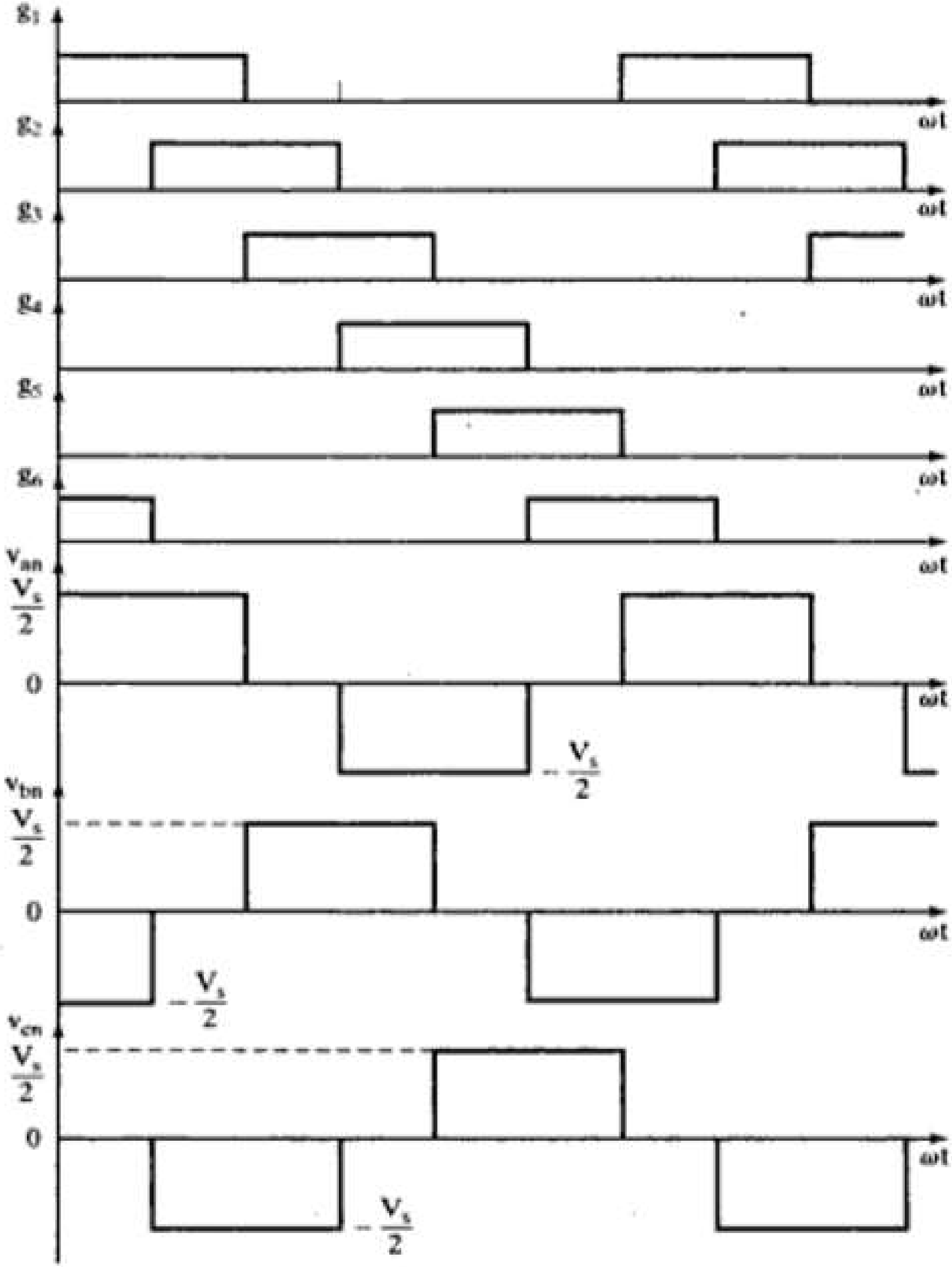
In this mode of conduction, each electronic device is in a conduction state for 120°. It is most suitable for a delta connection in a load because it results in a six-step type of waveform across any of its phases. Therefore, at any instant only two devices are conducting because each device conducts at only 120°.

The terminal A on the load is connected to the positive end while the terminal B is connected to the negative end of the source. The terminal C on the load is in a condition called floating state. Furthermore, the phase voltages are equal to the load voltages as shown below.

Phase voltages = Line voltages $V_{AB} = V$

$V_{BC} = -V/2$

$V_{CA} = -V/2$



Voltage control techniques for inverters

Pulse width modulation techniques

PWM is a technique that is used to reduce the overall harmonic distortion (THD) in a load current. It uses a pulse wave in rectangular/square form that results in a variable average waveform value f(t), after its pulse width has been modulated. The time period for modulation is given by T. Therefore, waveform average value is given by

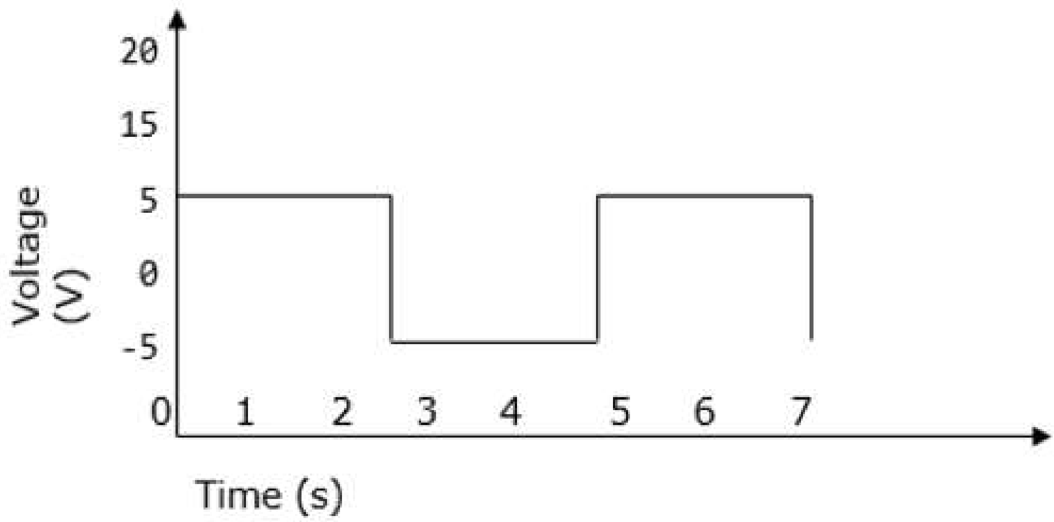


Figure: Square waveform used for PWM technique

Sinusoidal Pulse Width Modulation

In a simple source voltage inverter, the switches can be turned ON and OFF as needed. During each cycle, the switch is turned on or off once. This results in a square waveform. However, if the switch is turned on for a number of times, a harmonic profile that is improved waveform is obtained.

The sinusoidal PWM waveform is obtained by comparing the desired modulated waveform with a triangular waveform of high frequency. Regardless of whether the voltage of the signal is smaller or larger than that of the carrier waveform, the resulting output voltage of the DC bus is either negative or positive.

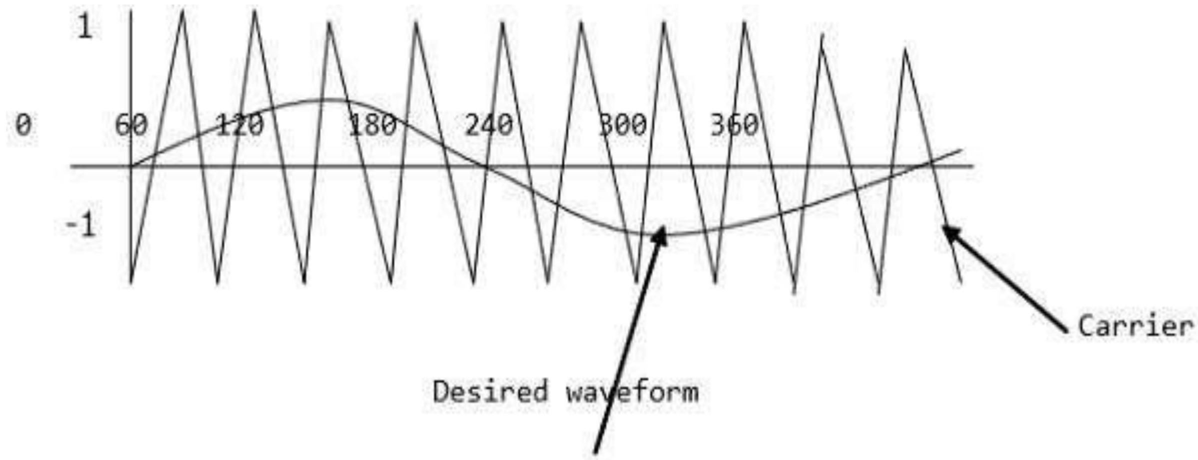
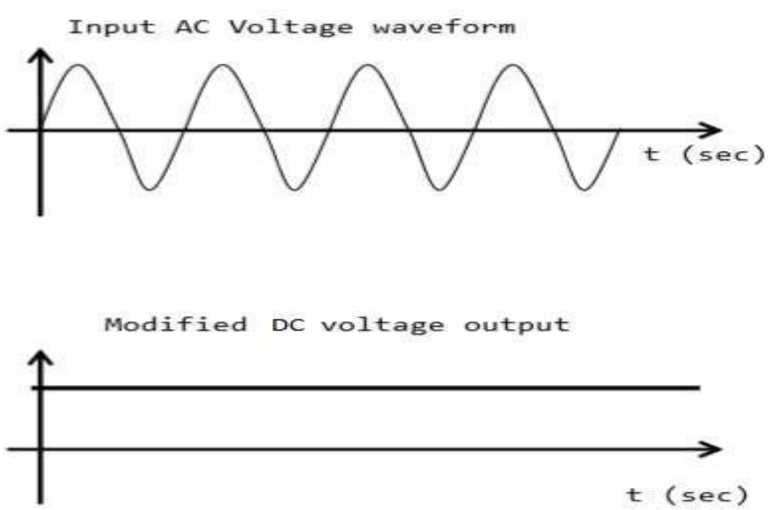


Figure: Sinusoidal PWM waveform

The sinusoidal amplitude is given as A_m and that of the carrier triangle is give as A_c. For sinusoidal PWM, the modulating index m is given by A_m/A_c.

Modified Sinusoidal Waveform PWM

A modified sinusoidal PWM waveform is used for power control and optimization of the power factor. The main concept is to shift current delayed on the grid to the voltage grid by modifying the PWM converter. Consequently, there is an improvement in the efficiency of power as well as optimization in power factor.



Multiple PWM

The multiple PWM has numerous outputs that are not the same in value but the time period over which they are produced is constant for all outputs. Inverters with PWM are able to operate at high voltage output.

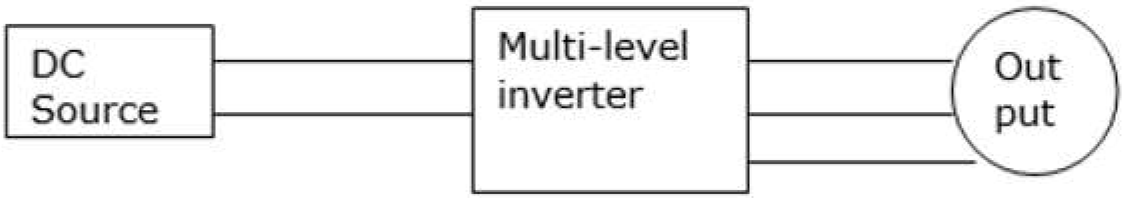


Figure: Block diagram of multiple PWM technique

The waveform below is a sinusoidal wave produced by a multiple PWM

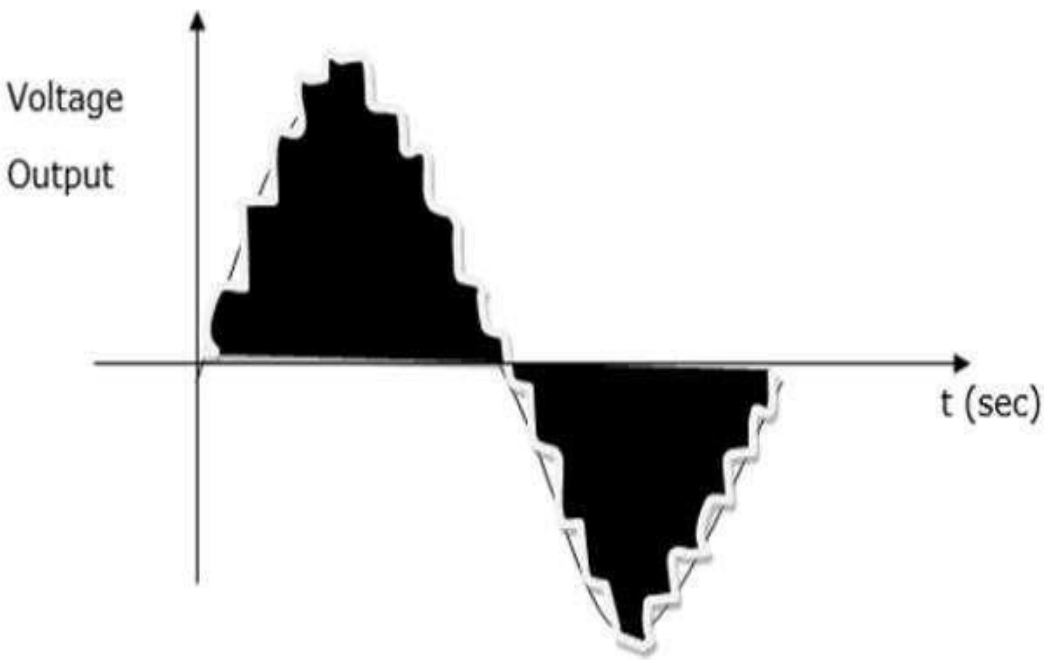


Figure: Waveform of multiple PWM technique

Operation of sinusoidal pulse width modulation

The sinusoidal PWM (SPWM) method also known as the triangulation, sub harmonic, or sub oscillation method, is very popular in industrial applications. The SPWM is explained with reference to Figure, which is the half-bridge circuit topology for a single-phase inverter.

For realizing SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference of the desired frequency. The intersection of and waves determines the switching instants and commutation of the modulated pulse. The PWM scheme is illustrated in Figure, in which v_c the peak value of triangular carrier wave and v_r is that of the reference, or modulating signal. The figure shows the triangle and modulation signal with some arbitrary frequency and magnitude. In the inverter of Figure the switches and are controlled based on the comparison of control signal and the triangular wave which are mixed in a comparator. When sinusoidal wave has magnitude higher than the triangular wave the comparator output is high, otherwise it is low.

$$v_r > v_c \qquad S_{11} \text{ is on}, \; V_{out} = \frac{V_d}{2}$$

and

$$v_r < v_c \qquad S_{12} \text{ is on}, \; V_{out} = -\frac{V_d}{2}$$

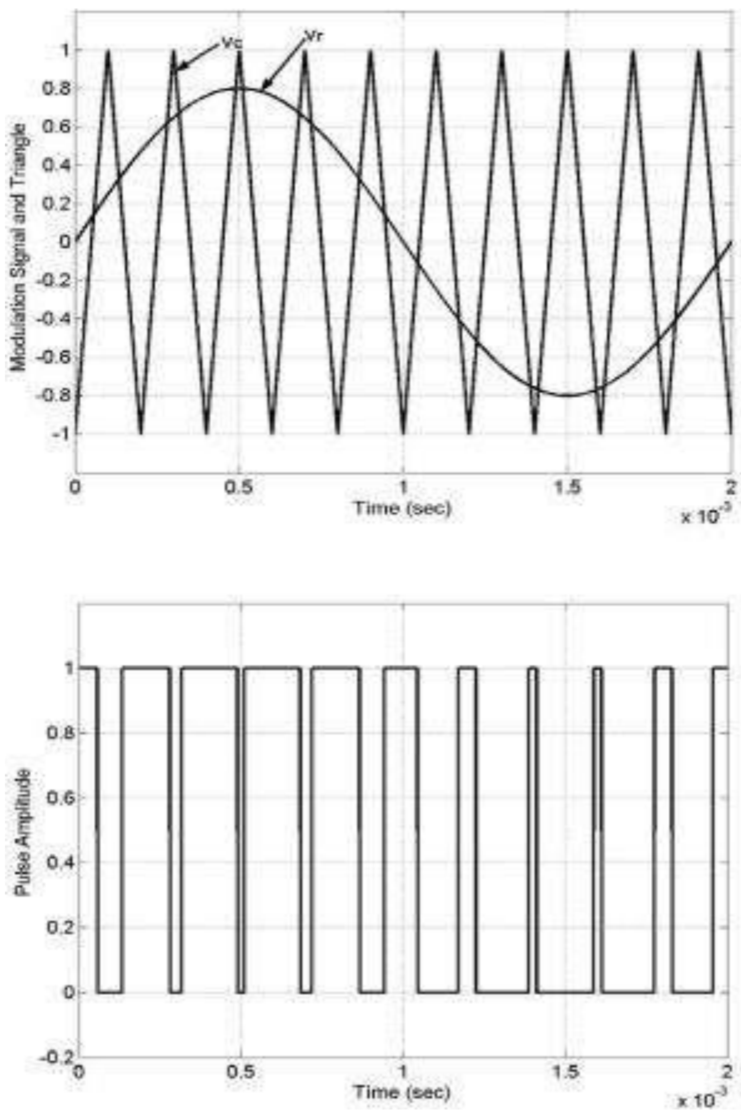
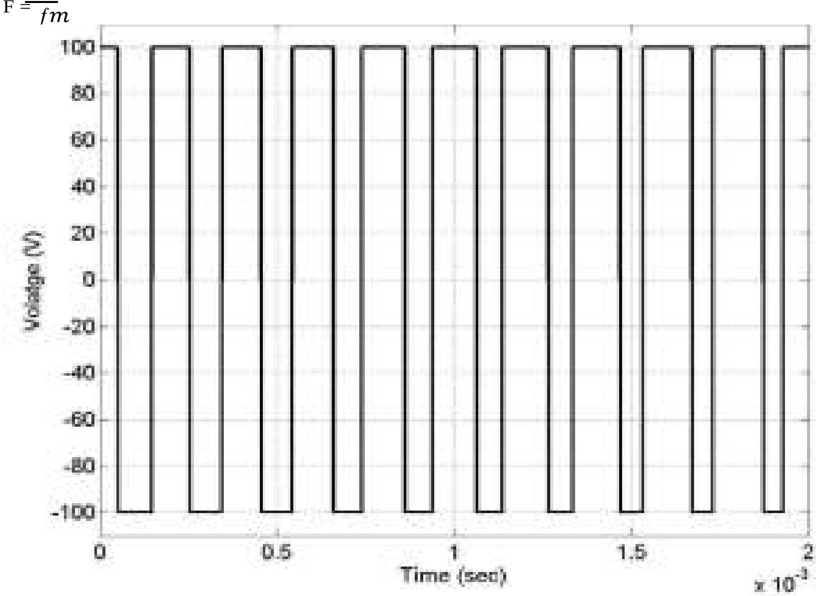


Figure: Sine-Triangle Comparison and switching pulses of half bridge PWM inverter

The comparator output is processes in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. The magnitude ratio of V_r/V_C is called the modulation index (MI) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to MI . The amplitude of the triangular wave is generally kept constant. The frequency modulation ratio is defined as

M^{fr}

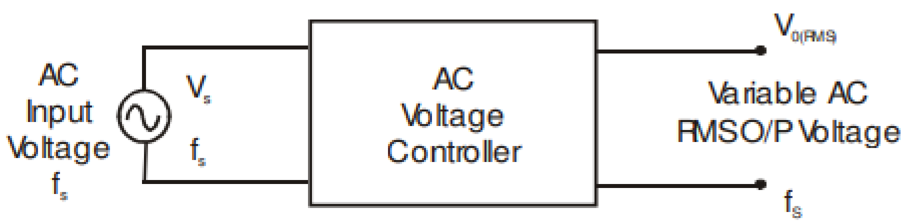
$F = \overline{} fm$



UNIT-V

AC-AC CONVERTERS:

AC voltage controllers (ac line voltage controllers) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing Thyristors between the load and a constant voltage ac source. The RMS value of alternating voltage applied to a load circuit is controlled by controlling the triggering angle of the Thyristors in the ac voltage controller circuits. In brief, an ac voltage controller is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency ac input supply to obtain a variable voltage ac output. The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle 'α'



- **<u>Types of Ac Voltage Controllers</u>**

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit. www.getmyuni.com Page 217
 • 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. Each type of controller may be sub divided into
• Uni-directional or half wave ac controller.
 • Bi-directional or full wave ac controller. In brief different types of ac voltage controllers are • Single phase half wave ac voltage controller (uni-directional controller)
. • Single phase full wave ac voltage controller (bi-directional controller)
. • Three phase half wave ac voltage controller (uni-directional controller).
 • Three phase full wave ac voltage controller (bi-directional controller).

<u>Applications of Ac Voltage Controllers</u>

• Lighting / Illumination control in ac power circuits.

• Induction heating.
• Industrial heating & Domestic heating.
• Transformer tap changing (on load transformer tap changing).
• Speed control of induction motors (single phase and poly phase ac induction motor

Principle of AC Phase Control :

The basic principle of ac phase control technique is explained with reference to a single phase half wave ac voltage controller (unidirectional controller) circuit shown in the below figure. The half wave ac controller uses one thyristor and one diode connected in parallel across each other in opposite direction that is anode of thyristor T1 is connected to the cathode of diode D1 and the cathode of T1 is connected to the anode of D1 . The output voltage across the load resistor 'R' and hence the ac power flow to the load is controlled by varying the trigger angle 'α'. The trigger angle or the delay angle 'α' refers to the value of ωt or the instant at which the thyristor T1 is triggered to turn it ON, by applying a suitable gate trigger pulse between the gate and cathode lead. The thyristor T1 is forward biased during the positive half cycle of input ac supply. It can be triggered and made to conduct by applying a suitable gate trigger pulse only during the www.getmyuni.com Page 226 positive half cycle of input supply. When T1 is triggered it conducts and the load current flows through the thyristorT1 , the load and through the transformer secondary winding .

By assuming T1 as an ideal thyristor switch it can be considered as a closed switch when it is ON during the period $\omega t = \alpha$ to π radians. The output voltage across the load follows the input supply voltage when the thyristor T1 is turned-on and when it conducts from $\omega t = \alpha$ to π radians. When the input supply voltage decreases to zero at $\omega t = \pi$, for a resistive load the load current also falls to zero at $\omega t = \pi$ and hence the thyristor T1 turns off at $\omega t = \pi$. Between the time period $\omega t = \pi$ to 2π , when the supply voltage reverses and becomes negative the diode D1 becomes forward biased and hence turns ON and conducts. The load current flows in the opposite direction during $\omega t = \pi$ to 2π radians when D1 is ON and the output voltage follows the negative half cycle of input supply.

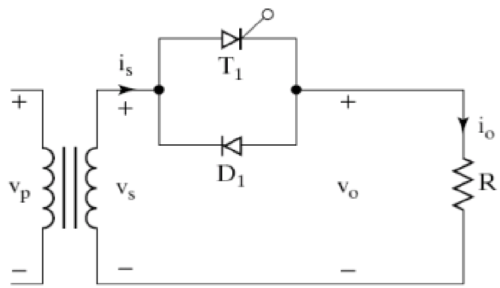
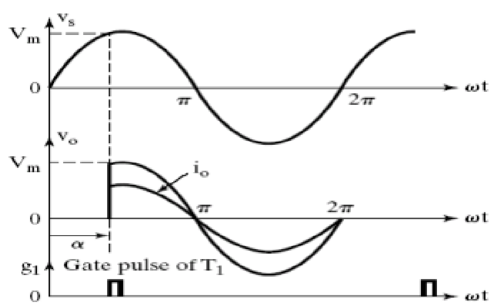


Fig 6.4: Halfwave AC phase controller (Unidirectional Controller)



Output Load Voltage

$$v_o = v_L = 0\text{; for } \omega t = 0 \text{ to } \alpha$$

$$v_o = v_L = V_m \sin \omega t\text{ ; for } \omega t = \alpha \text{ to } 2\pi\text{ .}$$

Output Load Current

$$i_o = i_L = \frac{v_o}{R_L} = \frac{V_m \sin \omega t}{R_L}\text{ ; for } \omega t = \alpha \text{ to } 2\pi\text{ .}$$

$$i_o = i_L = 0\text{; for } \omega t = 0 \text{ to } \alpha\text{ .}$$

(i) To Derive an Expression for rms Output Voltage $V_{O(RMS)}$.

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

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\int_{\alpha}^{2\pi}\left(\frac{1-\cos 2\omega t}{2}\right).d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{4\pi}\left[\int_{\alpha}^{2\pi}(1-\cos 2\omega t).d(\omega t)\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[\int_{\alpha}^{2\pi} d(\omega t) - \int_{\alpha}^{2\pi}\cos 2\omega t.d\omega t\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[(\omega t)\Big/_{\alpha}^{2\pi} - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{2\pi}\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(2\pi-\alpha) - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{2\pi}}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(2\pi-\alpha) - \left\{\frac{\sin 4\pi}{2} - \frac{\sin 2\alpha}{2}\right\}} \qquad ;\sin 4\pi = 0$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(2\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}\sqrt{2\pi}}\sqrt{(2\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

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

$$V_{O(RMS)} = V_{i(RMS)}\sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

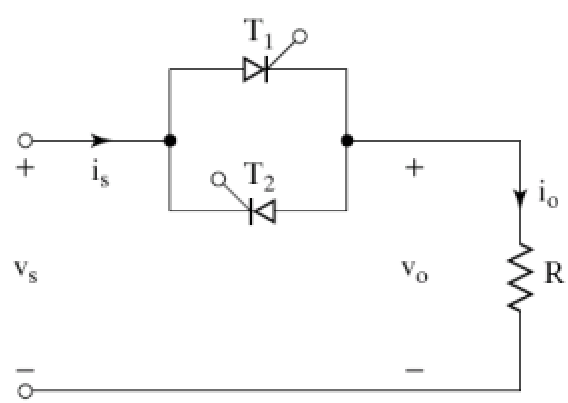
$$V_{O(RMS)} = V_S\sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

Where, $V_{i(RMS)} = V_S = \frac{V_m}{\sqrt{2}}$ = RMS value of input supply voltage (across the transformer secondary winding).

Single Phase Full Wave Ac Voltage Controller (Ac Regulator) or Rms Voltage Controller with Resistive Load :

Single phase full wave ac voltage controller circuit using two SCRs or a single triac is generally used in most of the ac control applications. The ac power flow to the load can be controlled in both the half cycles by varying the trigger angle '' α .

The RMS value of load voltage can be varied by varying the trigger angle '' α . The input supply current is alternating in the case of a full wave ac voltage controller and due to the symmetrical nature of the input supply current waveform there is no dc component of input supply current i.e., the average value of the input supply current is zero. A single phase full wave ac voltage controller with a resistive load is shown in the figure below. It is possible to control the ac power flow to the load in both the half cycles by adjusting the trigger angle '' α . Hence the full wave ac voltage controller is also referred to as to as to a bi directional controller.



The thyristor T1 is forward biased during the positive half cycle of the input supply voltage. The thyristor T1 is triggered at a delay angle of '' α ( ) 0 radians ≤ ≤ α π . Considering the ON thyristor T1 as an ideal closed switch the input supply voltage appears across the load resistor RL and the output voltage O S v v = during ωt =α to π radians. The load current flows through the ON thyristor T1 and through the load resistor RL in the downward direction during the conduction time of T1 from ωt =α to π radians.

At ωt = π , when the input voltage falls to zero the thyristor current (which is flowing through the load resistor RL) falls to zero and hence T1 naturally turns off . No current flows in the circuit during ωt = π to ( ) π +α .

The thyristor T2 is forward biased during the negative cycle of input supply and when thyristor T2 is triggered at a delay angle ( ) π +α , the output voltage follows the negative halfcycle of input from ωt = + ( ) π α to 2π . When T2 is ON, the load current flows in the reverse direction (upward direction) through T2 during ωt = + ( ) π α to 2π radians. The time interval (spacing) between the gate trigger pulses of T1 and T2 is kept at π radians or 1800 . At ωt = 2π the input supply voltage falls to zero and hence the load current also falls to zero and thyristor T2 turn off naturally.

(i) To Derive an Expression for the Rms Value of Output (Load) Voltage The RMS value of output voltage (load voltage) can be found using the expression

$$V_{O(RMS)}^2 = V^2_{L(RMS)} = \frac{1}{2\pi}\int_0^{2\pi} v_L^{\,2} d(\omega t);$$

For a full wave ac voltage controller, we can see that the two half cycles of output voltage waveforms are symmetrical and the output pulse time period (or output pulse repetition time) is π radians. Hence we can also calculate the RMS output voltage by using the expression given below.

$$V^2_{L(RMS)} = \frac{1}{\pi}\int_0^{\pi} V_m^{\,2}\sin^2\omega t.d\omega t$$

$$V^2_{L(RMS)} = \frac{1}{2\pi}\int_0^{2\pi} v_L^{\,2}.d(\omega t)\ ;$$

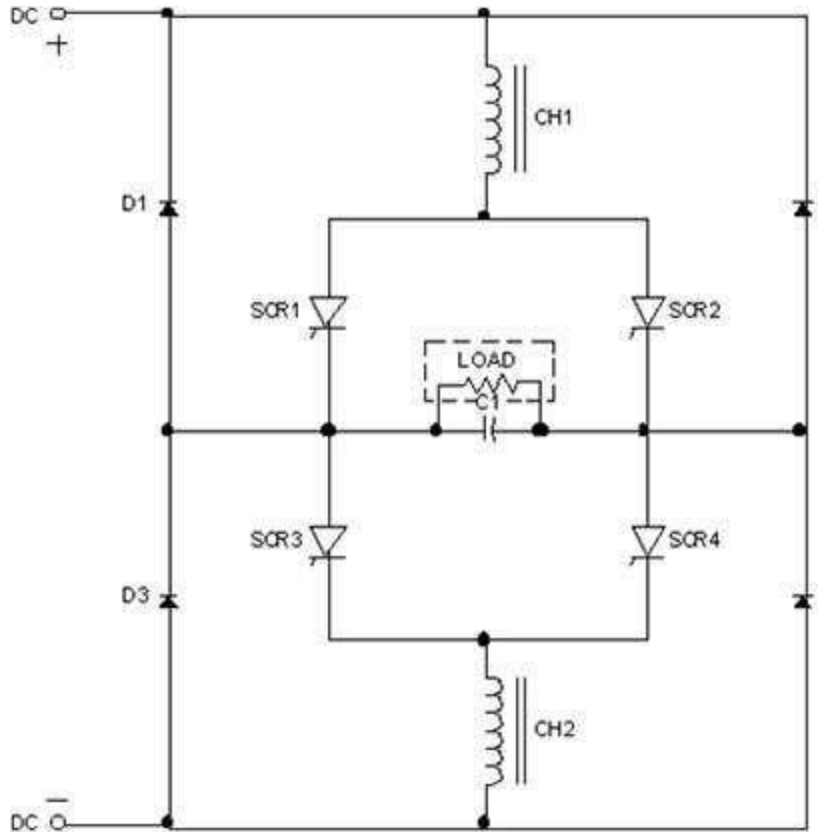
$$v_L = v_O = V_m \sin\omega t\,;\ \text{For}\ \ \omega t = \alpha\ \text{to}\ \pi\ \ \text{and}\ \ \omega t = (\pi+\alpha)\ \text{to}\ 2\pi$$

Hence,

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

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

$$= \frac{V_m^{\,2}}{2\pi}\left[\int_\alpha^{\pi}\frac{1-\cos 2\omega t}{2}d(\omega t) + \int_{\pi+\alpha}^{2\pi}\frac{1-\cos 2\omega t}{2}d(\omega t)\right]$$



$$=\frac{V_m^2}{2\pi\times 2}\left[\int_\alpha^\pi d(\omega t)-\int_\alpha^\pi \cos 2\omega t.d(\omega t)+\int_{\pi+\alpha}^{2\pi} d(\omega t)-\int_{\pi+\alpha}^{2\pi}\cos 2\omega t.d(\omega t)\right]$$

$$=\frac{V_m^2}{4\pi}\left[(\omega t)\Big/_{\alpha}^{\pi}+(\omega t)\Big/_{\pi+\alpha}^{2\pi}-\left[\frac{\sin 2\omega t}{2}\right]_\alpha^\pi-\left[\frac{\sin 2\omega t}{2}\right]_{\pi+\alpha}^{2\pi}\right]$$

$$=\frac{V_m^2}{4\pi}\left[(\pi-\alpha)+(\pi-\alpha)-\frac{1}{2}(\sin 2\pi-\sin 2\alpha)-\frac{1}{2}(\sin 4\pi-\sin 2(\pi+\alpha))\right]$$

$$=\frac{V_m^2}{4\pi}\left[2(\pi-\alpha)-\frac{1}{2}(0-\sin 2\alpha)-\frac{1}{2}(0-\sin 2(\pi+\alpha))\right]$$

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

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

-

Therefore,

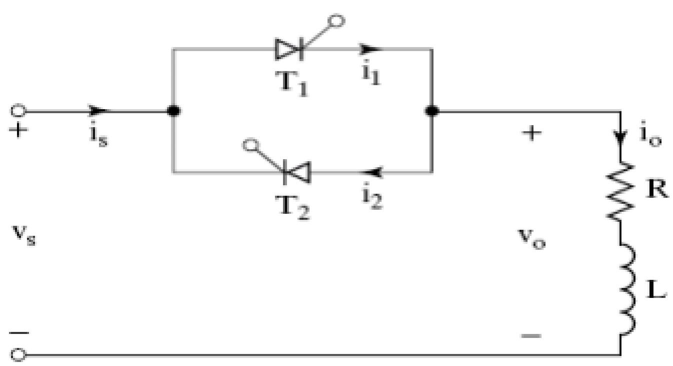
$$V^2_{L(RMS)} = \frac{V_m^2}{4\pi}\left[(2\pi - 2\alpha) + \sin 2\alpha\right]$$

$$V_{L(RMS)} = V_S\sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

Single Phase Full Wave Ac Voltage Controller (Bidirectional Controller) With RL Load:

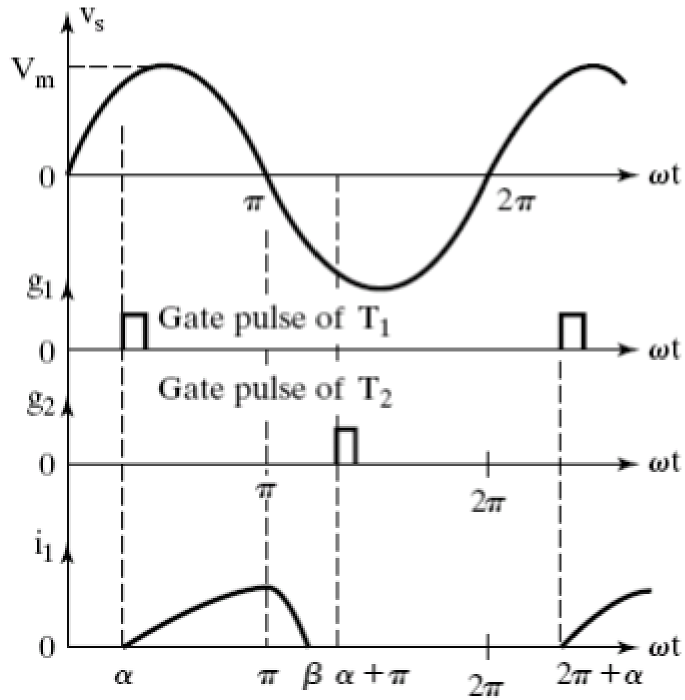
In this section we will discuss the operation and performance of a single phase full wave ac voltage controller with RL load. In practice most of the loads are of RL type. For example if we consider a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load, where R represents the motor winding resistance and L represents the motor winding inductance.

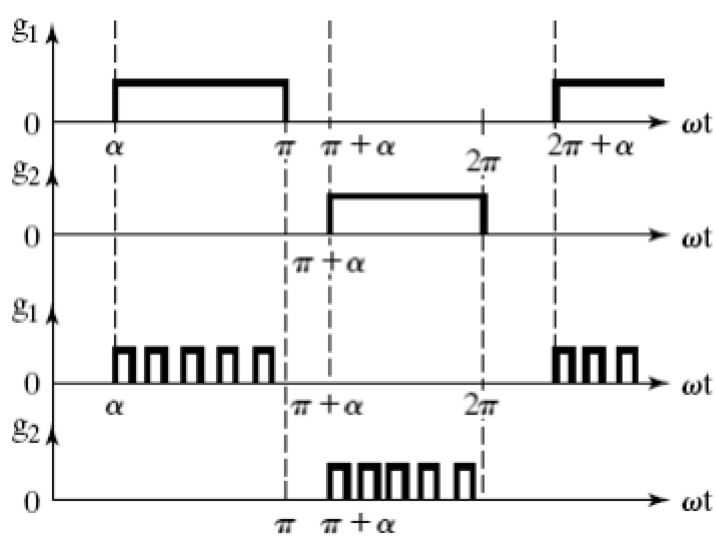
A single phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using two thyristors T1 and T2 (T1 and T2 are two SCRs) connected in parallel is shown in the figure below. In place of two thyristors a single Triac can be used to implement a full wave ac controller, if a suitable Traic is available for the desired RMS load current and the RMS output voltage ratings.



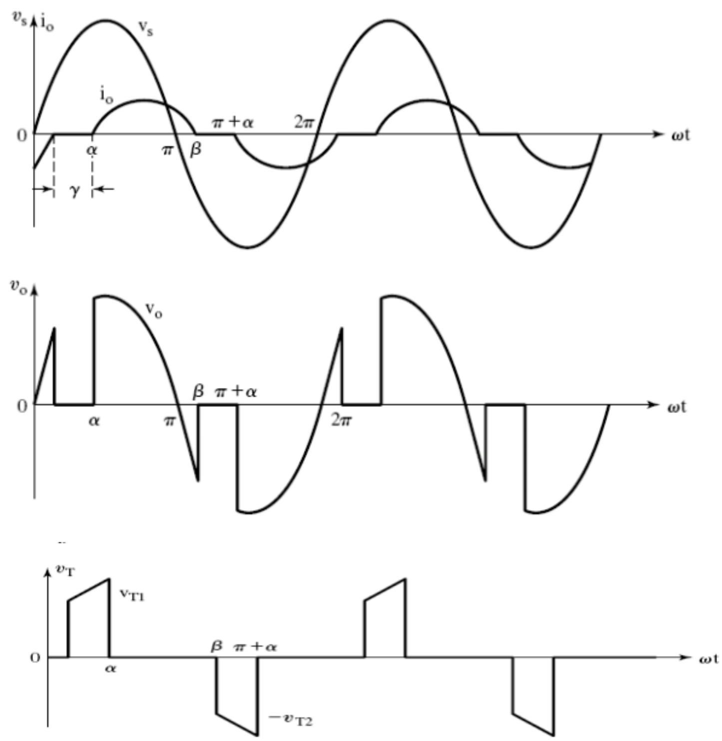
The thyristor T1 is forward biased during the positive half cycle of input supply. Let us assume that T1 is triggered atωt =α , by applying a suitable gate trigger pulse to T1 during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when T1 is ON. The load current O i flows through the thyristor T1 and through the load in the downward direction. This load current pulse flowing through T1 can be considered as the positive current pulse. Due to the inductance in the load, the load current O i flowing through T1 would not fall to zero at ωt = π , when the input supply voltage starts to become negative.

The thyristor T1 will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through T1 falls to zero at t ω β = , where β is referred to as the Extinction angle, (the value of ωt) at which theload current falls to zero. The extinction angle β is measured from the point of the beginning of the positive half cycle of input supply to the point where the load current falls to zero. The thyristor T1 conducts from ωt =α to β . The conduction angle of T1 is ( ) = − , which depends on the delay angle α and the load impedance angle φ . The waveforms of the input supply voltage, the gate trigger pulses of T1 and T2 , the thyristor current, the load current and the load voltage waveforms appear as shown in the figure below





Waveforms of single phase full wave ac voltage controller with RL load for α φ > . Discontinuous load current operation occurs for α φ > and ( ) β π α < + ; i.e., ( ) − < , conduction angle



(i) To Derive an Expression for the Output (Inductive Load) Current, During t to = When Thyristor T1 Conducts

Considering sinusoidal input supply voltage we can write the expression for the supply voltage as

Vs=Vm sinwt=instantaneous value of the input supply voltage.

Let us assume that the thyristor T1 is triggered by applying the gating signal to T1 at ωt =α . The load current which flows through the thyristor T1 during ωt =α to β can be found from the equation

$$L\left(\frac{di_O}{dt}\right)+Ri_O=V_m\sin\omega t\quad ;$$

The solution of the above differential equation gives the general expression for the output load current which is of the form

Where $V_m = \sqrt{2}V_S$ = maximum or peak value of input supply voltage.

ω

$Z = \sqrt{R^2 + (\quad L)^2}$ = Load impedance.

ω

$\phi = \tan^{-1}\left(\frac{\quad L}{R}\right)$ = Load impedance angle (power factor angle of load).

τ

$= \frac{L}{R}$ = Load circuit time constant.

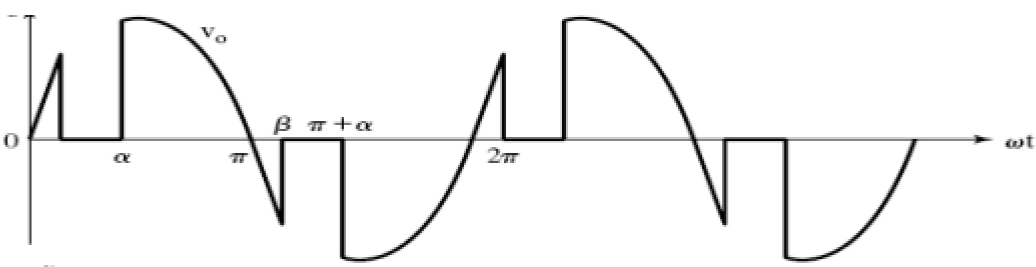
Therefore the general expression for the output load current is given by the equation

$i_O = \frac{V_m}{Z}\sin(\quad t - \quad) + A_1 e^{\frac{-R}{L}t}$;

therefore we obtain the final expression for the inductive load current of a single phase full wave ac voltage controller with RL load as

$$i_O = \frac{V_m}{Z}\left[\sin(\omega t - \phi) - \sin(\alpha - \phi)\, e^{\frac{-R}{\omega L}(\omega t - \alpha)}\right] \quad ; \quad \text{Where} \quad \le \quad t \le \quad .$$

(ii) **To Derive an Expression For rms Output Voltage O RMS ( ) V of a Single Phase Full-Wave Ac Voltage Controller with RL Load.**



When $\alpha > \phi$, the load current and load voltage waveforms become discontinuous as shown in the figure above.

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

Output $v_o = V_m \sin\omega t$, for $\quad t = \quad$ to $\quad$, when T_1 is ON.

$$V_{O(RMS)} = \left[\frac{V_m^{\,2}}{\pi}\int_{\alpha}^{\beta}\frac{(1-\cos 2\omega t)}{2}d(\omega t)\right]^{1/2}$$

$$V_{O(RMS)} = \left[\frac{V_m^{\ 2}}{2\pi} \left\{ (\omega t) \Big/_{\alpha}^{\beta} - \left(\frac{\sin 2\omega t}{2} \right) \Big/_{\alpha}^{\beta} \right\} \right]^{1/2}$$

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

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

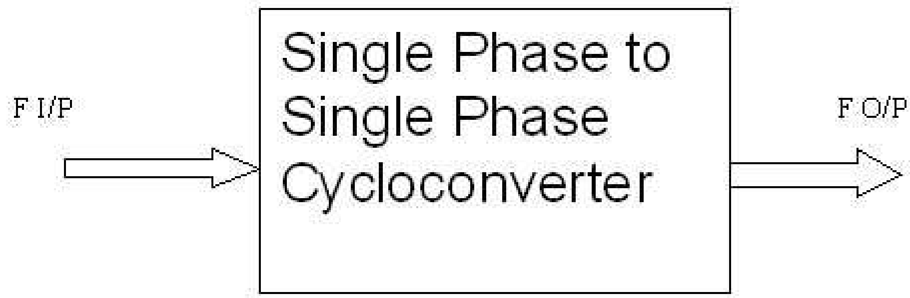
$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \left[\frac{1}{\pi} \left\{ (\beta - \alpha) + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2} \right\} \right]^{1/2}$$

$$\phi = \tan^{-1}\left(\frac{\omega L}{R} \right) = 0 \ ;$$

$$\beta = \pi \text{ radians} = 180^0$$

Introduction to Cyclo converters

The **Cycloconverter** has been traditionally used only in very high power drives, usually above one megawatt, where no other type of drive can be used. Examples are cement tube mill drives above 5 MW, the 13 MW German-Dutch wind tunnel fan drive, reversible rolling mill drives and ship propulsion drives. The reasons for this are that the traditional **Cycloconverter** requires a large number of thyristors, at least 36 and usually more for good motor performance, together with a very complex control circuit, and it has some performance limitations, the worst of which is an output frequency limited to about one third the input frequency .



The **Cycloconverter** has four thyristors divided into a positive and negative bank of two thyristors each. When positive current flows in the load, the output voltage is controlled by phase control of the two positive bank thyristors whilst the negative bank thyristors are kept off and vice versa when negative current flows in the load. An idealized output waveform for a sinusoidal load current and a 45 degrees load phase angle is shown in Figure 3.11. It is important to keep the non conducting thyristor bank off at all times, otherwise the mains could be shorted via the two thyristor banks, resulting in waveform distortion and possible device failure from the shorting current. A major control problem of the **Cycloconverter** is how to swap between banks in the shortest possible time to avoid distortion whilst ensuring the two banks do not conduct at the same time. A common addition to the power circuit that removes the requirement to keep one bank off is to place a centre tapped inductor called a circulating current inductor between the outputs of the two banks. Both banks can now conduct together without shorting the mains. Also, the circulating current in the inductor keeps both banks operating all the time, resulting in improved output waveforms. This technique is not often used, though, because the circulating current inductor tends to be expensive and bulky and the circulating current reduces the power factor on the input

In a **1-φ Cycloconverter,** the output frequency is less than the supply frequency. These converters require natural commutation which is provided by AC supply. During positive half cycle of supply, Thyristors P1 and N2 are forward biased. First triggering pulse is applied to P1 and hence it starts conducting.

As the supply goes negative,P1 gets off and in negative half cycle of supply, P2 and N1 are forward biased. P2 is triggered and hence it conducts. In the next cycle of supply,N2 in positive half cycle andN1 in negative half cycle are triggered. Thus, we can observe that here the output frequency is 1/2 times the supply frequency.

Operation Principles

The following sections will describe the operation principles of the **Cycloconverter** starting from the simplest one, **single-phase to single-phase (1f-1f) Cycloconverter.**

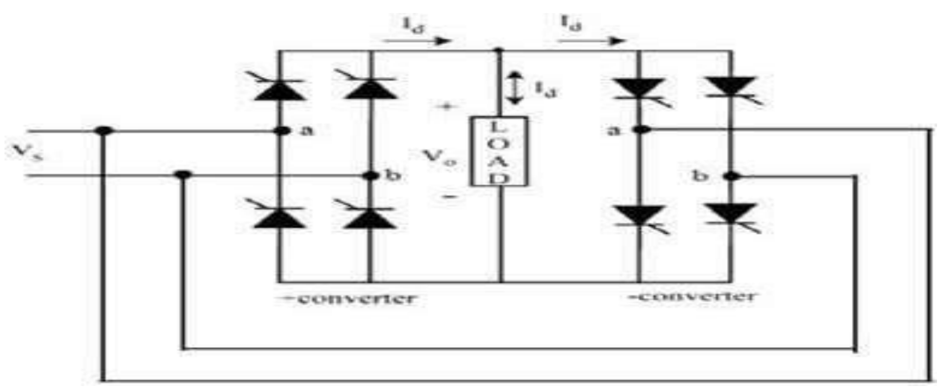
Single-phase to Single-phase (1 Φ-1 Φ) Cycloconverter

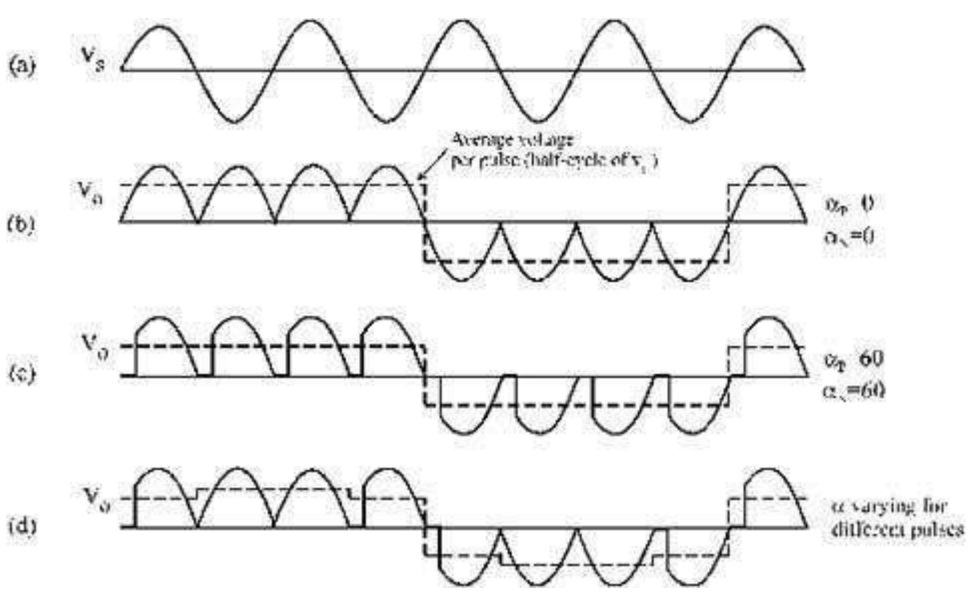
To understand the operation principles of **Cycloconverters**, the single-phase to single- phase **Cycloconverter** (Fig. 3.12) should be studied first. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 3.13 shows the operating waveforms for this converter with a resistive load.

Zero Firing angle, i.e. thyristors act like diodes. Note that the firing angles are named as αP for the positive converter and αN for the negative converter. The input voltage, vs is an ac voltage at a frequency, fi as shown in Fig. 3.13. For easy understanding assume that all the thyristors are fired at α=0°

Consider the operation of the **Cycloconverter** to get one-fourth of the input frequency at the output. For the first two cycles of vs, the positive converter operates supplying current to the load. It rectifies the input voltage; therefore, the load sees 4 positive half cycles as seen in Fig.

3.13. In the next two cycles, the negative converter operates supplying current to the load in the reverse direction. The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by t he resistance. Note thatwhen one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers.





Single phase midpoint Cyclo converters

Basically, these are divided into two main types, and are given below

Step-down cyclo-converter

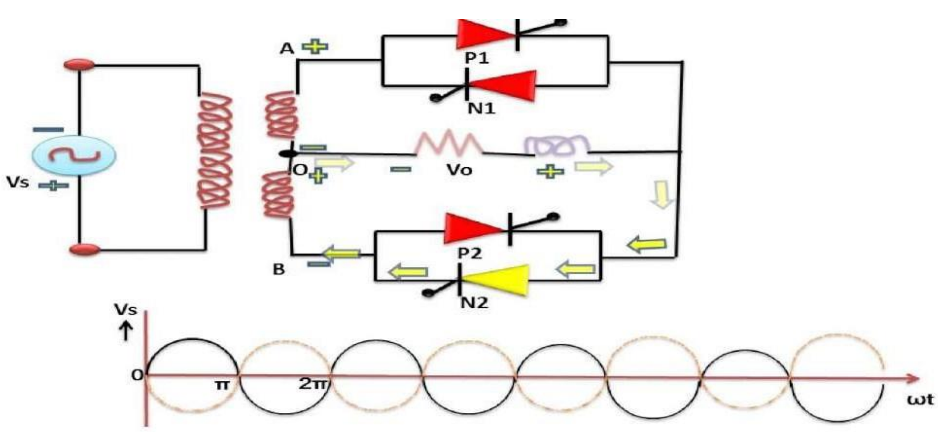
It acts like a step-down transformer that provides the output frequency less than that of input, fo < fi.

Step-up cyclo-converter

It provides the output frequency more than that of input, fo > fi.

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.

But in case of step-up cyclo-converter, forced commutation circuits are needed to turn OFF SCRs at desired frequency. Such circuits are relatively very complex. Therefore, majority of cyclo-converters are of step-down type that lowers the frequency than input frequency.



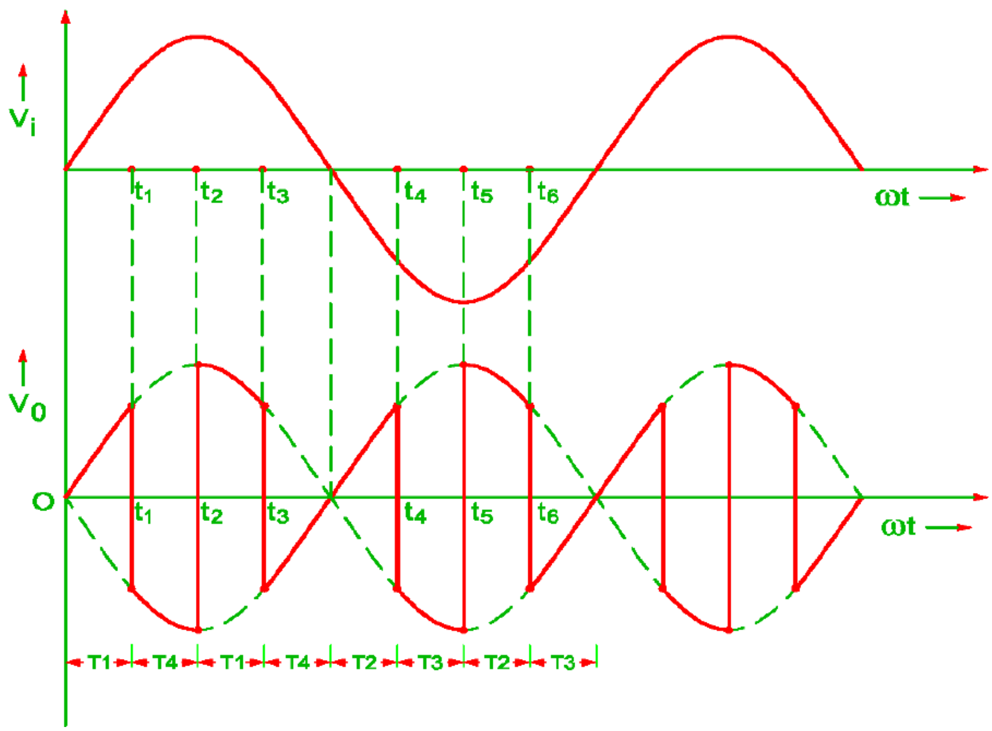


Figure Input and output waveforms of midpoint cycloconverter

It consists of single phase transformer with mid tap on the secondary winding and four thyristors. Two of these thyristors P1, P2 are for positive group and the other two N1, N2 are for the negative group. Load is connected between secondary winding midpoint 0 and the load terminal. Positive directions for output voltage and output current are marked in figure 3.14

In figure 3.14 during the positive half cycle of supply voltage terminal a is positive with respect to terminal b. therefore in this positive half cycle, both p1 and N2 are forward biased from wt= 0 to Π. As such SCR P1 is turned on at wt = 0 so that load voltage is positive with terminal A and 0 negative. Now the load voltage is positive. At instant t1 P1 is force commutated and forward biased thyristor N2 is turned on so that load voltage is negative with terminal 0 and A negative. Now the load voltage is negative. Now N2 is force commutated and P1 is turned on the load voltage is positive this is a continuous process and will get step up cyclo converter output

Bridge configuration of single phase Cyclo converter

The equivalent circuit of a cyclo-converter is shown in figure below. Here each two quadrant phase controlled converter is represented by a voltage source of desired frequency and consider that the output power is generated by the alternating current and voltage at desired frequency.

The diodes connected in series with each voltage source represent the unidirectional conduction of each two quadrant converter. If the output voltage ripples of each converter are neglected, then it becomes ideal and represents the desired output voltage.

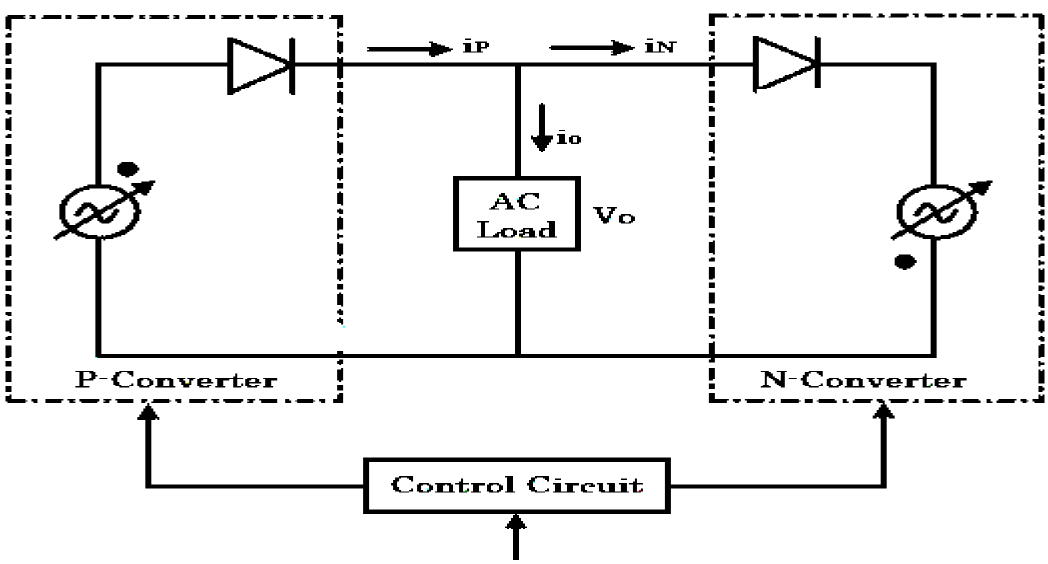


Figure Block diagram of bridge type cycloconverter

If the firing angles of individual converters are modulated continuously, each converter produces same sinusoidal voltages at its output terminals.

So the voltages produced by these two converters have same phase, voltage and frequency. The average power produced by the cyclo-converter can flow either to or from the output terminals as the load current can flow freely to and from the load through the positive and negative converters.

Therefore, it is possible to operate the loads of any phase angle (or power factor), inductive or capacitive through the cyclo-converter circuit.

Due to the unidirectional property of load current for each converter, it is obvious that positive converter carries positive half-cycle of load current with negative converter remaining in idle during this period.

Similarly, negative converter carries negative half cycle of the load current with positive converter remaining in idle during this period, regardless of the phase of current with respect to voltage.

This means that each converter operates both in rectifying and inverting regions during the period of its associated half cycles

Single-phase to single-phase cyclo-converters

These are rarely used in practice; however, these are required to understand fundamental principle of cyclo-converters.

It consists of two full-wave, fully controlled bridge thyristors, where each bridge has 4 thyristors, and each bridge is connected in opposite direction (back to back) such that both positive and negative voltages can be obtained as shown in figure below. Both these bridges are excited by single phase, 50 Hz AC supply.

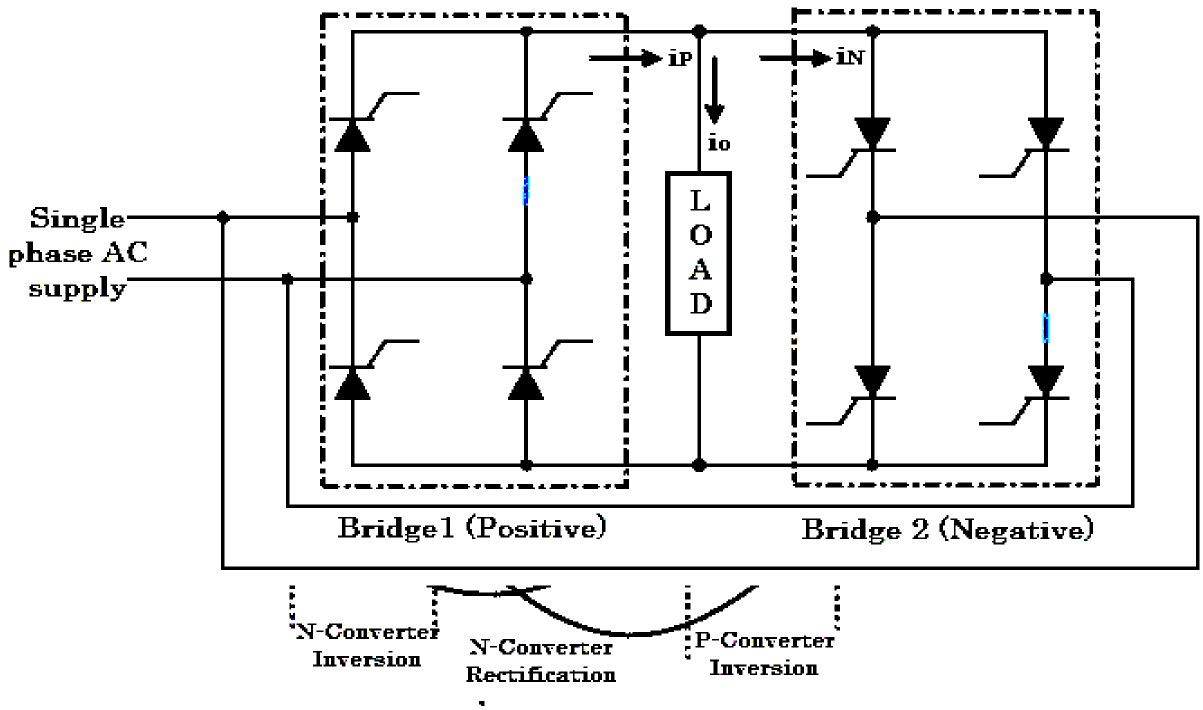
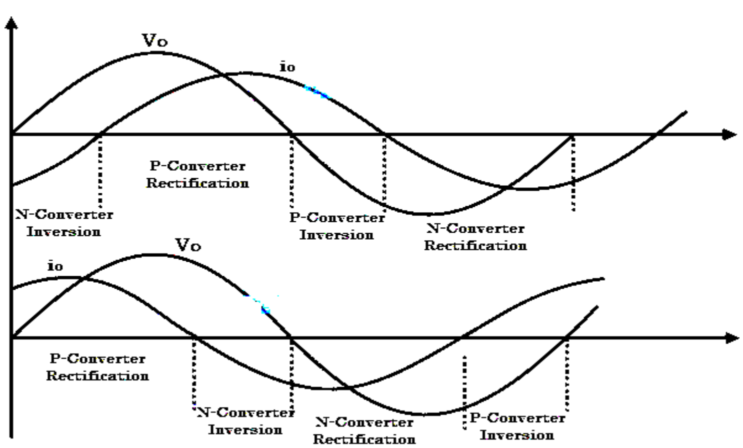


Figure Circuit diagram of bridge type cycloconverter

During positive half cycle of the input voltage, positive converter (bridge-1) is turned ON and it supplies the load current. During negative half cycle of the input, negative bridge is turned ON and it supplies loadcurrent. Both converters should not conduct together that cause short circuit at the input.



To avoid this, triggering to thyristors of bridge-2 is inhibited during positive half cycle of load current, while triggering is applied to the thyristors of bridge-1 at their gates. During negative half cycle of load.

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.

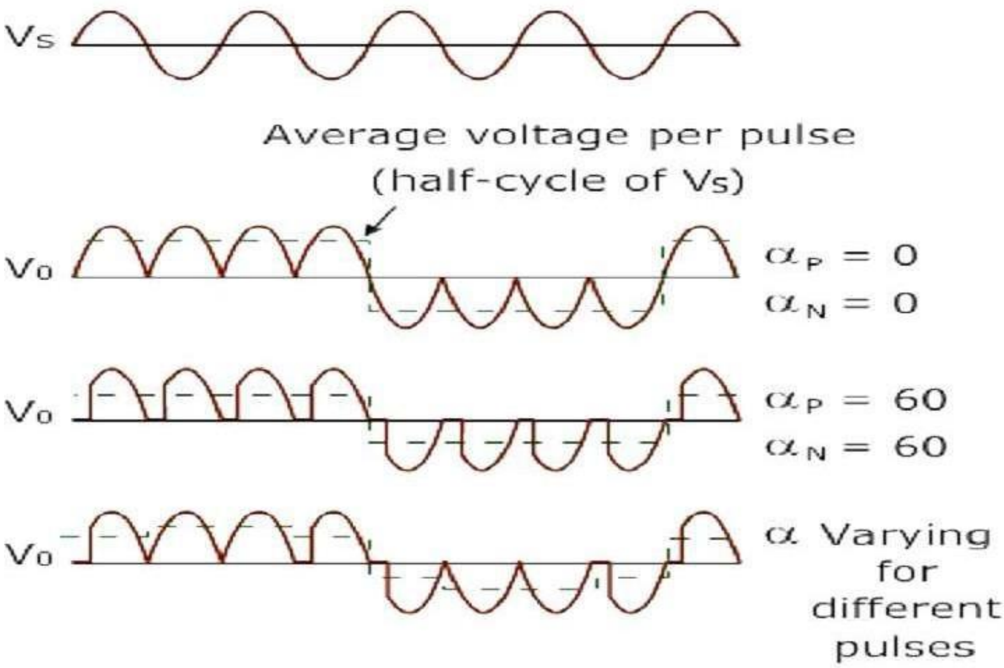


Figure Input and output waveforms of bridge type cycloconverter

The above figure shows output waveforms of a cyclo-converter that produces one-fourth of the input frequency. Here, for the first two cycles, the positive converter operates and supplies current to the load.

It rectifies the input voltage and produce unidirectional output voltage as we can observe four positive half cycles in the figure. And during next two cycles, the negative converter operates and supplies load current.

Here current waveforms are not shown because it is a resistive load in where current (with less magnitude) exactly follows the voltage.

Here one converter is disabled if another one operates, so there is no circulating current between two converters. Since the discontinuous mode of control scheme is complicated, most cyclo-converters are operates on circulating current mode where continuous current is allowed to flow between the converters with a reactor.

This circulating current type cyclo-converter can be operated on with both purely resistive (R) and inductive (R-L) loads.

<u>Circulating Current mode of operations</u>:

In this case, both of the converters operate at all times producing the same fundamental output voltage. The firing angles of the converters satisfy the firing angle condition , thus when one converter is in rectification mode the other one is in inversion mode and vice versa. If both of the converters are producing pure sine waves, then there would not be any circulating current because the instantaneous potential difference between the outputs of the converters would be zero. In reality, an IGR is connected between the outputs of two phase controlled converters (in either rectification or inversion mode). This is the difference of the instantaneous output voltages produced by the two converters. Note that it is zero when both of the converters produce the same instantaneous voltage. The center tap voltage of IGR is the voltage applied to the load and it is the mean of the voltages applied to the ends of IGR, thus the load voltage ripple is reduced.

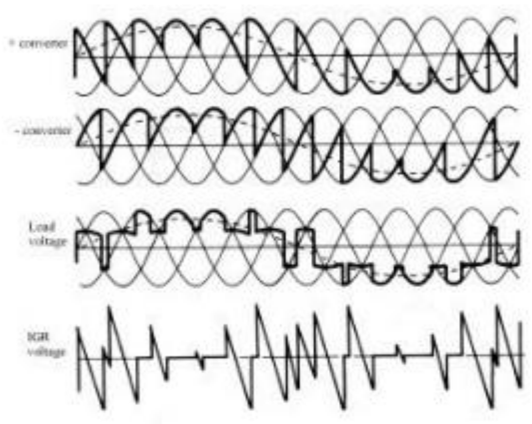


Fig. 11 Circulating mode operation waveforms
a) + converter output voltage
b) – converter output voltage
c) load voltage
d) IGR voltage

The circulating current cycloconverter applies a smoother load voltage with less harmonics compared to the blocking mode case. Moreover, the control is simple because there is no current reversal problem. However, the bulky IGR is a big disadvantage for this converter. In addition to this, the number of devices conducting at any time is twice that of the blocking mode converter.

Due to these disadvantages, this cycloconverter is not attractive. The blocked mode cycloconverter converter and the circulating current cycloconverter can be combined to give a hybrid system, which has the advantages of both. The resulting cycloconverter looks like a circulating mode cycloconverter circuit, but depending on the polarity of the output current only one converter is enabled and the other one is disabled as with the blocking mode cycloconverters. When the load current decreases below a threshold, both of the converters are enabled. Thus, the current has a smooth reversal. When the current increases above a threshold in the other direction, the outgoing converter is disabled. This hybrid cycloconverter operates in the blocking mode most of the time so a smaller IGR can be used.

The efficiency is slightly higher than that of the circulating current cycloconverter but much less than the blocking mode cycloconverter. Moreover, the distortion caused by the blocking mode operation disappears due to the circulating current operation around zero current. Moreover, the control of the converter is still less complex than that of the blocking mode cycloconverter.

Advantages :-

- It is an ac to ac converter therefore no "dc link" is required to be used as in case of the inverters.
- The power flow is bidirectional, from source to load or load to source.

Disadvantages of Cycloconverter :

- It is possible to change the output frequency only in steps. ...
- Output voltage waveform distortion may creep in at low operating frequencies.
- Control Circuit is very complex and difficult to design.
- Input power factor is poor at large values of (α).

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

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

Modes of operation:

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

Non Circulating Current Mode

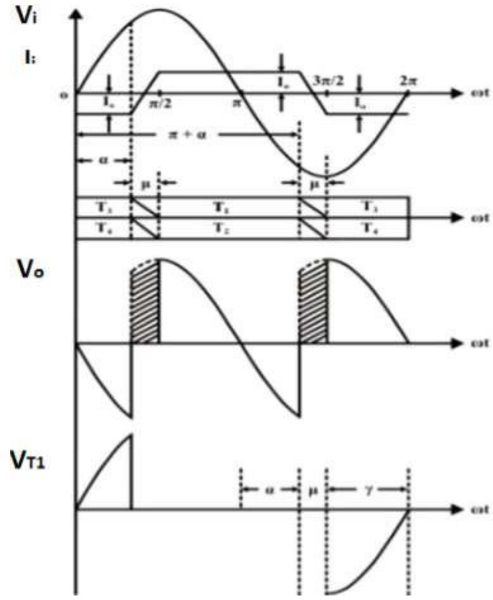
- One converter will perform at a time. So there is no circulating current between the converters.
- During the converter 1 operation, firing angle (α1) will be 0<α1< 90o; Vdc and Idc are positive.
- During the converter 2 operation, firing angle (α2) will be 0<α2< 90o; Vdc and Idc are negative.

Circulating Current Mode

- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α1) + firing angle of converter 2

  (α2) = 180o.
- Converter 1 performs as a controlled rectifier when firing angle be 0<α1< 90o and Converter 2 performs as an inverter when the firing angle be 90o<α2< 180o. In this condition, Vdc and Idc are positive.

   i. Converter 1 performs as an inverter when firing angle be 90o<α1< 180o and Converter 2 performs as a controlled rectifier when the firing angle be 0<α2< 90o In this condition, Vdc and Idc are negative.
   ii. The four quadrant operation is shown below



b.

Figure: single phase full converter output waveforms with source inductance

2. During overlap interval the load current freewheels through the thyristors and the output voltage is clamped to zero. On the other hand, the input current starts changing polarity as the current through T1 and T2 increases and T3 T4 current decreases. At the end of the overlap interval the current through T3 and T4 becomes zero and they commutate, T1 and T2 starts conducting the full load current
3. The same process repeats during commutation from T1 T2 to T3T4 at ωt = π + α . From Fig. 2.14 it is clear that, commutation overlap not only reduces average output dc voltage but also reduces the extinction angle γ which may cause commutation failure in the inverting mode of operation if α is very close to 180º.
4. In the following analysis an expression of the overlap angle "μ" will be determined. From the
    a. equivalent circuit of the converter during overlap period.

$$L\frac{di_i}{dt} = v_i \;\; for \;\; \alpha \leq \omega t + \mu$$

$$i_i(\omega t = \alpha) = -I_0$$

$$i_i = I - \frac{\sqrt{2}V_i}{\omega L} cos\omega t$$

$$\therefore i_i|_{\omega t - \alpha} = I - \frac{\sqrt{2}V_i}{\omega L} cos\alpha = -I_0$$

$$I = \frac{\sqrt{2}V_i}{\omega L}\cos\alpha - I_0$$

$$\therefore \quad i_i = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu \quad i_i = I_0$

$$I_0 = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos(\alpha + \mu)) - I_0$$

$$\therefore \quad \cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_0} I_0$$

$$V_0 = \frac{I}{\pi}\int_{\alpha}^{\alpha+\pi} V_i d\,\omega t$$

or $$V_0 = \frac{I}{\pi}\int_{\alpha+\mu}^{\alpha+\pi} \sqrt{2}v_i \sin\omega t d\,\omega t$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos(\alpha + \mu) - \cos(\pi + \alpha)$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos\alpha + \cos(\alpha + \mu)]$$

$$\therefore V_0 = 2\sqrt{2}\frac{v_i}{\pi}[cos\alpha - cos(\alpha + \mu)]$$

$$\therefore V_0 = \frac{2\sqrt{2}}{\pi}v_i cos\alpha - \frac{2}{\pi}\omega L I_0$$