POWER ELECTRONICS

UNIT I POWER SEMICONDUCTOR DEVICES :

Construction, Principle of operation Power diodes , power transistors SCR, TRIAC, GTO, MOSFET, IGBT – driver circuit, turn – on method – commutation series and parallel connections

UNIT II PHASE CONTROLLED CONVERTERS :

Converter inverters operation – Single phase and three phase controlled rectifiers(half and full converters) with R,RL and RLE load effect of source inductance and firing circuits – Dual converters – single phase & three phase dual converters

UNIT III DC TO DC CHOPPER :

Voltage, current load commutated chopper – step-up chopper and firing circuits – one, two and four quadrant chopper application to DC driving control

UNIT IV INVERTERS :

Series inverter – parallel inverter – current source inverter – voltage source inverter - Modified McMurray, auto sequential inverter– PWM inverter – UPS.

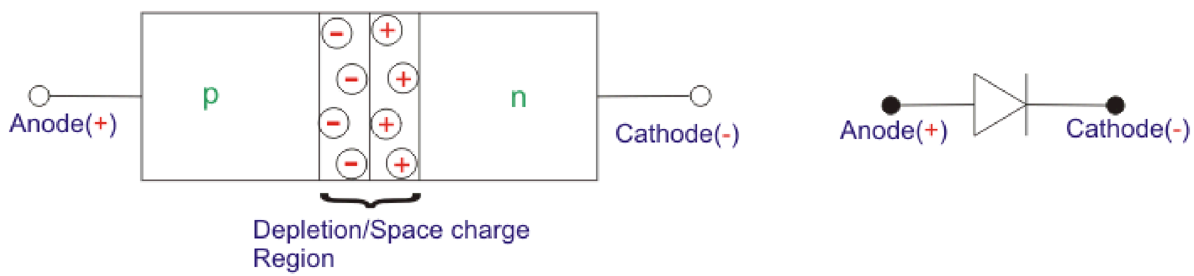
UNIT V AC CHOPPER,CYCLOCONVERTER&VOLTAGE CONTROLER :

Single phase AC chopper, multistage sequence control – step up and step down cyclo-converter – three phase to single phase and single phase to three phase cyclo-converter – triggering circuit based on micro controller – single phase AC voltage controller with R, RL, RLE.

UNIT I POWER SEMICONDUCTOR DEVICES

CONSTRUCTION OF POWER DIODES:

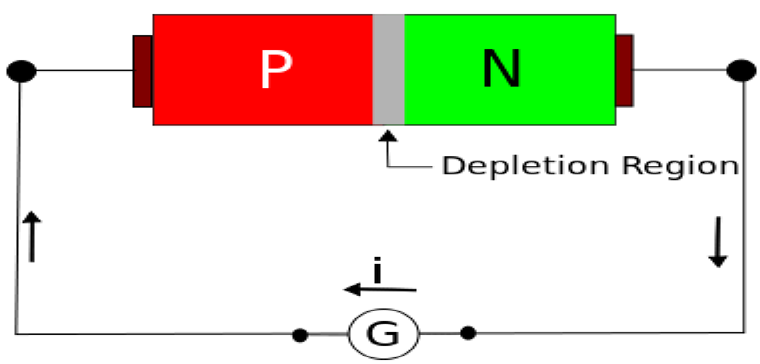
Diodes are the simplest semiconductor device having only two layers, two terminals and one junction. The ordinary signal diodes have a junction formed by p type semiconductor and n type semiconductor, the lead joining p type is called anode and the other side lead joining the n type is called cathode. The figure below depicts the structure of an ordinary diode and its symbol.



Power diodes are also similar to signal diodes but have a little difference in its construction.

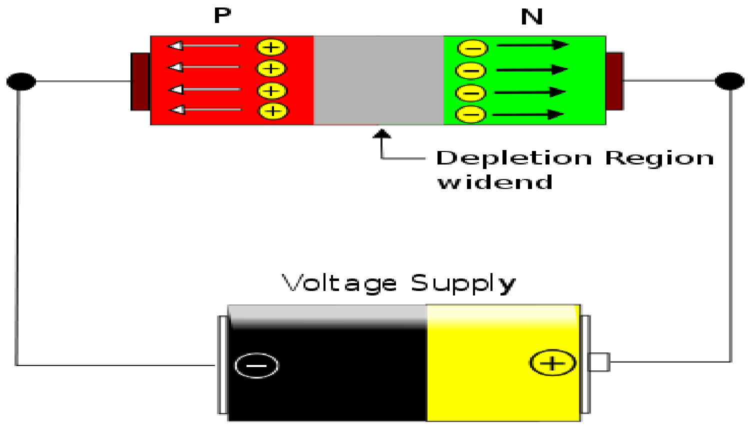
DIODE BIASED VOLTAGE:

ZERO BIAS:



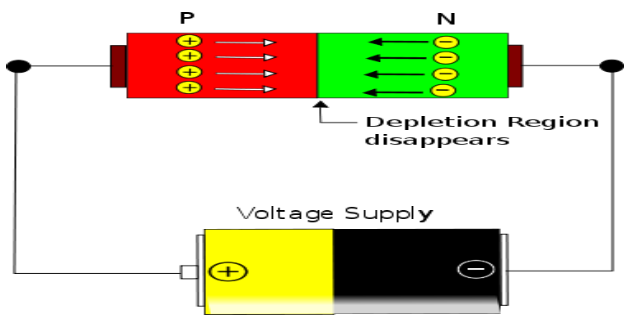
When a diode is zero biased, that is has no bias, it just stays. Almost no current passes through the diode. However if you connect the anode and cathode of the diode you might be able to observe small voltage or current that is insignificant. This is because the electromagnetic spectrum that's present in our environment by default (microwave background, heat, light, radio waves) knocks off electrons in the semiconductor lattice that constitutes current. For practical reasons this current can be considered zero.

Reverse Bias:



In reverse bias the P-type region is connected to negative voltage and N-type is connected to positive terminal as shown above. In this condition the holes in P-type gets filled by electrons from the battery / cell (in other words the holes get sucked out of the diode). The electrons in N-type material is sucked out of the diode by the positive terminal of the battery. So the diode gets depleted of charge. So initially the depletion layer widens (see image above) and it occupies the entire diode. The resistance offered by the diode is very huge. The current that flows in reverse bias is only due to minority charge which is in nano amperes in silicon and micro amperes in high power silicon and germanium diodes.

Forward Bias:

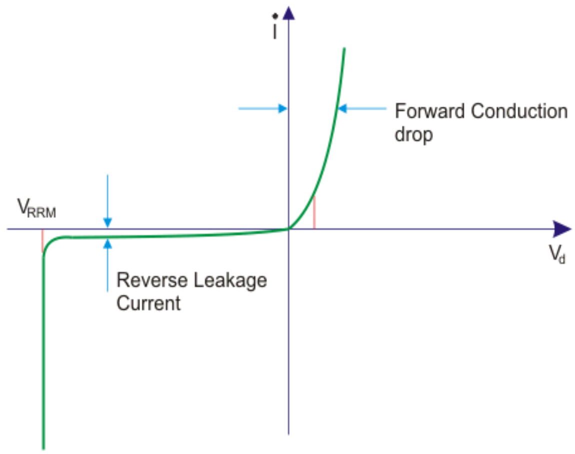


In forward bias the P-Region of the diode is connected with the positive terminal of the battery and N-region is connected with the negative region. During the forward bias the following process occurs. The positive of the battery pumps more holes into the P-region of the diode. The negative terminal pumps electrons into the N-region. The excess of charge in P and N region will apply pressure on the depletion region and will make it shrink. As the voltage increases the depletion layer will become thinner and thinner and hence diode will offer lesser and lesser resistance. Since the resistance decreases the current will increase (though not proportional) to the voltage.

At one particular voltage level $\mathbf{V_f}$ called the threshold / firing / cut-off voltage the depletion layer disappears (overwhelmed by the charge) and hence from this point on the diode starts to conduct very easily. From this point on the diode current increases exponentially to the voltage applied.

V-I Characteristics of Power Diodes

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



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

SILICON CONTROLLED RECTIFIER:

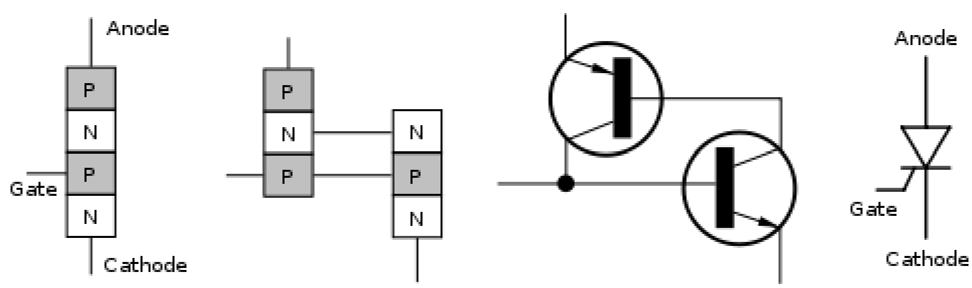
A **silicon controlled rectifier** or **semiconductor-controlled rectifier** is a four-layer solid-state current-controlling device. SCRs are unidirectional devices (i.e. can conduct current only in one direction) as opposed to TRIACs, which are bidirectional (i.e. current can flow through them in either direction). SCRs can be triggered normally only by currents going into the gate as opposed to TRIACs, which can be triggered normally by either a positive or a negative current applied to its gate electrode.

CONSTRUCTION:

The silicon control rectifier (SCR) consists of four layers of semiconductors, which form **NPNP** or **PNPN** structures have three P-N junctions labeled **J1**, **J2** and **J3**, and three terminals. The anode terminal of an SCR is connected to the p-type material of a PNPN structure, and the cathode terminal is connected to the n-type layer, while the gate of the SCR is connected to the p-type material nearest to the cathode.[9]

An SCR consists of four layers of alternating p- and n-type semiconductor materials. Silicon is used as the intrinsic semiconductor, to which the proper dopants are added. The junctions are either diffused or alloyed (alloy is a mixed semiconductor or a mixed metal). The planar construction is used for low-power SCRs (and all the junctions are diffused). The mesa-type construction is used for high-power SCRs. In this case, junction J2 is obtained by the diffusion method, and then the outer two layers are alloyed to it, since the PNPN pellet is required to handle large currents. It is properly braced with tungsten or molybdenum plates to provide greater mechanical strength. One of these plates is hard-soldered to a copper stud, which is threaded for attachment of heat sink. The doping of PNPN depends on the application of SCR, since its characteristics are similar to those of the thyristor. Today, the term "thyristor" applies to the larger family of multilayer devices that exhibit bistable state-change behaviour, that is, switching either on or off.

The operation of an SCR and other thyristors can be understood in terms of a pair of tightly coupled bipolar junction transistors, arranged to cause the self-latching action:



MODES OF OPERATION:

There are three modes of operation for an SCR depending upon the biasing given to it:

1. **Forward blocking mode (off state)**

2. **Forward conduction mode (on state)**
3. **Reverse blocking mode (off state)**

Forward blocking mode:

In this mode of operation, the anode is given a positive voltage while the cathode is given a negative voltage, keeping the gate at zero potential i.e. disconnected. In this case junction **J1** and **J3** are forward-biased, while **J2** is reverse-biased, due to which only a small leakage current exists from the anode to the cathode until the applied voltage reaches its breakover value, at which **J2** undergoes avalanche breakdown, and at this breakover voltage it starts conducting, but below breakover voltage it offers very high resistance to the current and is said to be in the off state.

Forward conduction mode:

SCR can be brought from blocking mode to conduction mode in two ways: either by increasing the voltage across anode to cathode beyond breakover voltage or by applying positive pulse at gate. Once SCR starts conducting, no more gate voltage is required to maintain it in the on state. There are two ways to turn it off: 1. Reduce the current through it below a minimum value called the holding current and 2. With the gate turned off, short out the anode and cathode momentarily with a push-button switch or transistor across the junction.

Reverse blocking mode:

SCRs are available with reverse blocking capability, which adds to the forward voltage drop because of the need to have a long, low-doped P1 region. (If one cannot determine which region is P1, a labeled diagram of layers and junctions can help). Usually, the reverse blocking voltage rating and forward blocking voltage rating are the same. The typical application for reverse blocking SCR is in current-source inverters.

SCRs incapable of blocking reverse voltage are known as **asymmetrical SCR**, abbreviated **ASCR**. They typically have a reverse breakdown rating in the tens of volts. ASCRs are used where either a reverse conducting diode is applied in parallel (for example, in voltage-source inverters) or where reverse voltage would never occur (for example, in switching power supplies or DC traction choppers).

Asymmetrical SCRs can be fabricated with a reverse conducting diode in the same package. These are known as RCTs, for reverse conducting thyristors.

THYRISTOR TURN ON METHODS:

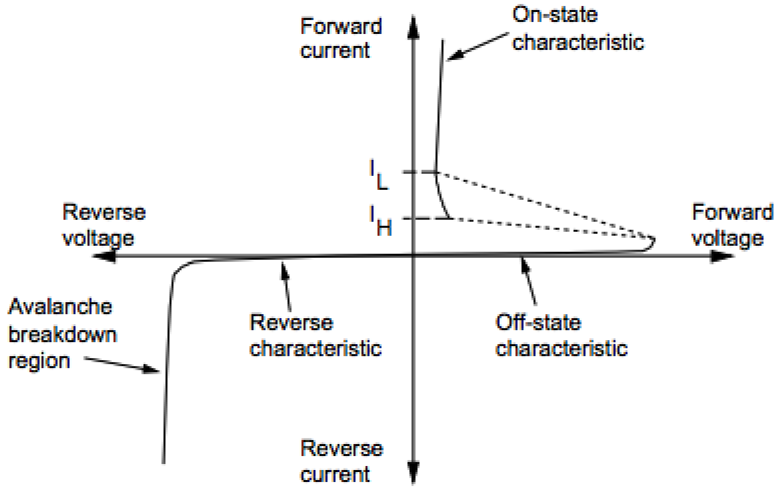
1. forward-voltage triggering
2. gate triggering
3. *dv*/*dt* triggering
4. temperature triggering
5. light triggering

Forward-voltage triggering occurs when the anode–cathode forward voltage is increased with the gate circuit opened. This is known as avalanche breakdown, during which junction J2 will break down. At sufficient voltages, the thyristor changes to its on state with low voltage drop and large forward current. In this case, J1 and J3 are already forward-biased

V-I Characteristics of SCR

In his article we will draw and explain the V-I characteristics of SCR in detail.
It is the curve between anode-cathode voltage (V) and anode current (I) of an SCR at constant gate current.

V-I characteristics of a typical SCR .



Important Points About The V-I Characteristics of SCR

Forward Characteristics

When anode is positive w.r.t. cathode, the curve between V and I is called the forward characteristics.

In fig.1, OABC is the forward characteristics of SCR at $I_G=0$.
If the supply voltage is increased from zero, a point reached (point A) when the SCR starts conducting.
Under this condition,the voltage across SCR suddenly drops as shown by dotted curve AB and most of supply voltage appears across the load resistance R_L.
If proper gate current is made to flow, SCR can close at much smaller supply voltage.
Reverse Characteristics

When anode is negative w.r.t. cathode, the curve between V and I is known as reverse characteristics.

The reverse voltage does come across SCR when it is operated with a.c. supply.
If the reverse voltage is gradually increased, at first the anode current remains small (i.e. leakage current) and at some reverse voltage, avalanche breakdown occurs and the SCR starts conducting heavily in the reverse direction as shown by the curve DE.
This maximum reverse voltage at which SCR starts conducting heavily is known as reverse breakdown voltage.

SCR in Normal Operation

In order to operate the SCR in normal operation, the following points are kept in view:

1. The supply voltage is generally much less than breakover voltage.
2. The SCR is turned on by passing appropriate amount of gate current (a few mA) and not by breakover voltage.
3. When SCR is operated from a.c. supply, the peak reverse voltage which comes during negative half-cycle should not exceed the reverse breakdown voltage.
4. When SCR is to be turned OFF from the ON state, anode current should be reduced to holding current.
5. If gate current is increased above the required value, the SCRwill close at much reduced supply voltage.

Important Terms In The V-I Characteristics of SCR

The following terms are much used in the study of SCR :

1. Breakover voltage
2. Peak reverse voltage
3. Holding current
4. Forward current rating
5. Circuit fusing rating

1. Breakover Voltage

It is the minimum forward voltage, gate being open, at which SCR starts conducting heavily i.e. turned on.

Thus, if the breakover voltage of an SCR is 200 V, it means that it can block a forward voltage (i.e. SCR remains open) as long as the supply voltage is less than 200 V. If the supply voltage is more than this value, then SCR will be turned on.

In practice, the SCR is operated with supply voltage less than breakover voltage and it is then turned on by means of a small voltage applied to the gate.

Commercially available SCRs have breakover voltages from about 50 V to 500 V.

2. Peak Reverse Voltage (PRV)

It is the maximum reverse voltage (cathode positive w.r.t. anode) that can be applied to an SCR without conducting in the reverse direction.

PRV is an important consideration while connecting an SCR in an a.c. circuit. During the negative half of a.c. supply, reverse voltage is applied across SCR. If PRV is exceeded, there may be avalanche breakdown and the SCR will be damaged if the external ciruit does not limit the current.

Commercially available SCRS have PRV ratings upto 2.5 kV.

3. Holding Current

It is the maximum anode current, gate being open, at which SCR is turned OFF from ON condition.

When SCR is in the conducting state, it can not be turned OFF even if gate voltage is removed.

The only way to turn off or open the SCR is to reduce the supply voltage to almost zero at which point the internal transistor comes out of saturation and opens the SCR.

The anode current under this condition is very small (a few mA) and is called holding current.

Thus, if an SCR has a holding current of 5mA, it means that if anode current is made less than 5 mA, then SCR will be turned off.

4. Forward Current Rating

It is the maximum anode current that an SCR is capable of passing without destruction.

Every SCR has a safe value of forward current which it can conduct. If the value of current exceeds this value, the SCR may be destroyed due to intensive heating at the junction.

For example, if an SCR has a forward current rating of 40 A, it means that the SCR can safely carry only 40 A. Any attempt to exceed this value will result in the destruction of the SCR.

Commercially available SCRs have forward current ratings from about 30A to 100A.

5. Circuit Fusing (I^2t) Rating

It is the product of square forward surge current and the time of duration of the surge i.e.,

$$\text{Circuit fusing rating} = I^2t$$

The circuit fusing rating indicates the maximum forward surge current capability of SCR.

For example, consider an SCR having circuit fusing rating of 90 A^2s. If this rating is exceeded in the SCR circuit , the device will be destroyed by excessive powerdissipation.

APPLICATIONS:

SCRs are mainly used in devices where the control of high power, possibly coupled with high voltage, is demanded. Their operation makes them suitable for use in medium- to high-voltage AC power control applications, such as lamp dimming, power regulators and motor control.

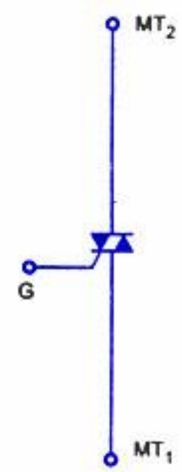
SCRs and similar devices are used for rectification of high-power AC in high-voltage direct-current power transmission. They are also used in the control of welding machines, mainly MTAW (metal tungsten arc welding) and GTAW (gas tungsten arc welding) processes similar.

TRIAC

Construction And Operation

The triac is another three-terminal ac switch that is triggered into conduction when a low-energy signal is applied to its gate terminal. Unlike the SCR, the triac conducts in either direction when turned on. The triac also differs from the SCR in that either a positive or negative gate signal triggers it into conduction. Thus the triac is a three terminal, four layer bidirectional semiconductor device that controls ac power whereas an **SCR controls** dc power or forward biased half cycles of ac in a load. Because of its bidirectional conduction property, the triac is widely used in the field of power electronics for control purposes. Triacs of 16 kW rating are readily available in the market.

"Triac" is an abbreviation for three terminal ac switch. 'Tri'-indicates that the device has three terminals and 'ac' indicates that the device controls alternating current or can conduct in either direction.

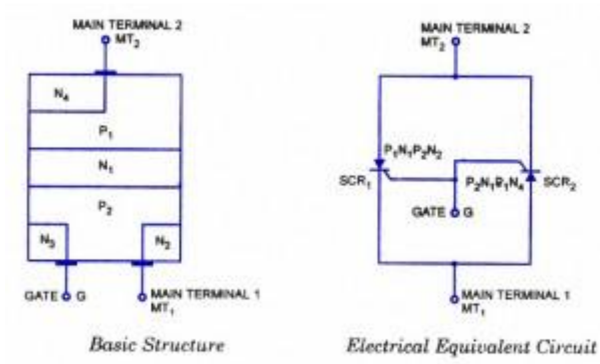


Schematic Symbol

Triac Circuit Symbol

Construction of a Triac

As mentioned above, triac is a three terminal, four layer bilateral semiconductor device. It incorporates two SCRs connected in inverse parallel with a common gate terminal in a single chip device. The arrangement of the triac is shown in figure. As seen, it has six doped regions. The gate terminal G makes ohmic contacts with both the N and P materials. This permits trigger pulse of either polarity to start conduction. Electrical equivalent circuit and schematic symbol are shown in figure.b and figure.c respectively. Since the triac is a bilateral device, the term “anode” and “cathode” has no meaning, and therefore, terminals are designated as main terminal 1. (MT_1), main terminal 2 (MT_2) and gate G. To avoid confusion, it has become common practice to specify all voltages and currents using MT_1 as the reference.



Triac Basic Structure

Operation and Working of a Triac

Though the triac can be turned on without any gate current provided the supply voltage becomes equal to the breakover voltage of the triac but the normal way to turn on the triac is by applying a proper gate current. As in case of SCR, here too, the larger the gate current, the smaller the supply voltage at which the triac is turned on. Triac can conduct current irrespective of the voltage polarity of terminals MT_1 and MT_2 with respect to each other and that of gate and terminal MT_2. Consequently four different possibilities of operation of triac exists. They are:

1. **Terminal MT_2 and gate are positive with respect to terminal MT_1**

When terminal MT_2 is positive with respect to terminal MT_1 current flows through path P_1-N_1-P_2-N_2. The two junctions P_1-N_1 and P_2-N_2 are forward biased whereas junction N_1 P_2 is blocked. The triac is now said to be positively biased.

A positive gate with respect to terminal MT_1 forward biases the junction P_2-N_2 and the break-down occurs as in a normal SCR.

2. Terminal MT_2 is positive but gate is negative with respect to terminal MT_1

Though the flow path of current remains the same as in mode 1 but now junction P_2-N_3 is forward biased and current carriers injected into P_2 turn on the triac.

3.Terminal MT_2 and gate are negative with respect to terminal MT_1

When terminal MT_2 is negative with respect to terminal MT_1, the current flow path is P_2-N_1-P_1-N_4. The two junctions P_2-N_1 and P_1 – N_4 are forward biased whereas junction N_1-P_1 is blocked. The triac is now said to be negatively biased.

A negative gate with respect to terminal MT_1 injects current carriers by forward biasing junction P_2-N_3 and thus initiates the conduction.

4. Terminal MT_2 is negative but gate is positive with respect to terminal MT_1

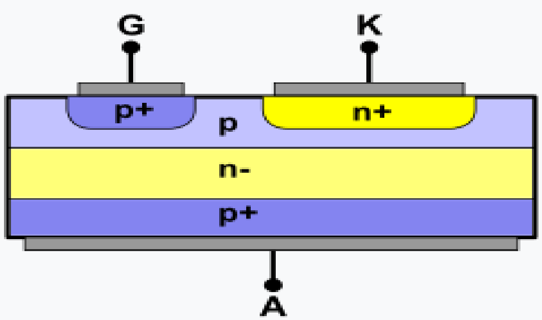
Though the flow path of current remains the same as in mode 3 but now junction P_2-N_2 is forward biased, current carriers are injected and therefore, the triac is turned on.

Generally, trigger mode 4 should be avoided especially in circuits where high di/dt may occur. The sensitivity of triggering modes 2 and 3 is high and in case of marginal triggering capability negative gate pulses should be used. Though the triggering mode 1 is more sensitive compared to modes 2 and 3, it requires a positive gate trigger. However, for bidirectional control and uniform gate trigger modes 2 and 3 are preferred.

Gate turn-off thyristor :

A **gate turn-off thyristor (GTO)** is a special type of thyristor, which is a high-power semiconductor device. It was invented at General Electric.[1] GTOs, as opposed to normal thyristors, are fully controllable switches which can be turned on and off by their third lead, the gate lead.

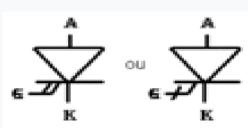
Gate turn-off thyristor GTO



Simplified cross section of a GTO thyristor

Type	active
Pin configuration	anode, gate, cathode

Electronic symbol



REVERSE BIAS:

GTO thyristors are available with or without reverse blocking capability. Reverse blocking capability adds to the forward voltage drop because of the need to have a long, low doped P1 region.

GTO thyristors capable of blocking reverse voltage are known as Symmetrical GTO thyristors, abbreviated S-GTO. Usually, the reverse blocking voltage rating and forward blocking voltage rating are the same. The typical application for symmetrical GTO thyristors is in current source inverters.

GTO thyristors incapable of blocking reverse voltage are known as asymmetrical GTO thyristors, abbreviated A-GTO, and are generally more common than Symmetrical GTO thyristors. They typically have a reverse breakdown rating in the tens of volts. A-GTO thyristors are used where either a reverse conducting diode is applied in parallel (for example, in voltage source inverters) or where reverse voltage would never occur (for example, in switching power supplies or DC traction choppers).

GTO thyristors can be fabricated with a reverse conducting diode in the same package. These are known as RCGTO, for Reverse Conducting GTO thyristor.

Safe Operating Area:

GTO thyristor requires external devices ("snubber circuits") to shape the turn on and turn off currents to prevent device destruction.

During turn on, the device has a maximum dI/dt rating limiting the rise of current. This is to allow the entire bulk of the device to reach turn on before full current is reached. If this rating is exceeded, the area of the device nearest the gate contacts will overheat and melt from over current. The rate of dI/dt is usually controlled by adding a saturable reactor (turn-on snubber), although turn-on dI/dt is a less serious constraint with GTO thyristors than it is with normal thyristors, because of the way the GTO is constructed from many small thyristor cells in parallel. Reset of the saturable reactor usually places a minimum off time requirement on GTO based circuits.

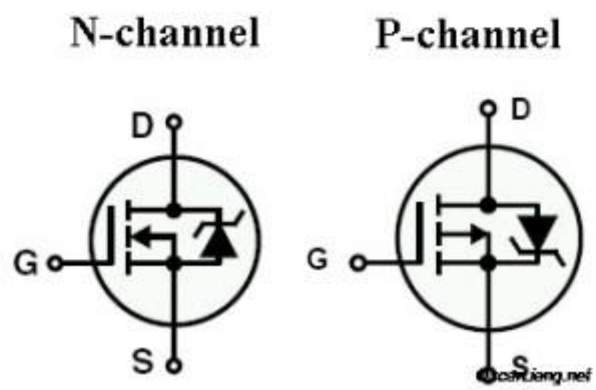
During turn off, the forward voltage of the device must be limited until the current tails off. The limit is usually around 20% of the forward blocking voltage rating. If the voltage rises too fast at turn off, not all of the device will turn off and the GTO will fail, often explosively, due to the high voltage and current focused on a small portion of the device. Substantial snubber circuits are added around the device to limit the rise of voltage at turn off. Reseting the snubber circuit usually places a minimum on time requirement on GTO based circuits.

The minimum on and off time is handled in DC motor chopper circuits by using a variable switching frequency at the lowest and highest duty cycle. This is observable in traction applications where the frequency will ramp up as the motor starts, then the frequency stays constant over most of the speed ranges, then the frequency drops back down to zero at full speed.

MOSFET

MOSFET **stands for** metal-oxide semiconductor field-effect transistor**. It is a special type of field-effect transistor (FET).**

Unlike BJT which is 'current controlled', the MOSFET is a voltage controlled device. The MOSFET has "**gate**", "**Drain**" and "**Source**" terminals instead of a "base", "collector", and "emitter" terminals in a bipolar transistor. By applying voltage at the gate, it generates an electrical field to control the current flow through the channel between drain and source, and there is no current flow from the gate into the MOSFET.



A MOSFET may be thought of as a variable resistor, where the Gate-Source voltage difference can control the Drain-Source Resistance. When there is no applying voltage between the Gate-Source , the Drain-Source resistance is very high, which is almost like a open circuit, so no current may flow through the Drain-Source. When Gate-Source potential difference is applied, the Drain-Source resistance is reduced, and there will be current flowing through Drain-Source, which is now a closed circuit.

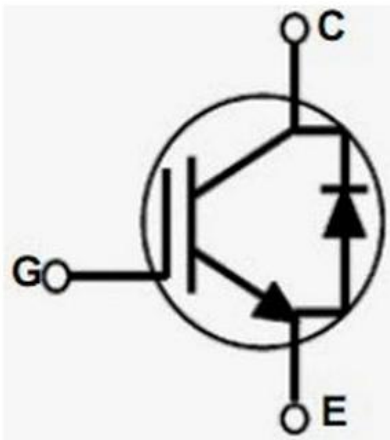
In a nutshell, a FET is controlled by the Gate-Source voltage applied (which regulates the electrical field across a channel), like pinching or opening a straw and stopping or allowing current flowing. Because of this property, FETs are great for large current flow, and the MOSFET is commonly used as a switch.

Differences between BJT and MOSFET.

- Unlike bipolar transistors, MOSFET is voltage controlled. While BJT is current controlled, the base resistor needs to be carefully calculated according to the amount of current being switched. Not so with a MOSFET. Just apply enough voltage to the gate and the switch operates.
- Because they are voltage controlled, MOSFET have a very high input impedance, so just about anything can drive them.
- MOSFET has high input impedence
- working
- MOSFET is a voltage controlled field effect transistor that differs from a JFET. The Gate electrode is electrically insulated from the main semiconductor by a thin layer of insulating material (glass, seriously!). This insulated metal gate is like a plate of a capacitor which has an extremely high input resistance (as high as almost infinite!). Because of the isolation of the Gate there is no current flow into the MOSFET from Gate.
- When voltage is applied at the gate, it changes the width of the Drain-Source channel along which charge carriers flow (electron or hole). The wider the channel, the better the device conducts.

IGBT:

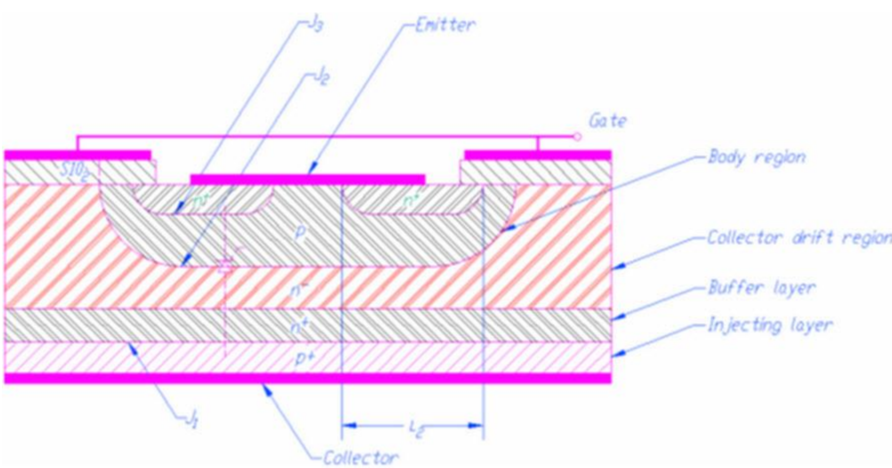
The IGBT (insulated gate bipolar transistor) is a three-terminal electronic component, and these terminals are termed as emitter, collector and gate. Two of its terminals namely collector and emitter are associated with a conductance path and the remaining terminal 'G' is associated with its control.The sum of amplification is achieved by the IGBT is a radio between its input and output signal. For a conventional BJT, the amount of gain is almost equal to the radio to the o/p current to the i/p current that is called a beta.



IGBT Symbol

Basic Structure of IGBT

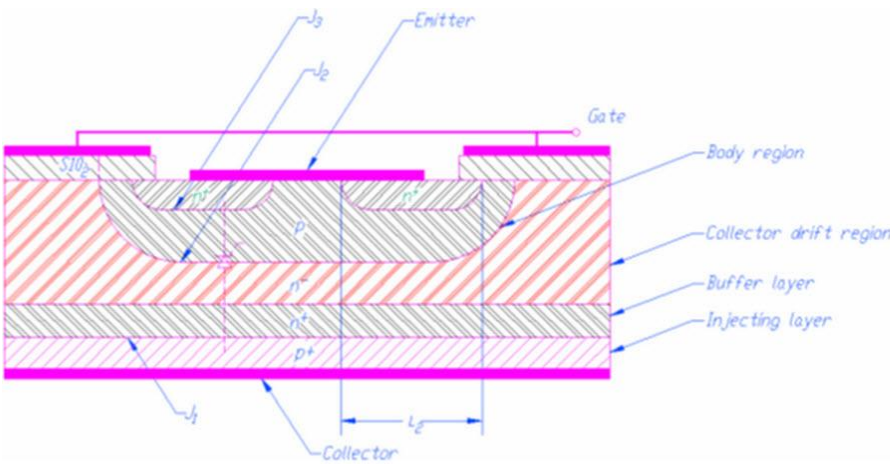
The basic structure of the N-channel IGBT is shown below. This structure is plain that the IGBTs silicon cross section is almost equal to that of a vertical power MOSFET except P+ injecting layer. It shares the same structure of MOS gate & P-wells with N+ source regions. In the following structure, the N+ layer is located at the top is called as the source and the bottom layer is called as a drain or collector.



Basic Structure of N-Channel IGBT

IGBT takes a parasitic thyristor includes the 4-layer NPN structures. There are some IGBs that are fabricated without the N+ buffer layer is called as NPT IGBTS non punch through), whereas some IGBTs are fabricated with the N+ buffer layer called as PT IGBTs (punch through). The performance of the device can considerably increase by existing the buffer layer. The operation of an IGBT is faster to that of power BJT than a power MOSFET.

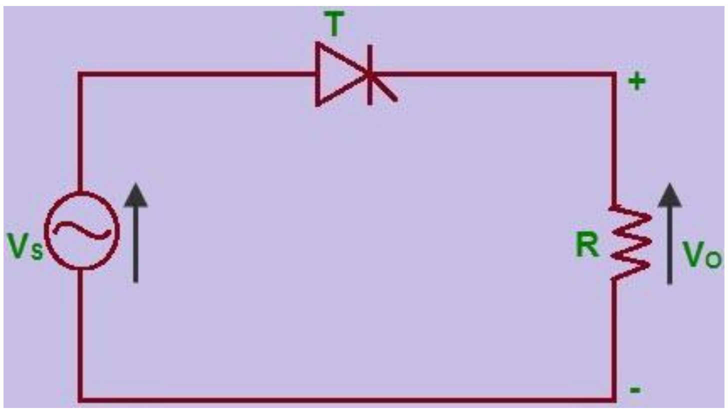
The basic structure of the N-channel IGBT is shown below. This structure is plain that the IGBTs silicon cross section is almost equal to that of a vertical power MOSFET except P+ injecting layer. It shares the same structure of MOS gate & P-wells with N+ source regions. In the following structure, the N+ layer is located at the top is called as the source and the bottom layer is called as a drain or collector.



Circuit Diagram of a IGBT

NATURAL COMMUTATION:

Generally, if we consider AC supply, the current will flow through the zero crossing line while going from positive peak to negative peak. Thus, a reverse voltage will appear across the device simultaneously, which will turn off the thyristor immediately. This process is called as natural commutation as thyristor is turned off naturally without using any external components or circuit or supply for commutation purpose.



Natural Commutation

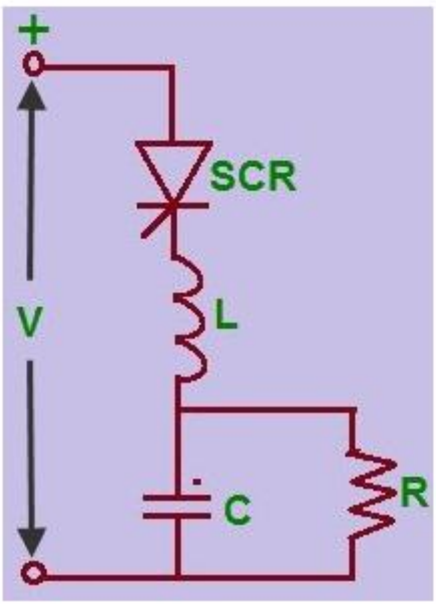
Natural commutation can be observed in AC voltage controllers, phase controlled rectifiers and cyclo converters

Forced Commutation Methods

- Class A: Self commutated by a resonating load
- Class B: Self commutated by an LC circuit
- Class C: C or L-C switched by another load carrying SCR
- Class D: C or L-C switched by an auxiliary SCR
- Class E: An external pulse source for commutation
- Class F: AC line commutation

Class A: Self Commutated by a Resonating Load

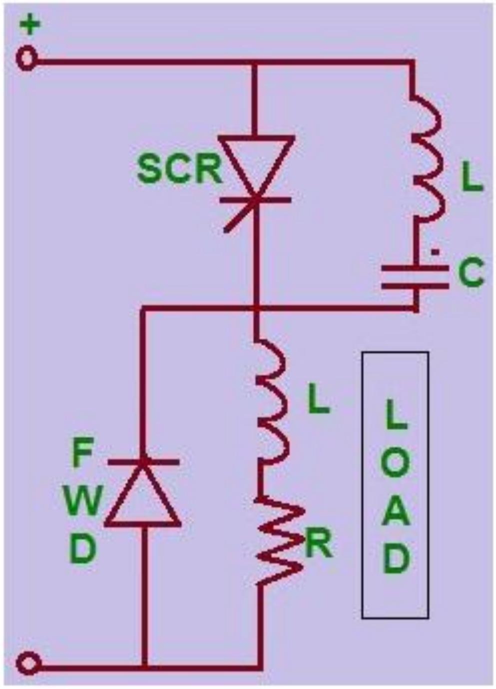
Class A is one of frequently used thyristor commutation techniques. If thyristor is triggered or turned on, then anode current will flow by charging capacitor C with dot as positive. The second order under-damped circuit is formed by the inductor or AC resistor, capacitor and resistor. If the current builds up through SCR and completes the half cycle, then the inductor current will flow through the SCR in the reverse direction which will turn off thyristor.



Class A-Commutation

Class B: Self Commutated by an L-C Circuit

The major difference between the class A and class B thyristor commutation techniques is that the LC is connected in series with thyristor in class A, whereas in parallel with thyristor in class B. Before triggering on the SCR, the capacitor is charged up (dot indicates positive). If the SCR is triggered or given triggering pulse, then the resulting current has two components. The constant load current flowing through the R-L load is ensured by the large reactance connected in series with the load which is clamped with freewheeling diode. If sinusoidal current flows through the resonant L-C circuit, then the capacitor C is charged up with dot as negative at the end of the half cycle.

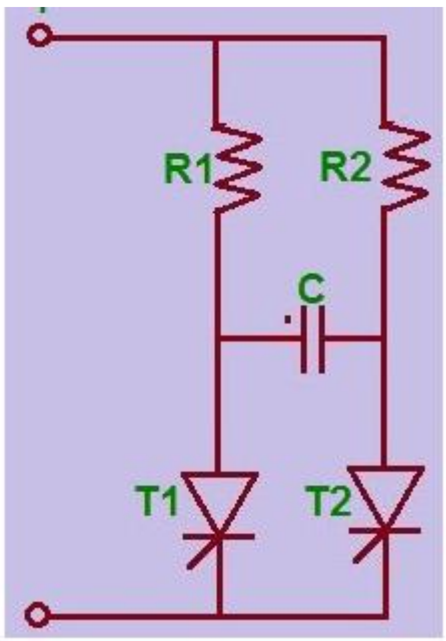


Class B-Commutation

The total current flowing through the SCR becomes zero with the reverse current flowing through the SCR opposing the load current for a small a small fraction of the negative swing. If the resonant circuit current or reverse current becomes just greater than the load current, then the SCR will be turned OFF.

Class C: C or L-C Switched by another Load Carrying SCR

In the above thyristor commutation techniques we observed only one SCR but in these class C commutation techniques of thyristor there will be two SCRs. One SCR is considered as main thyristor and the other as auxiliary thyristor. In this classification both may act as main SCRs carrying load current and they can be designed with four SCRs with load across the capacitor by using a current source for supplying an integral converter.

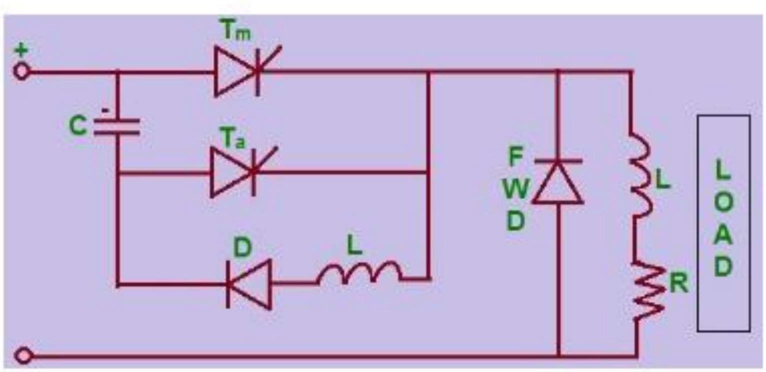


Class C-Commutation

If the thyristor T2 is triggered, then the capacitor will be charged up. If the thyristor T1 is triggered, then the capacitor will discharge and this discharge current of C will oppose the flow of load current in T2 as the capacitor is switched across T2 via T1.

Class D: L-C or C Switched by an Auxiliary SCR

The class C and class D thyristor commutation techniques can be differentiated with the load current in class D: only one of the SCR's will carry the load current while the other acts as an auxiliary thyristor whereas in class C both SCRs will carry load current. The auxiliary thyristor consists of resistor in its anode which is having resistance of approximately ten times the load resistance.

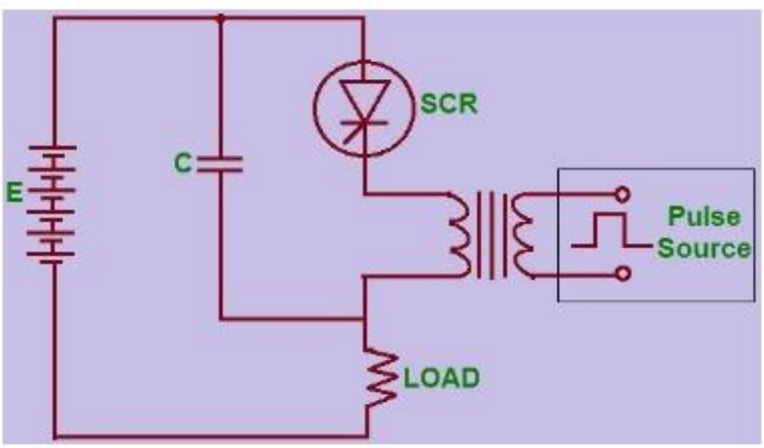


Class D-Commutation

By triggering the Ta (auxiliary thyristor) the capacitor is charged up to supply voltage and then the Ta will turn OFF. The extra voltage if any, due to substantial inductance in the input lines will be discharged through the diode-inductor-load circuit. If the Tm (main thyristor) is triggered, then the current will flow in two paths: commutating current will flow through the C-Tm-L-D path and load current will flow through the load. If the charge on the capacitor is reversed and held at that level using the diode and if Ta is re-triggered, then the voltage across the capacitor will appear across the Tm via Ta. Thus, the main thyristor Tm will be turned off.

Class E: External Pulse Source for Commutation

For the class E thyristor commutation techniques, a transformer which can not saturate (as it is having a sufficient iron and air gap) and capable to carry the load current with small voltage drop compared with the supply voltage. If the thyristor T is triggered, then the current will flow through the load and pulse transformer

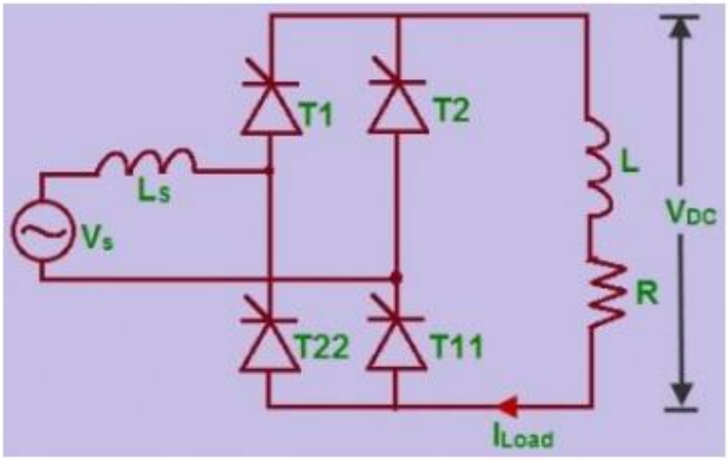


Class E-Commutation

An external pulse generator is used to generate a positive pulse which is supplied to the cathode of the thyristor through pulse transformer. The capacitor C is charged to around 1v and it is considered to have zero impedance for the turn off pulse duration. The voltage across the thyristor is reversed by the pulse from the electrical transformer which supplies the reverse recovery current, and for the required turn off time it holds the negative voltage.

Class F: AC Line Commutated

In class F thyristor commutation techniques, an alternating voltage is used for supply and, during the positive half cycle of this supply, load current will flow. If the load is highly inductive, then the current will remain until the energy stored in the inductive load is dissipated. During the negative half cycle as the load current becomes zero, then thyristor will turn off. If voltage exists for a period of rated turn off time of the device, then the negative polarity of the voltage across the outgoing thyristor will turn it off.



Class F-Commutation

Here, the duration of the half cycle must be greater than the turn off time of thyristor. This commutation process is similar to the concept of three phase converter. Let us consider, primarily T1 and T11 are conducting with the triggering angle of the converter, which is equal to 60 degrees, and is operating in continuous conduction mode with highly inductive load. If the thyristors T2 and T22 are triggered, then instantaneously the current through the incoming devices will not rise to the load current level. If the current through the incoming thyristors reaches the load current level, then the commutation process of outgoing thyristors will be initiated. This reverse biasing voltage of thyristor should be continued until the forward blocking state is reached. Thyristor can be simply called as a controlled rectifier. There are different types of thyristors, which are used for designing power electronics based innovative electrical projects. The process of turning on thyristor by providing triggering pulses to gate terminal is called as triggering. Similarly, the process of turning off thyristor is called as commutation. Hope this article give brief information about different commutation techniques of the thyristor. Further technical assistance will be provided based on your comments and queries in the comments section below.

UNIT-2

PHASE CONTROLLED CONVERTERS

INTRODUCTION :

Unlike diode rectifiers, phase controlled rectifiers has and advantage of controlling the output voltage. The diode rectifiers are called uncontrolled rectifiers. When these diodes are replaced with thyristors, then in becomes phase controlled rectifiers. The output voltagecan be controlled by varying the firing angle of the thyristors. These phase controlled rectifiers has its main application in speed control of DC motors.

APPLICATIONS

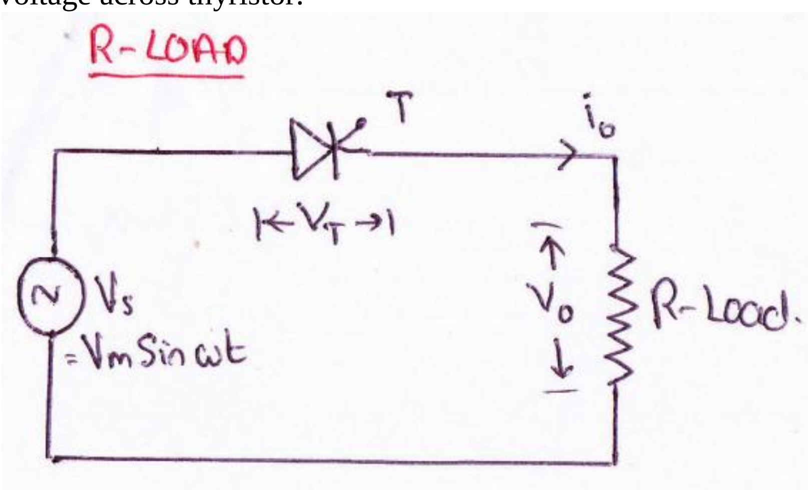
- Steel rolling mills, paper mills, textile mills where speed control of DC motors are necessary.
- Electric traction.
- High voltage DC transmission
- Electromagnet power supplies

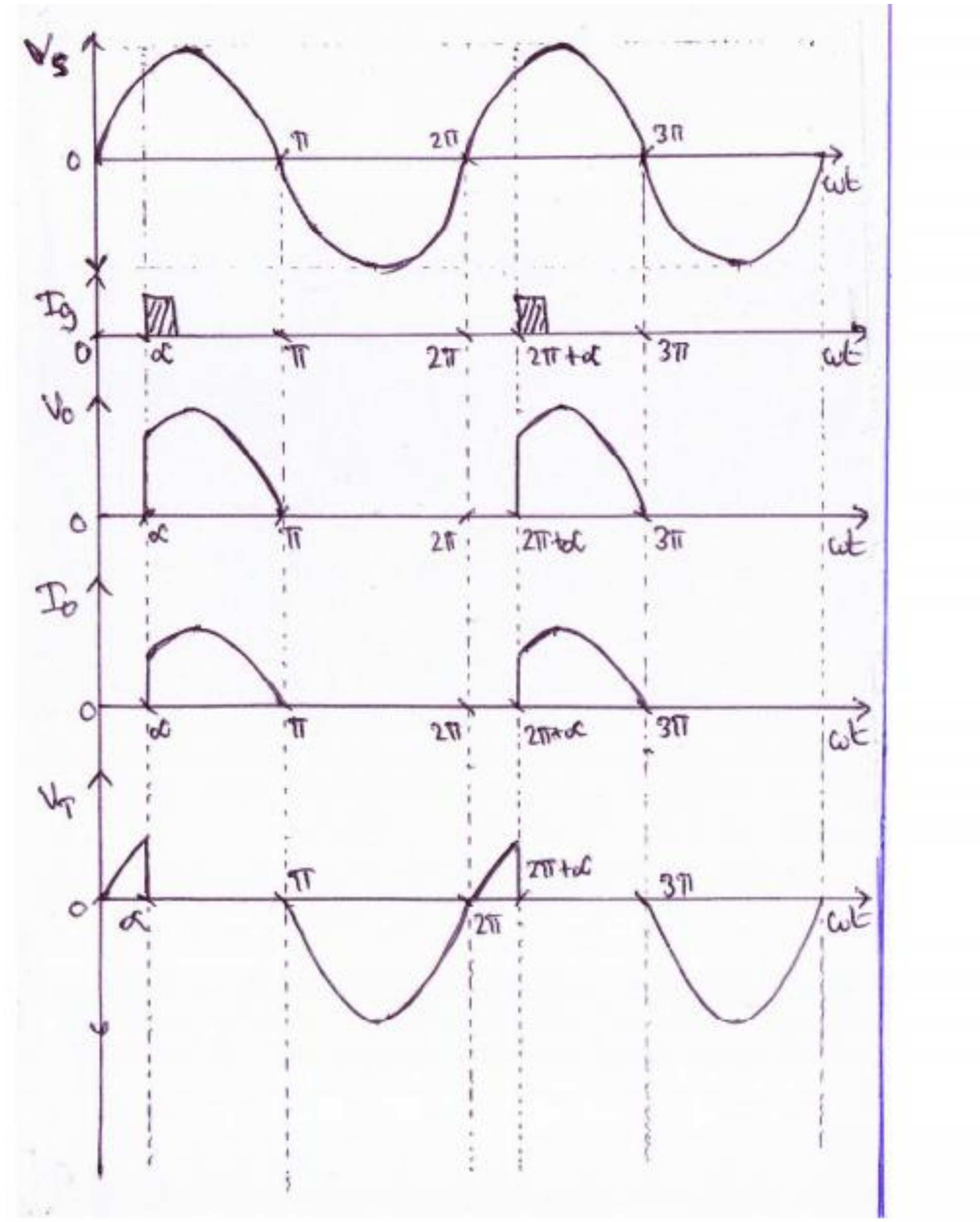
In this unit, the following categories of phase controlled rectifiers will be studied in detail.

1. Single Phase Half Wave Controlled Rectifier with R Load.
2. Single Phase Half Wave Controlled Rectifier with RL Load.
3. Single Phase Half Wave Controlled Rectifier with RL Load and Freewheeling Diode.
4. Single Phase Full Wave Controlled Rectifier with R Load.
5. Single Phase Full Wave Controlled Rectifier with RL Load.
6. Single Phase Full Wave Controlled Rectifier with RL Load and Freewheeling Diode.
7. Single Phase Full Wave Half Controlled Rectifier (Semi Converter).
8. Three Phase Half Wave Controlled Rectifier.
9. Three Phase Full Wave Controlled Rectifier

Single Phase Half Wave Controlled Rectifier with R Load:

- The circuit consist of a thyristor T, a voltage source Vs and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the thyristor is ON, the input voltage is applied to the load.
- During the negative half cycle, the thyristor T gets reverse biased and gets tuned OFF.
- So the load receives voltage only during the positive half cycle only.
- The average value of output voltage can be varied by varying the firing angle α.
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Half Wave Controlled Rectifier with RL Load

- The circuit consist of a thyristor T, a voltage source Vs, an inductive load L and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at ωt = α, it gets turned ON and begins to conduct.

• When the thyristor is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly.

• During the negative half cycle, the thyristor T gets reverse biased but the current through the thyristors is not zero due to the inductor.

• The current through the inductor slowly decays to zero and when the load current (i.e the current through the thyristor) falls below holding current, it gets turned off.

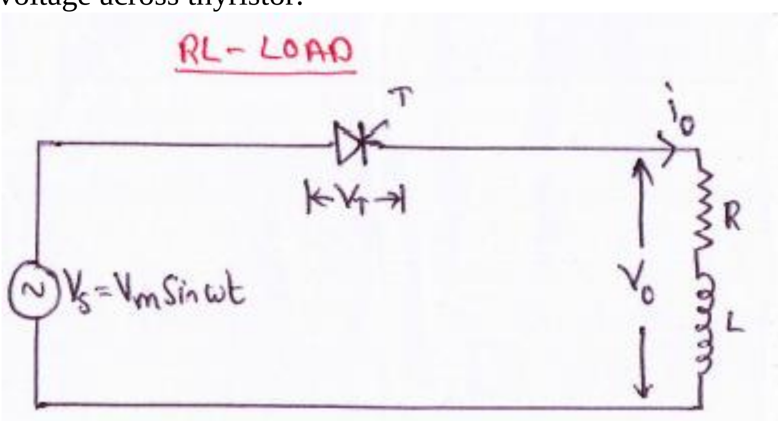
• So here the thyristor will conduct for a few duration in the negative half cycle and turns off at ωt = β. The angle β is called extinction angle.

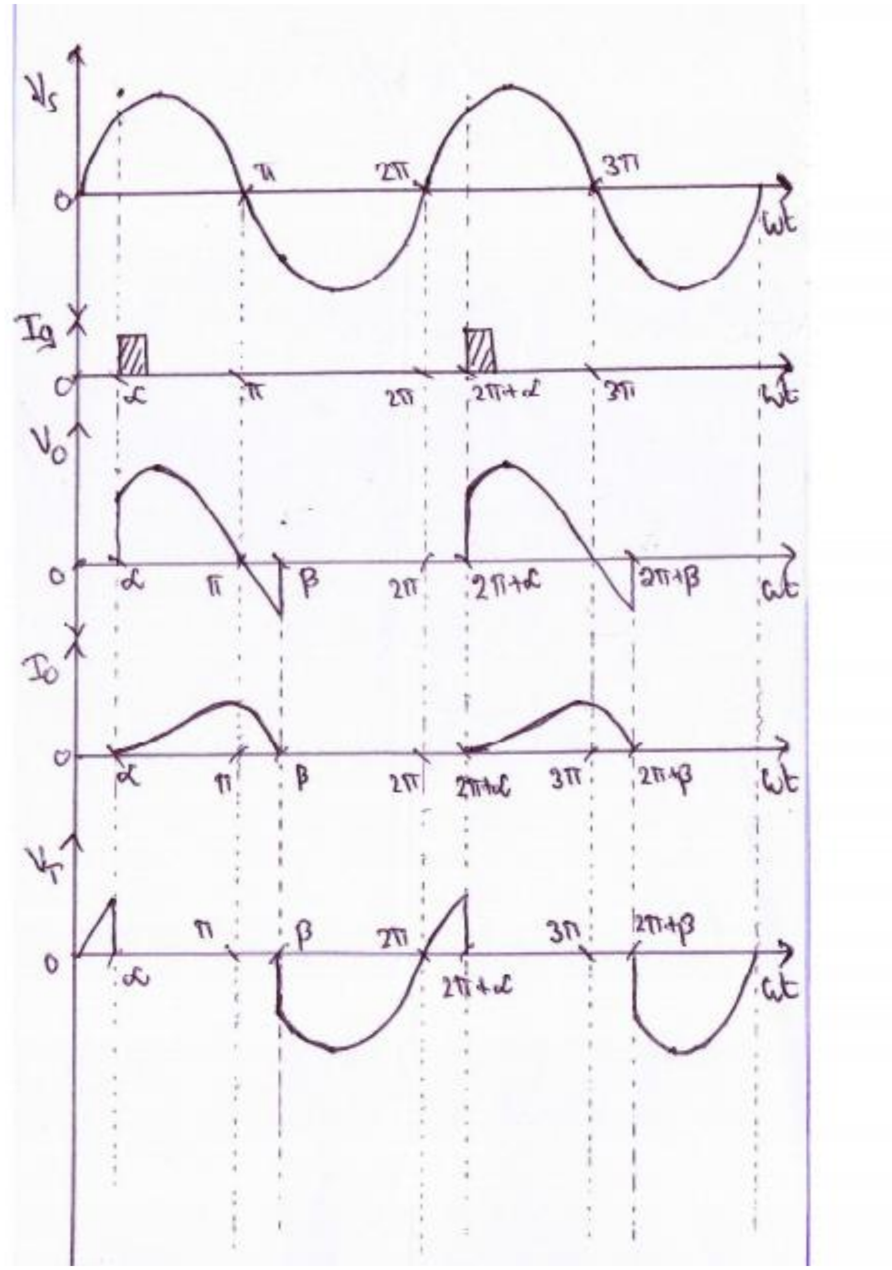
• The duration from α to β is called conduction angle.

• So the load receives voltage only during the positive half cycle and for a small duration in negative half cycle.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Half Wave Controlled Rectifier with RL Load and Freewheeling Diode

• The circuit consist of a thyristor T, a voltage source Vs, a diode FD across the RL load, an inductive load L and a resistive load R.

• During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.

• When a gate pulse is given to the thyristor T at $\omega t = \alpha$, it gets turned ON and begins to conduct.

• When the thyristor is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly.

• During the negative half cycle, the thyristor T gets reverse biased. At this instant i.e at ωt = π, the load current shift its path from the thyristor to the freewheeling diode.

• When the current is shifted from thyristor to freewheeling diode, the thyristor turns OFF.

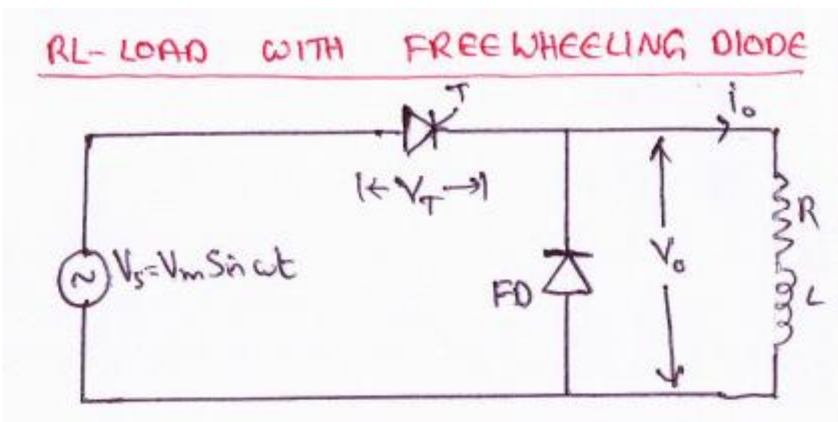
• The current through the inductor slowly decays to zero through the loop Rfreewheeling diode-L.

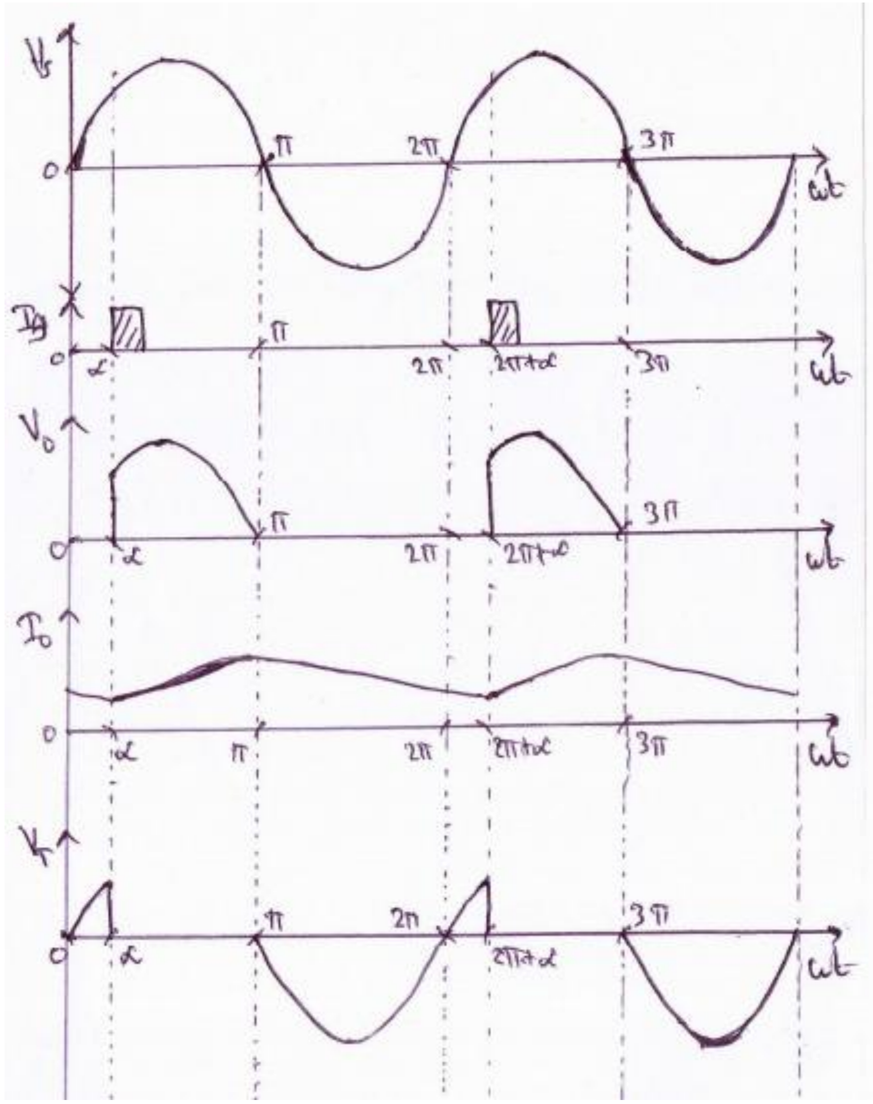
• So here the thyristor will not conduct in the negative half cycle and turns off at ωt = π.

• So the load receives voltage only during the positive half cycle.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Full Wave Controlled Rectifier with R Load

- The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source Vs and a R Load.
- During the positive half cycle of the input voltage, the thyristors T1 & T2 is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristors T1 & T2 at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the T1 & T2 is ON, the input voltage is applied to the load through the path VsT1-Load-T2-Vs.
- During the negative half cycle, T3 & T4 is forward biased, the thyristor T1 & T2 gets reverse biased and turns OFF

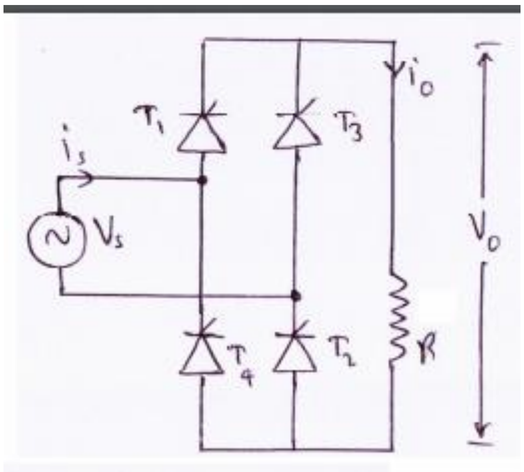
• When a gate pulse is given to the thyristor T3 & T4 at $\omega t = \pi+\alpha$, it gets turned ON and begins to conduct.

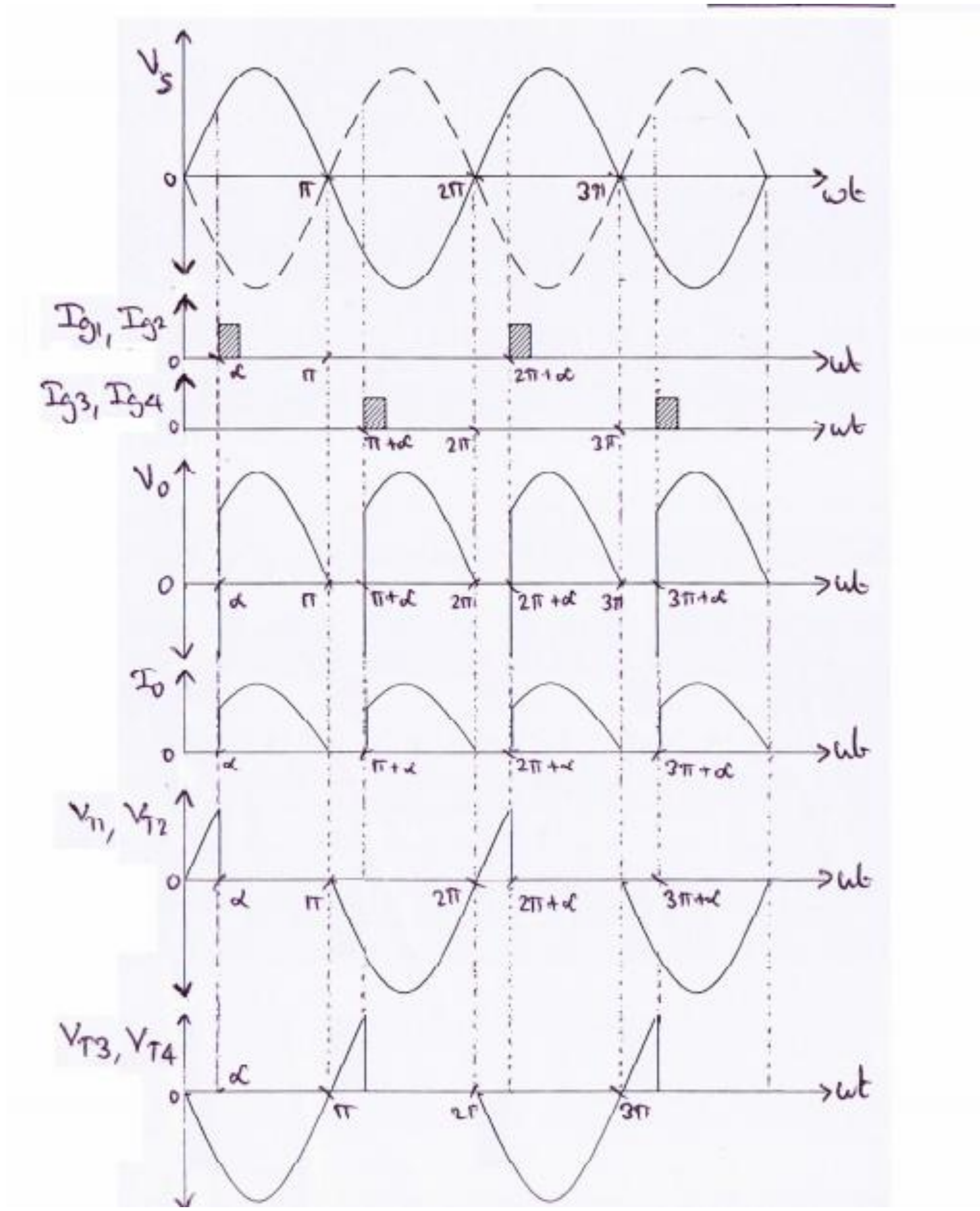
• When T3 & T4 is ON, the input voltage is applied to the load Vs-T3-Load-T4-Vs.

• Here the load receives voltage during both the half cycles.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Full Wave Controlled Rectifier with RL Load

A. MID POINT CONVERTER

• The circuit consist of two thyristors T1 and T2, a center tap transformer, a voltage source Vs and a RL Load.

• During the positive half cycle of the input voltage, the thyristor T1 is forward biased but it does not conduct until a gate signal is applied to it.

• When a gate pulse is given to the thyristor T1 at $\omega t = \alpha$, it gets turned ON and begins to conduct.

• When the thyristor T1 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly through the path A-T1-Load-N-A.

• During the negative half cycle, T2 is forward biased, the thyristor T1 gets reverse biased but the current through the thyristor T1 is not zero due to the inductor and T1 does not turns OFF

• The current through the inductor begins to decay to zero and T1 conducts for a small duration in negative half cycle.

• When a gate pulse is given to the thyristor T2 at ωt = π+α, it gets turned ON and begins to conduct.

• When the thyristor T2 is ON, the load current shifts its path from the T1 to T2 and thyristor T1 turns OFF at ωt = π+α.

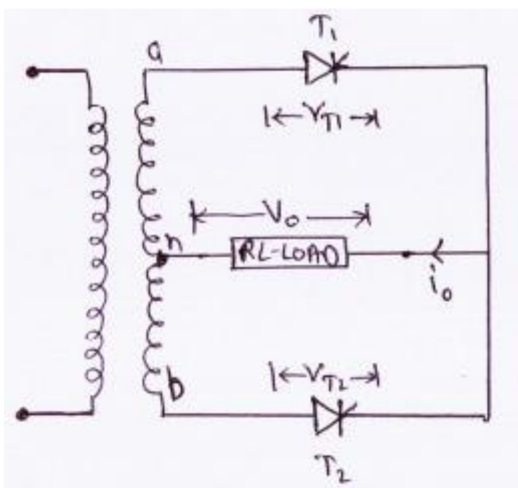
• When T2 is ON, the current through the load builds up slowly through the path B-T2- Load-N-B.

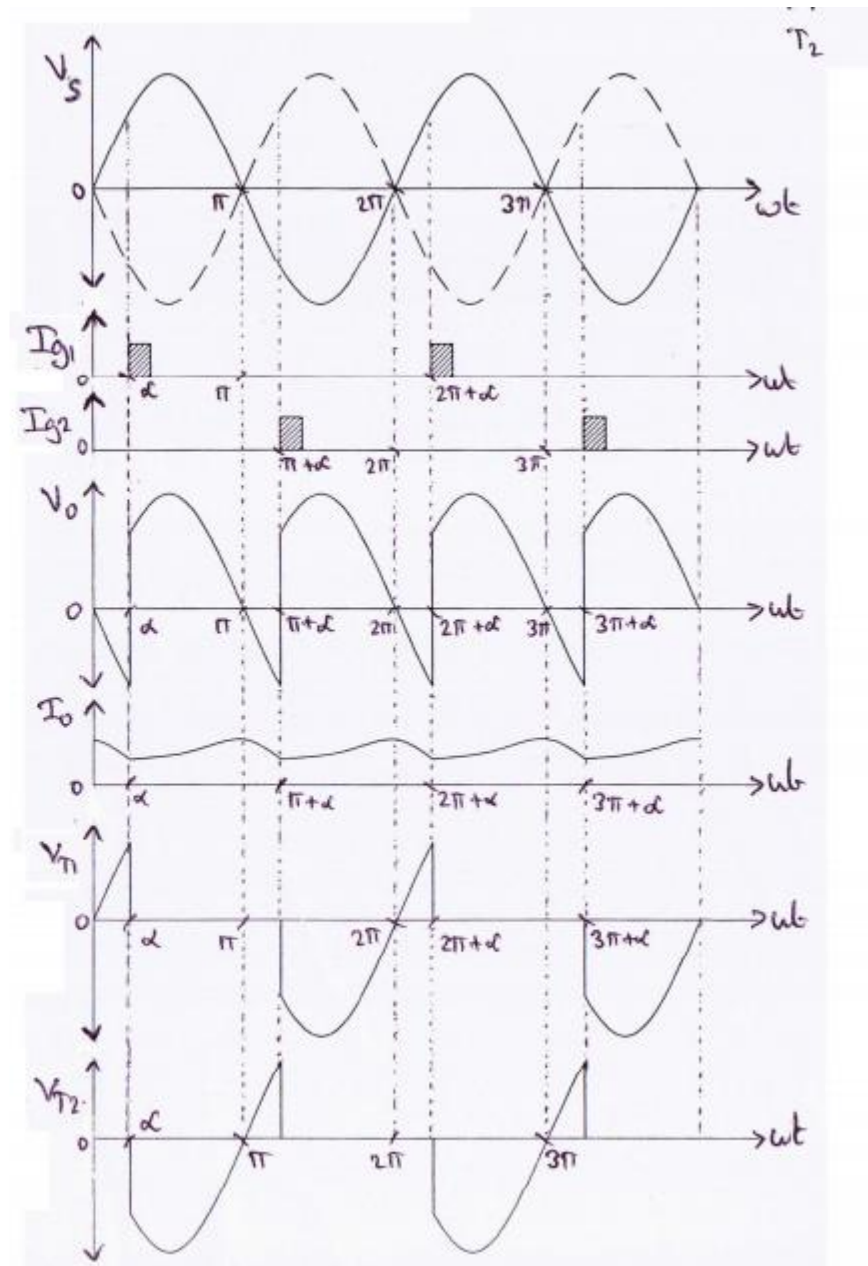
• So here both the thyristor will conduct for a few duration in the negative half cycle.

• The load receives voltage during both the half cycles.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor





B. BRIDGE CONVERTER

- The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source Vs and a RL Load.

- During the positive half cycle of the input voltage, the thyristors T1 & T2 is forward biased but it does not conduct until a gate signal is applied to it.

- When a gate pulse is given to the thyristors T1 & T2 at ωt = α, it gets turned ON and begins to conduct.
- When the T1 & T2 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly through the path Vs-T1-Load-T2-Vs.

- During the negative half cycle, T3 & T4 is forward biased, the thyristor T1 & T2 gets reverse biased but the current through them is not zero due to the inductor and does not turns OFF

• The current through the inductor begins to decay to zero and T1 & T2 conducts for a small duration in negative half cycle.

• When a gate pulse is given to the thyristor T3 & T4 at ωt = π+α, it gets turned ON and begins to conduct.

• When the thyristor T3 & T4 is ON, the load current shifts its path to T3 & T4 and turns OFF T1 & T2 at ωt = π+α.

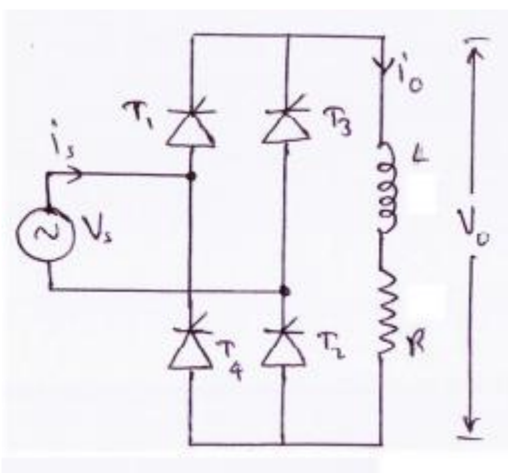
• When T3 & T4 is ON, the current through the load builds up slowly through the path Vs-T3-Load-T4-Vs.

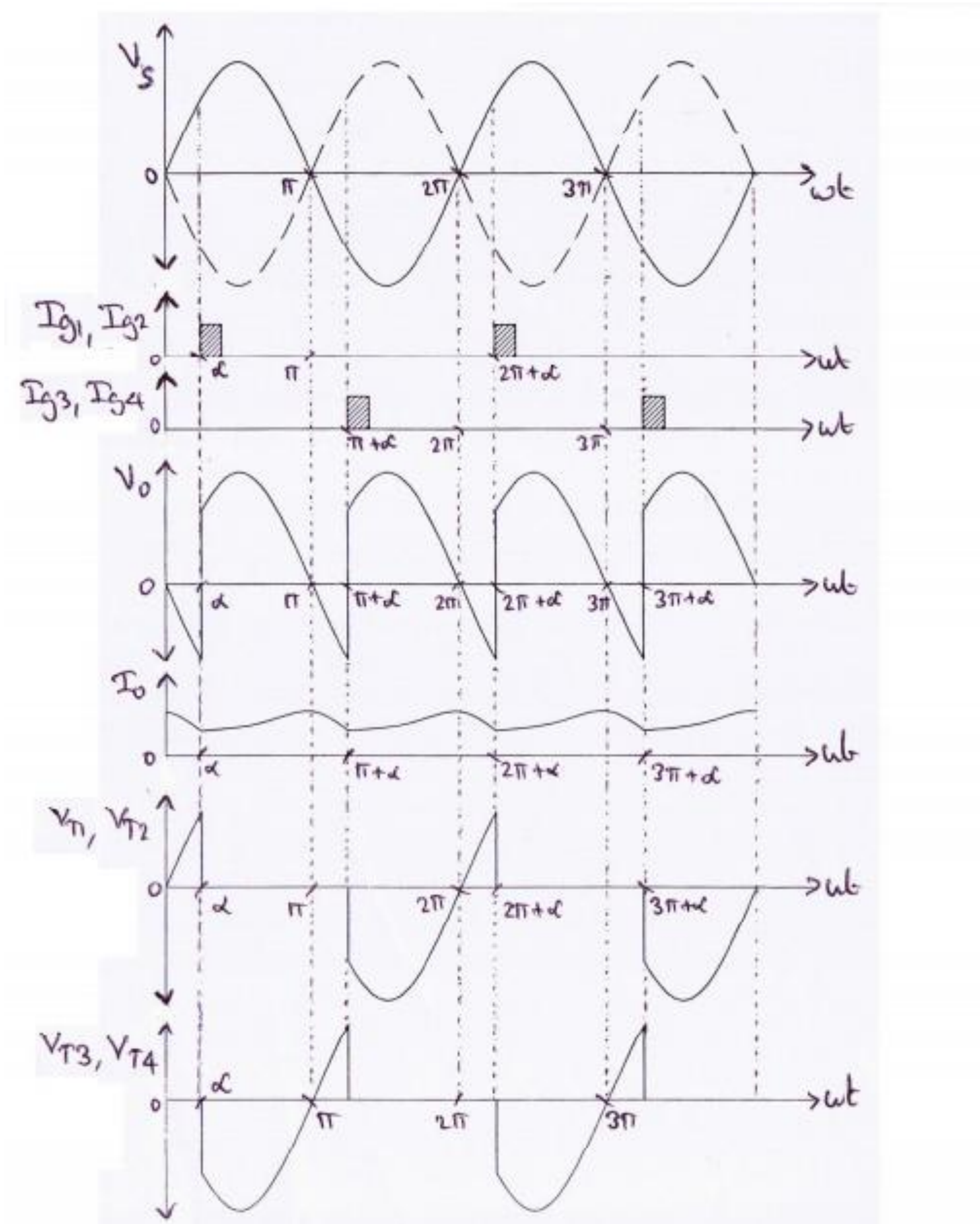
• So here all the thyristor will conduct for a few duration in the negative half cycle.

• The load receives voltage during both the half cycles.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Full Wave Controlled Rectifier with RL Load and Freewheeling Diode.

• The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source Vs, a RL Load and a freewheeling diode across the load.

• During the positive half cycle of the input voltage, the thyristors T1 & T2 is forward biased but it does not conduct until a gate signal is applied to it.

• When a gate pulse is given to the thyristors T1 & T2 at ωt = α, it gets turned ON and begins to conduct.
• When the T1 & T2 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly through the path Vs-T1-Load-T2-Vs.

• During the negative half cycle (at ωt = π), T3 & T4 is forward biased, the thyristor T1 & T2 gets reverse biased.

• The current shifts its path to the freewheeling diode and circulates through the loop FD-R-L-FD. • Thus T1 & T2 turns off at ωt = π

• When a gate pulse is given to the thyristor T3 & T4 at ωt = π+α, it gets turned ON and begins to conduct.

• When T3 & T4 is ON, the current through the load builds up slowly through the path Vs-T3-Load-T4-Vs.

• During the next positive half cycle (at ωt = 2π), T1 & T2 is forward biased, the thyristor T3 & T4 gets reverse biased.

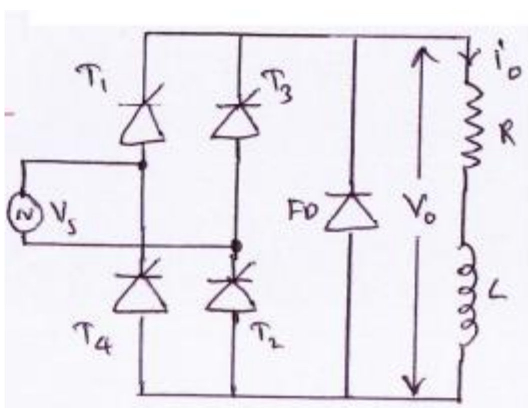
• The current shifts its path to the freewheeling diode and circulates through the loop FD-R-L-FD. • Thus T3 & T4 turns off at ωt = 2π

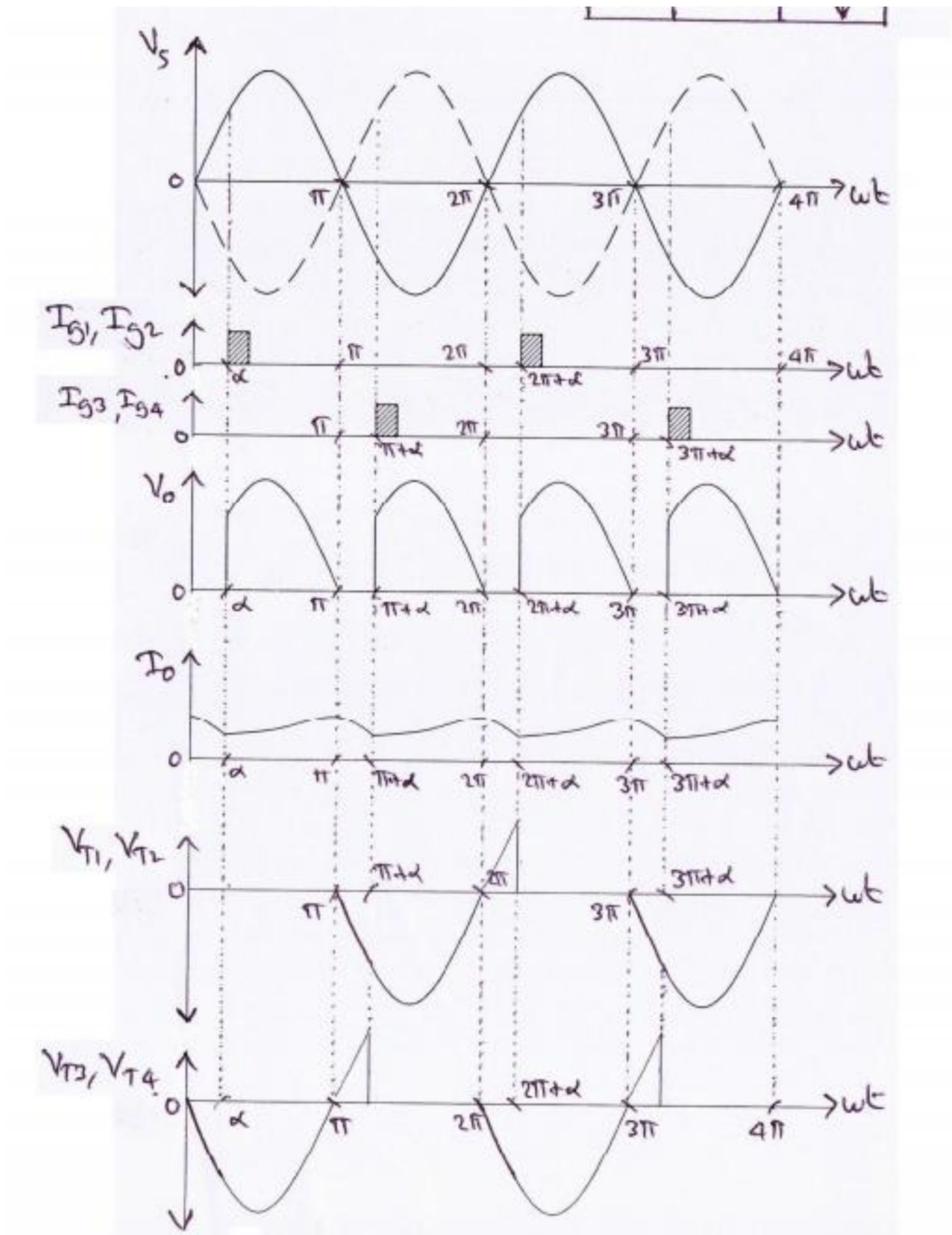
• So here all the thyristor will conduct only in the positive half cycle.

• The load receives voltage during both the half cycles.

• The average value of output voltage can be varied by varying the firing angle α.

• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.





Single Phase Full Wave Half Controlled Rectifier (Semi Converter)

• The circuit consist of two thyristors T1 & T2, two diodes D1 and D2, a voltage source Vs, a RL Load.

• During the positive half cycle of the input voltage, the thyristors T1 & D1 is forward biased but it does not conduct until a gate signal is applied to T1.

• When a gate pulse is given to the thyristors T1 at ωt = α, it gets turned ON and begins to conduct.

• When the T1 & D1 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up.

• During the negative half cycle (at ωt = π), T2 & D2 is forward biased, the thyristor T1 & D1 gets reverse biased.

• The current shifts its path to D2 and T1 in case of symmetrical converter (D1 & D2 in case of asymmetical converter) and circulates through the load.

• When a gate pulse is given to the thyristor T2 at ωt = π+α, it gets turned ON and begins to conduct.

• When T2 & D2 is ON, the current through the load builds up.

• During the next positive half cycle (at ωt = 2π), T1 & D1 is forward biased, the thyristor T2 & D2 gets reverse biased.

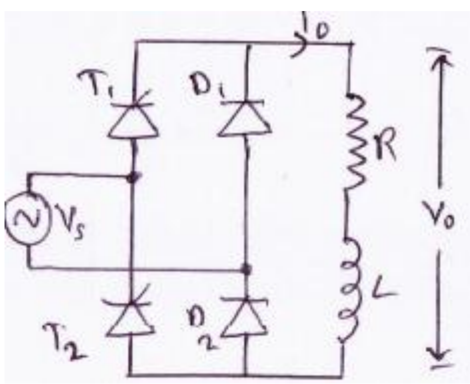
• The current shifts its path to D1 and T2 in case of symmetrical converter (D1 & D2 in case of asymmetical converter) and circulates through the load.

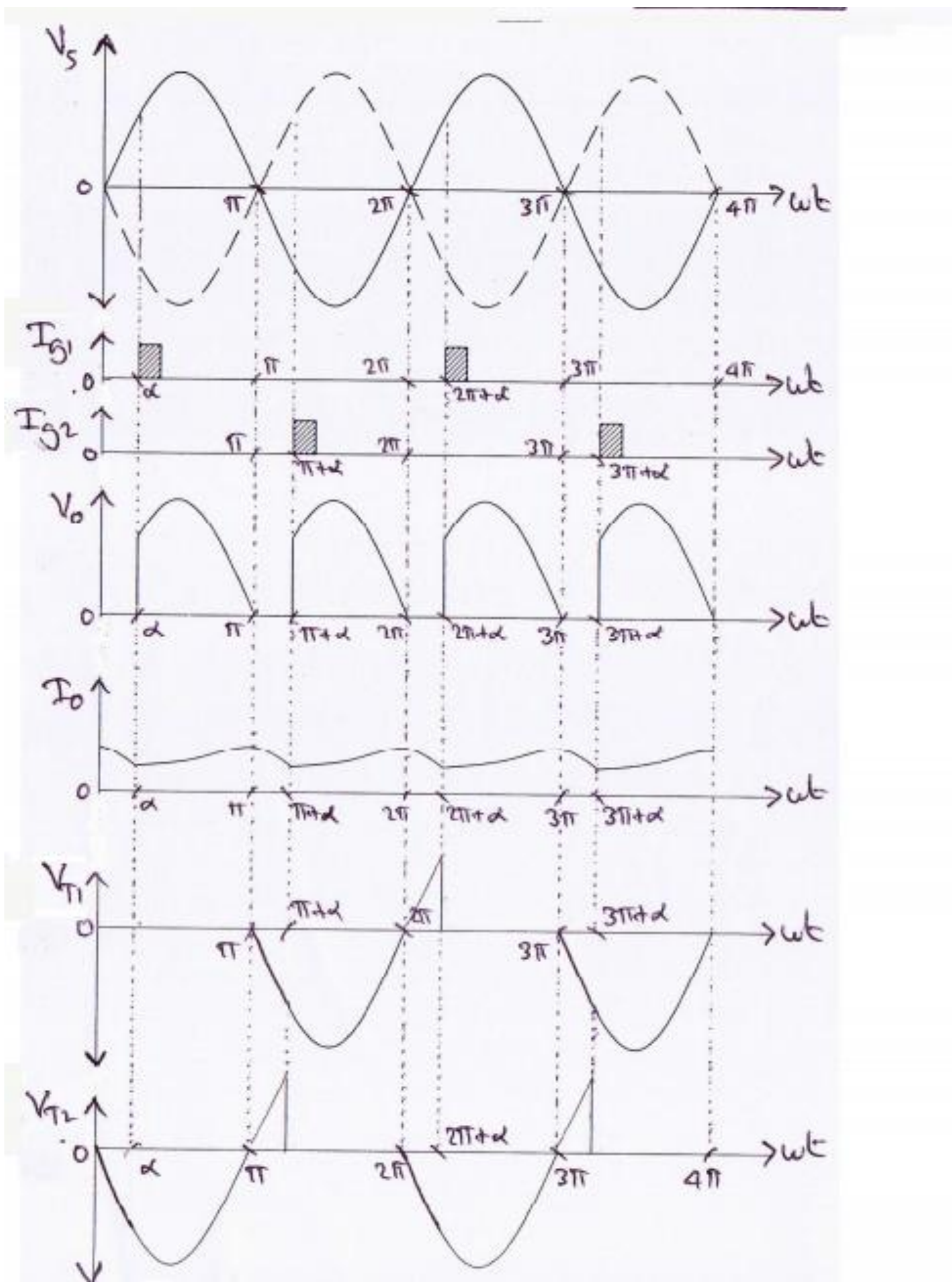
• The load receives voltage during both the half cycles.

• The average value of output voltage can be varied by varying the firing angle α.

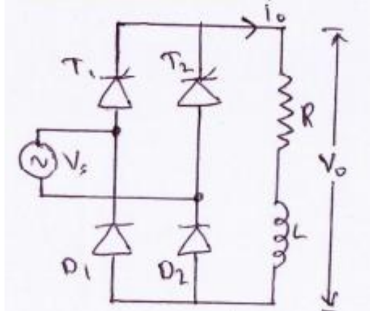
• The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.

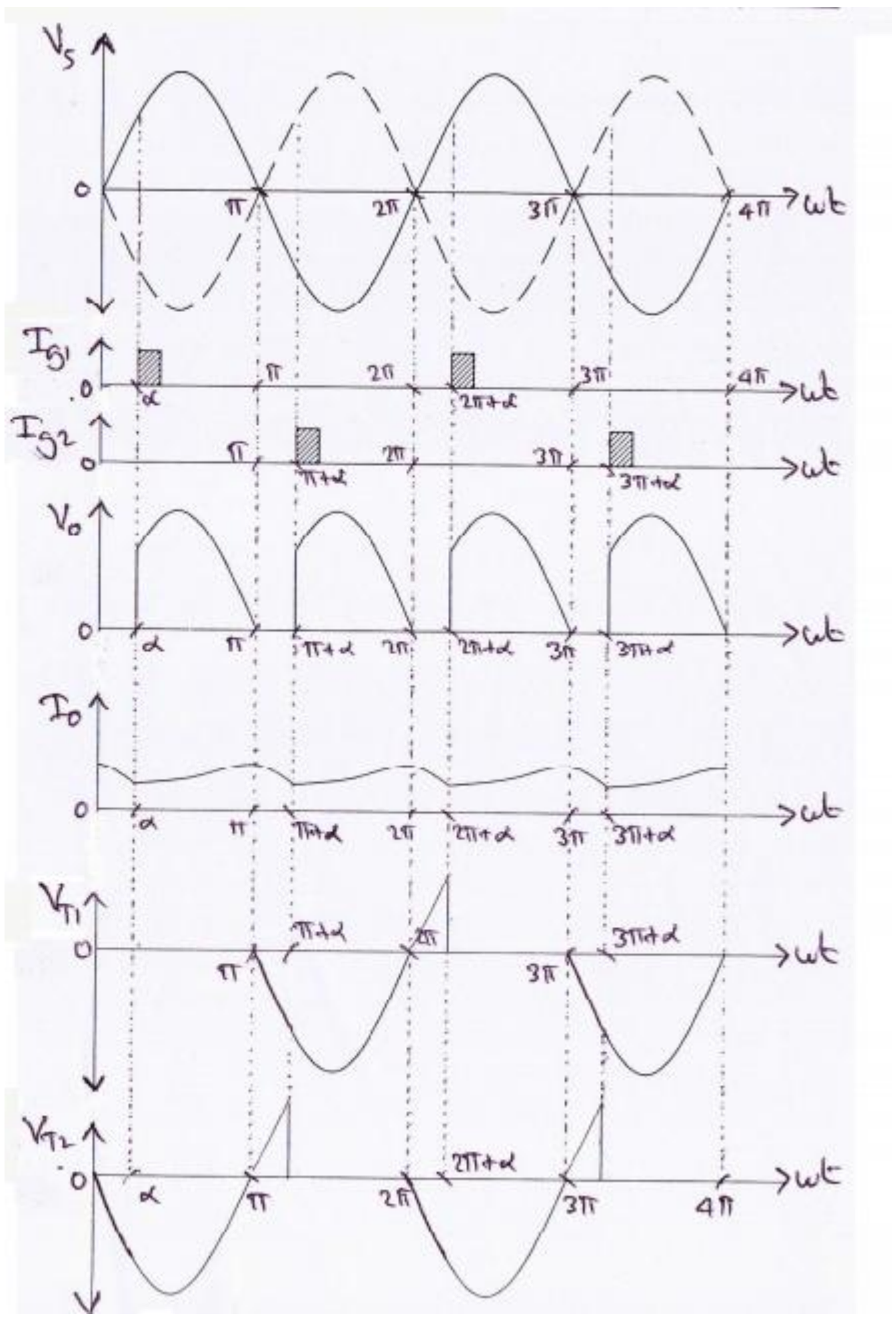
Single Phase Semi Converter **(**symmetical semi converter**)**





Single Phase Semi Converter **(**asymmetical semi converter**)**



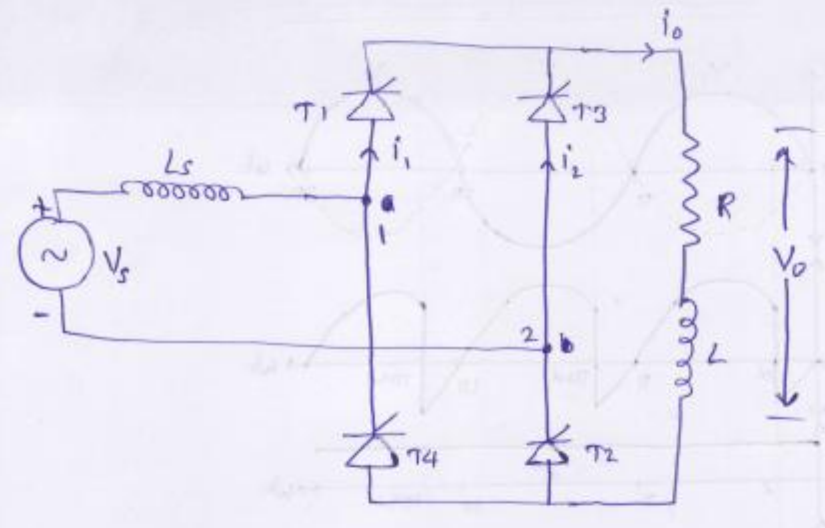


Vs
Ig1
Ig2
Vo
Io
VT1
VT2
ωt

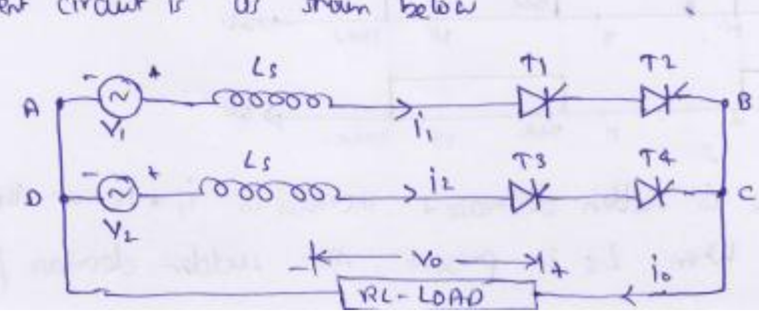
Effect of source impedance on 1ϕ full converter

So far we have studied the effect of Inductive load on o/p current, o/p voltage & firing of thyristor. In those cases, the impedance of source was taken to be 0. Now we will consider the working of 1ϕ full wave converter with RL load, along with an inductive impedance at source side.

Consider a 1ϕ full converter as shown below. Let the i/p inductance be L_s. The load current is assumed to be continuous due to large inductive load.



The equivalent circuit is as shown below



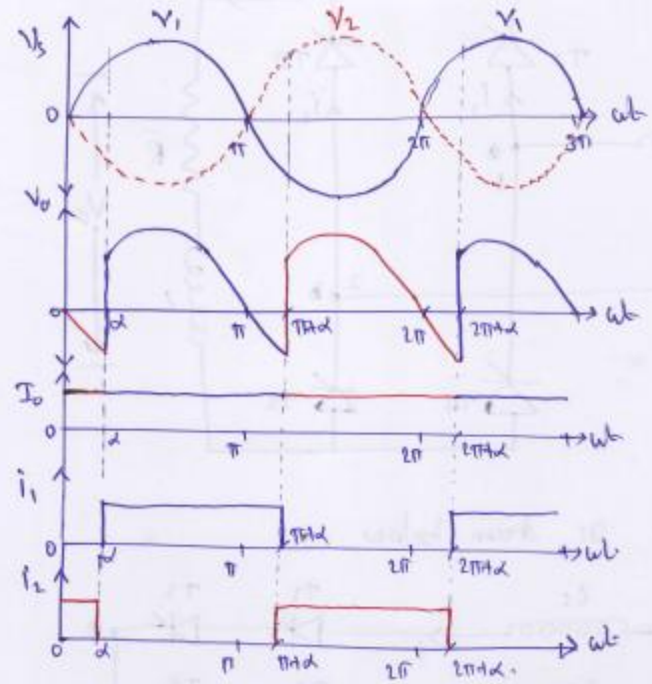
Let us consider the case when L_s is not present i.e. when the source inductance is zero. Here the SCR [illegible] T1 & T2 are fired at α.

So from α to $(\pi+\alpha)$ the o/p current i_o is same as current through T1 & T2 i.e. i_1

i.e. from α to $\pi+\alpha$; $i_o = i_1$

At $\pi+\alpha$; T3 & T4 is fired. Now the load current shifts its path from T1 & T2 to T3 & T4. At this time, i_o is same as current through T3 & T4 is i_2

ie from $\pi+\alpha$ to $2\pi+\alpha$; $i_o = i_2$

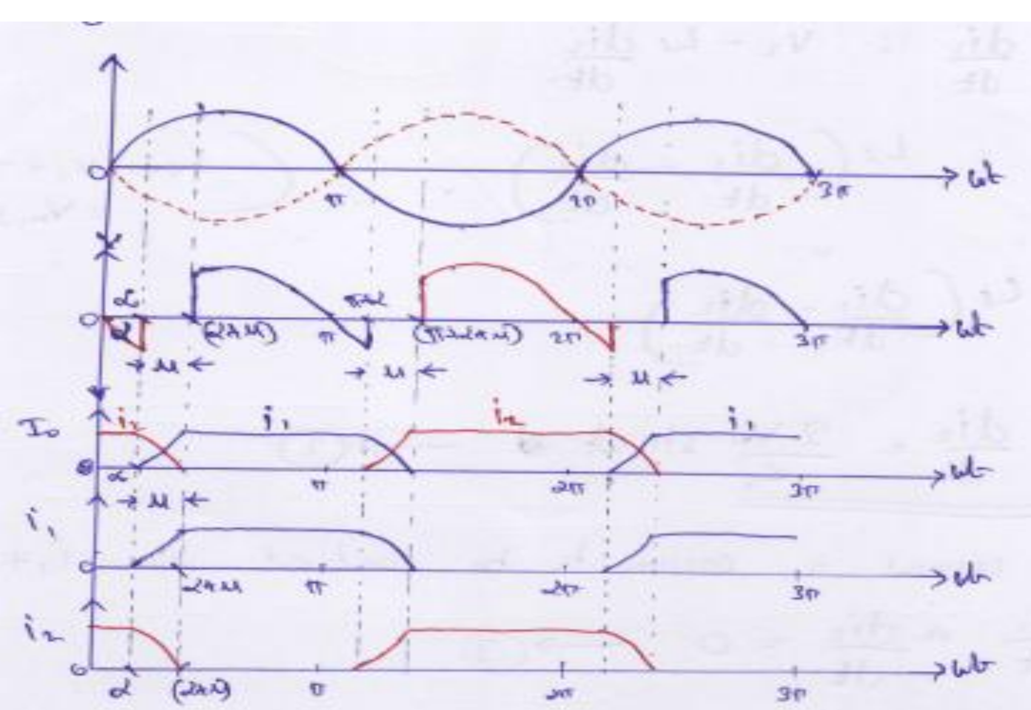


Here we can see a sudden decrease & increase in i_1 & i_2 at α, $\pi+\alpha$, $2\pi+\alpha$ ...etc. When L_s is present, this sudden decrease / increase in load current will not take place, instead a gradual decrease / increase in current take place. as shown below

In the waveform shown below, the thyristor T1 & T2 are triggered at (α). so the current i_1 builds up gradually & attains maximum value I_0 at an angle $(\alpha + \mu)$.

Next the thyristors T3 & T4 are triggered at $(\pi + \alpha)$. At this time, the current i_1 (through T1 & T2) decrease gradually from I_0 to 0 at $(\pi + \alpha + \mu)$ and current i_2 through T_3 & T_4 increases from 0 to I_0 at $(\pi + \alpha + \mu)$ and this process repeats at each firing.

· Here we can see that during the period 'μ', all thyristor T1, T2, T3 & T4 are conducting. ie during the period 'μ', the o/p voltage will be 0.



from figure, we can see that, V_0 is 0 for α to $\alpha+\mu$

So the o/p voltage is available only for $\omega t = (\alpha+\mu)$ to $(\alpha+\pi)$.

$$\therefore \quad V_0 = \frac{V_m}{\pi}\int_{\alpha+\mu}^{\alpha+\pi} \sin \omega t \; d\omega t$$

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

$$V_0 = \frac{V_m}{\pi}\Big[\cos\alpha + \cos(\alpha+\mu)\Big] \longrightarrow ①$$

Now load current I_0 ~~during~~ during time on of T1 & T2 is zero at 'α' & builds up to I_0 at '$\alpha+\mu$'

Looking to equivalent circuit, Apply KVL to the loop ABCDA.

$$\Rightarrow V_1 - L_s\frac{di_1}{dt} = V_2 - L_s\frac{di_2}{dt}.$$

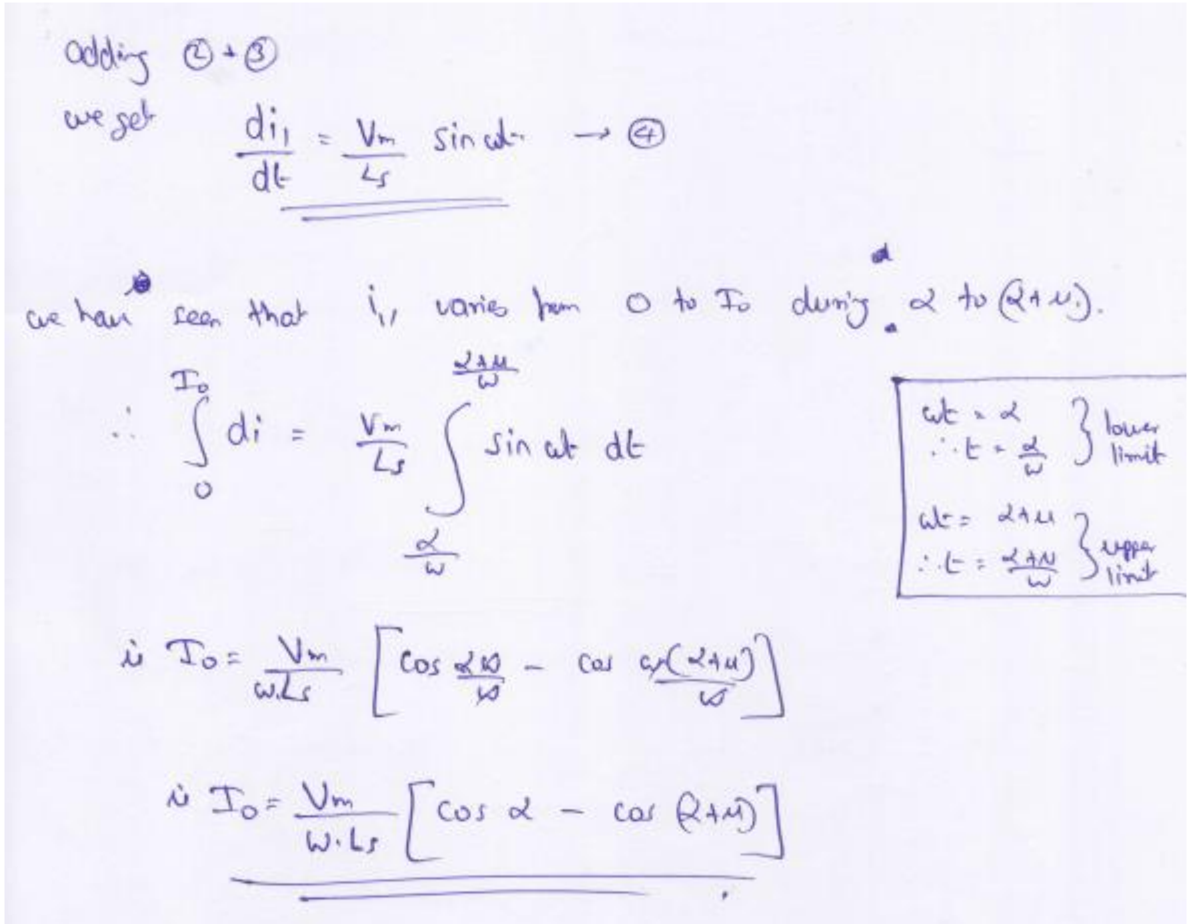
$$\text{ie } V_1 - V_2 = L_s\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right). \quad \left(\text{here } V_1 = -V_2 = V_m \sin\omega t\right)$$

$$\text{ie } 2V_1 = L_s\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right)$$

$$\text{ie } \frac{di_1}{dt} - \frac{di_2}{dt} = \frac{2V_m}{L_s}\sin\omega t \longrightarrow ②$$

Since load current is assume to be constant ie $i_1 + i_2 = I_0$,

$$\frac{di_1}{dt} + \frac{di_2}{dt} = 0 \longrightarrow ③$$



adding ② + ③

we get $\frac{di_1}{dt} = \frac{V_m}{L_s} \sin \omega t \rightarrow$ ④

we have seen that i_1 varies from 0 to I_o during α to $(\alpha+\mu)$.

$$\therefore \int_0^{I_o} di = \frac{V_m}{L_s} \int_{\alpha/\omega}^{(\alpha+\mu)/\omega} \sin \omega t \, dt$$

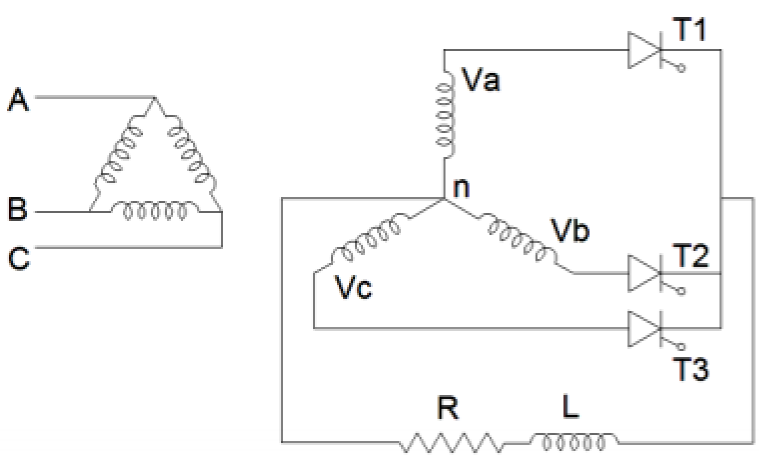
$\omega t = \alpha$, $\therefore t = \frac{\alpha}{\omega}$ } lower limit

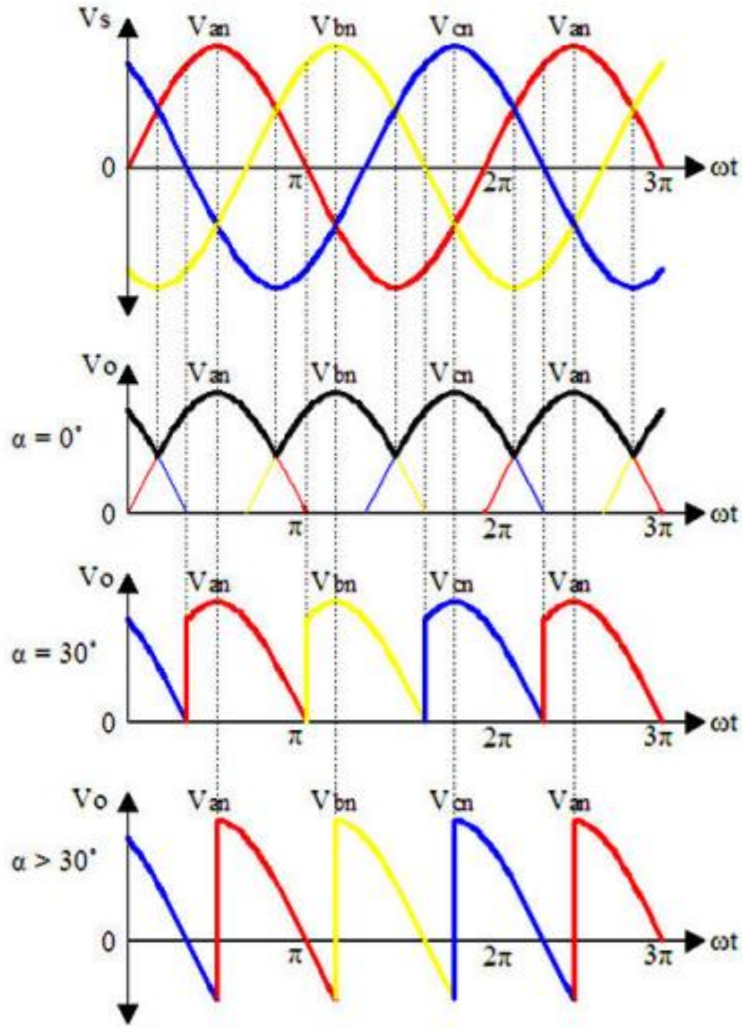
$\omega t = \alpha+\mu$, $\therefore t = \frac{\alpha+\mu}{\omega}$ } upper limit

$$I_o = \frac{V_m}{\omega L_s}\left[\cos \frac{\alpha\omega}{\omega} - \cos \frac{\omega(\alpha+\mu)}{\omega}\right]$$

$$I_o = \frac{V_m}{\omega \cdot L_s}\left[\cos \alpha - \cos(\alpha+\mu)\right]$$

Circuit Diagram and Waveform of 3 Phase Half Controlled Rectifier with RL Load:





Circuit Diagram and Waveform of 3 Phase Half Controlled Rectifier with RL Load

• The circuit consist of a delta star transformer and 3 thyristors T1, T2, T3 which are connected on the secondary star connected winding and a RL load.

• When Va is positive, T1 becomes forward biased and conducts. During the negative cycle of Va, the current through T1 is not zero due to inductor present in the load.

• So T1 will remain ON during the negative cycle of Va

• When Vb is positive, T2 is triggered and the load current gets transferred from T1 to T2. At this instant, T1 turns OFF.

• During the negative cycle of Vb, the current through T2 is not zero due to inductor present in the load.
• So T2 will remain ON during the negative cycle of Vb

• When T3 is triggered during positive cycle of Vc, the load current is transferred from T2 to T3. At this instant, T2 turns OFF

• Similarly T3 conducts during the negative cycle of Vc and turns OFF when T1 is triggered.

• The average output voltage can be varied by varying the firing angles of the thyristors.

• The waveforms shows the output voltage for various firing angles.

• In the waveform, Va is denoted as Van, Vb as Vbn, Vc as Vcn.

Circuit Diagram and Waveform of 3 Phase Half Controlled Rectifier with RL Load

• The circuit consist of a delta star transformer and 3 thyristors T1, T2, T3 which are connected on the secondary star connected winding and a RL load.

• When Va is positive, T1 becomes forward biased and conducts. During the negative cycle of Va, the current through T1 is not zero due to inductor present in the load.

• So T1 will remain ON during the negative cycle of Va • When Vb is positive, T2 is triggered and the load current gets transferred from T1 to T2. At this instant, T1 turns OFF.

• During the negative cycle of Vb, the current through T2 is not zero due to inductor present in the load.
• So T2 will remain ON during the negative cycle of Vb

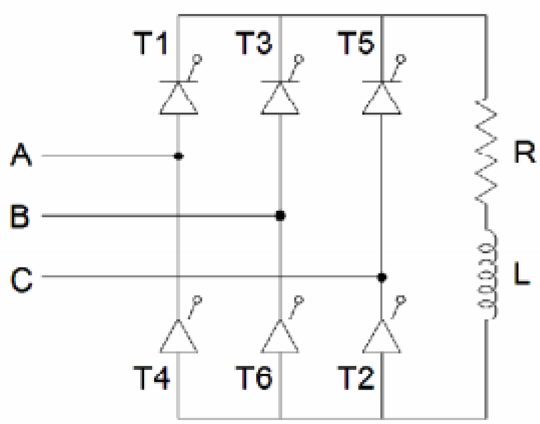
• When T3 is triggered during positive cycle of Vc, the load current is transferred from T2 to T3. At this instant, T2 turns OFF

• Similarly T3 conducts during the negative cycle of Vc and turns OFF when T1 is triggered.

• The average output voltage can be varied by varying the firing angles of the thyristors.

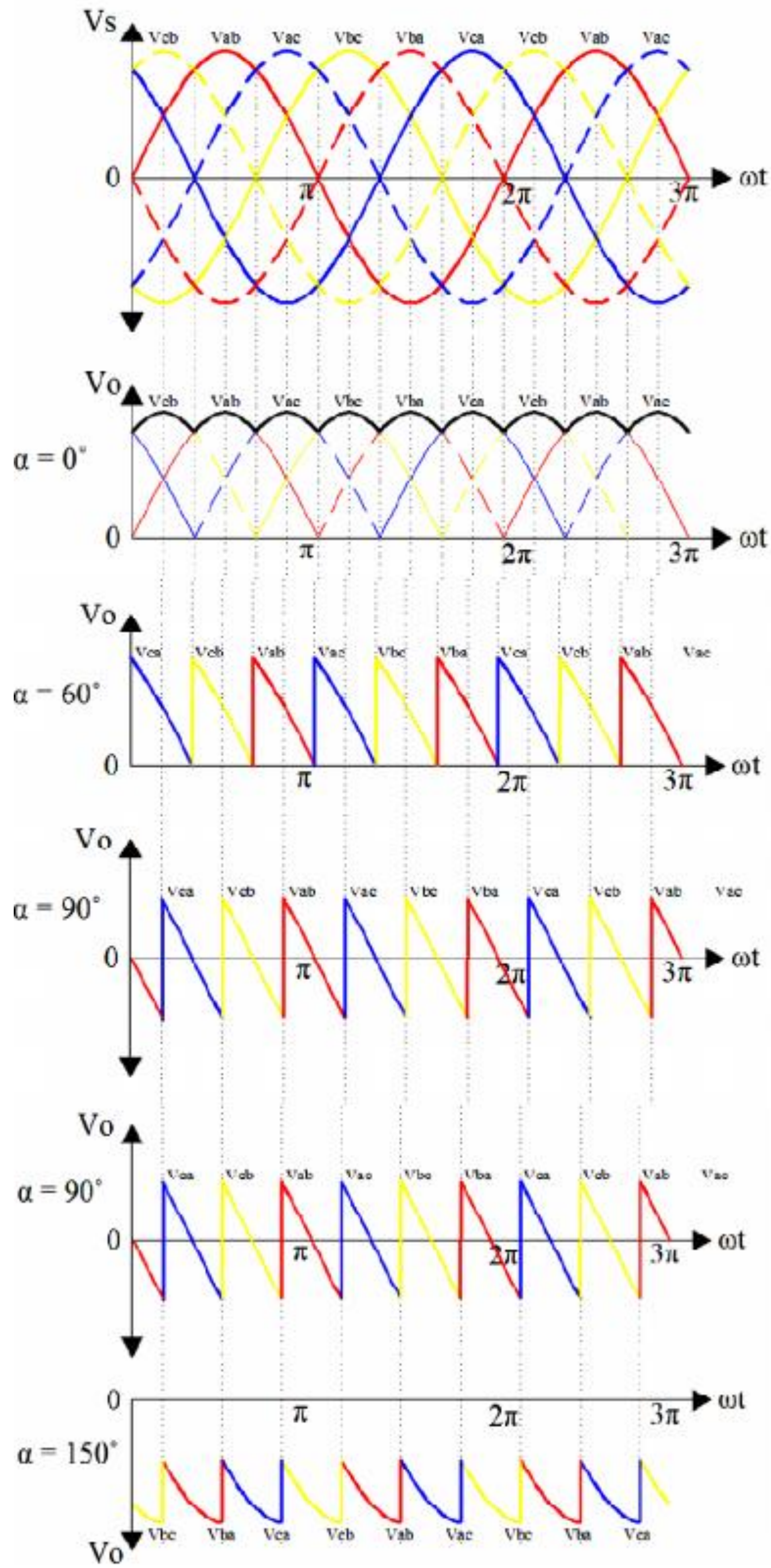
• The waveforms shows the output voltage for various firing angles. • In the waveform, Va is denoted as Van, Vb as Vbn, Vc as Vcn.

Circuit Diagram and Waveform of 3 Phase Full Controlled Rectifier with RL Load



• The circuit consist of 6 thyristors, T1, T2, T3, T4, T5, T6, a three phase supply and a RL load.

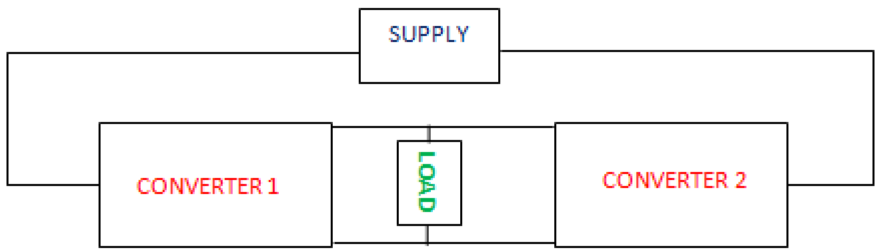
- The thyristors T1, T3, T5 form the positive group.
- The thyristors T4, T6, T2 form the negative group.
- Thyristors T1, T3, T4, T6 produces the full wave recitified output of Vab across the load.
- Thyristors T3, T5, T6, T2 produces the full wave recitified output of Vbc across the load.
- Thyristors T1, T5, T4, T2 produces the full wave recitified output of Vca across the load.
- All these 3 outputs are given simultaneously to the same RL load. The effect is that all the 3 individual output mentioned above gets superimposed on each other to get the final output.
- The waveform of the output for different firing angles are shown below.
- The average output voltage can be varied by varying the firing angle.
- For firing angle < 90, the circuit works as rectifier.
- For firing angle > 90, the circuit works as Line commutated inverter.



Vs
Vcb Vab Vac Vbc Vba Vca Vcb Vab Vac
0
π
2π
3π
ωt
Vo
Vcb Vab Vac Vbc Vba Vca Vcb Vab Vac
α = 0°
0
π
2π
3π
ωt
Vo
Vca Vcb Vab Vac Vbc Vba Vca Vcb Vab Vac
α = 60°
0
π
2π
3π
ωt
Vo
Vca Vcb Vab Vac Vbc Vba Vca Vcb Vab Vac
α = 90°
0
π
2π
3π
ωt
Vo
Vca Vcb Vab Vac Vbc Vba Vca Vcb Vab Vac
α = 90°
0
π
2π
3π
ωt
0
π
2π
3π
ωt
α = 150°
Vbc Vba Vca Vcb Vab Vac Vbc Vba Vca
Vo

Dual Converter

Dual converter, the name itself says two converters. It is really an electronic converter or circuit which comprises of two converters. One will perform as 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.



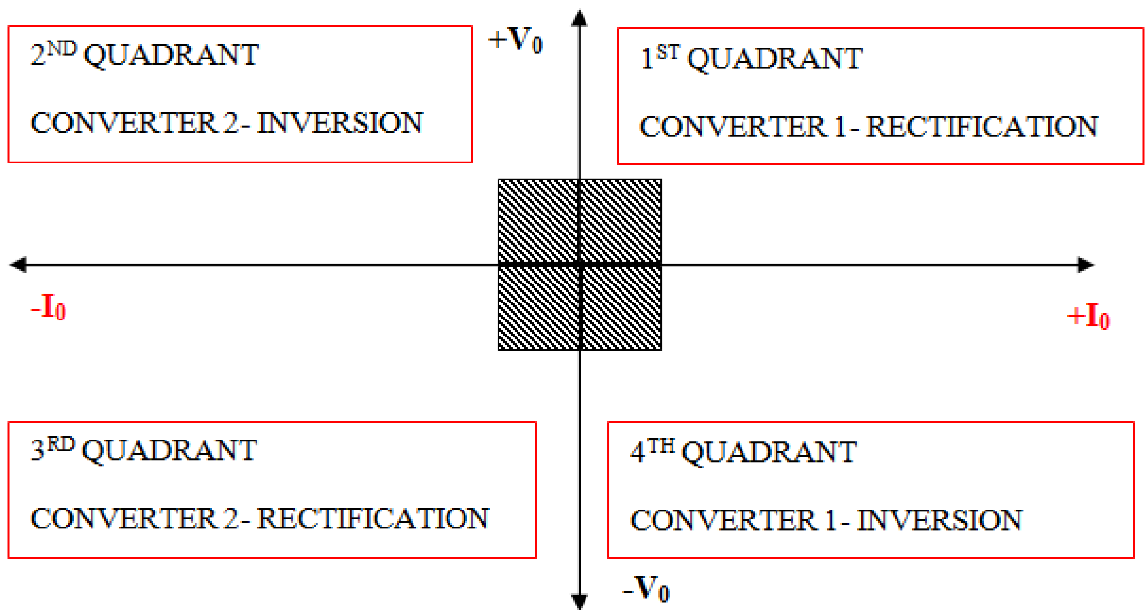
Modes of Operation of Dual Converter

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 $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.

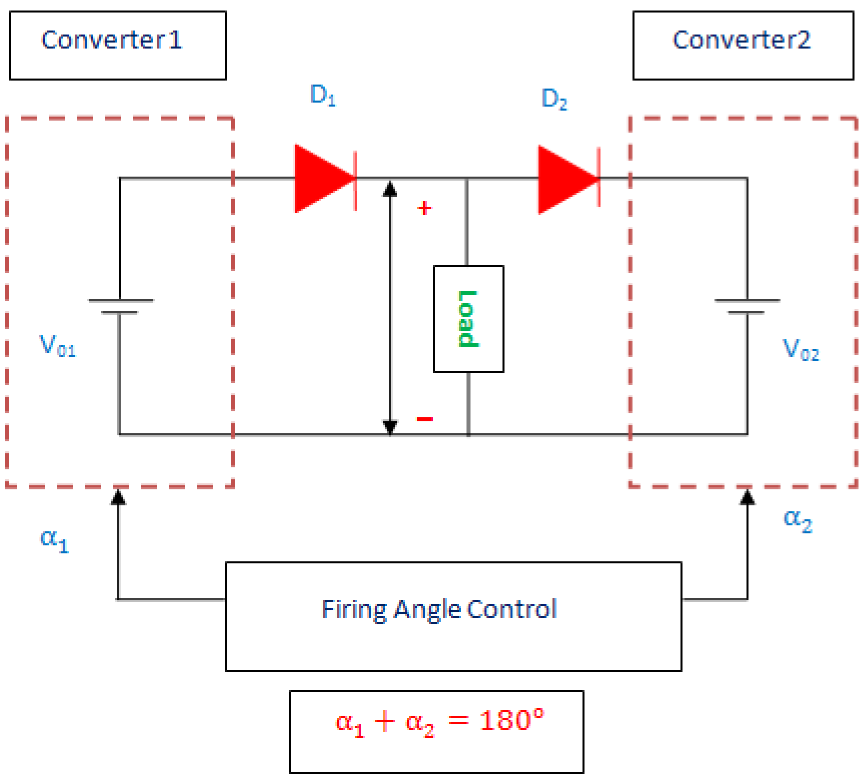
Circulating Current Mode

- Two converters will be in the ON condition at the same time. 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, V_{dc} and I_{dc} are positive.
- Converter 1 performs as an inverter when firing angle be $90^o<\alpha_1< 180^o$ and Converter 2 performs as a controlled rectifier when the firing angle be $0<\alpha_2< 90^o$ In this condition, $V_{dc}$and I_{dc} are negative.
- The four quadrant operation is shown below.



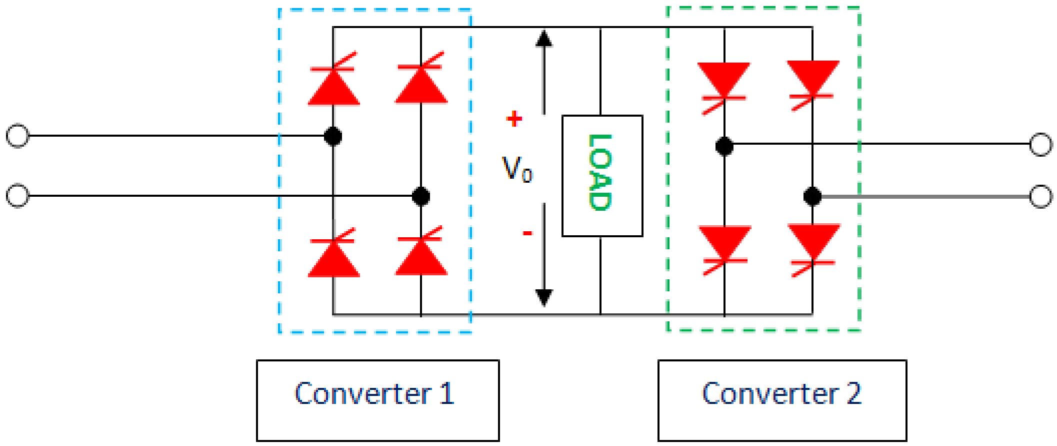
Ideal Dual Converter

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.



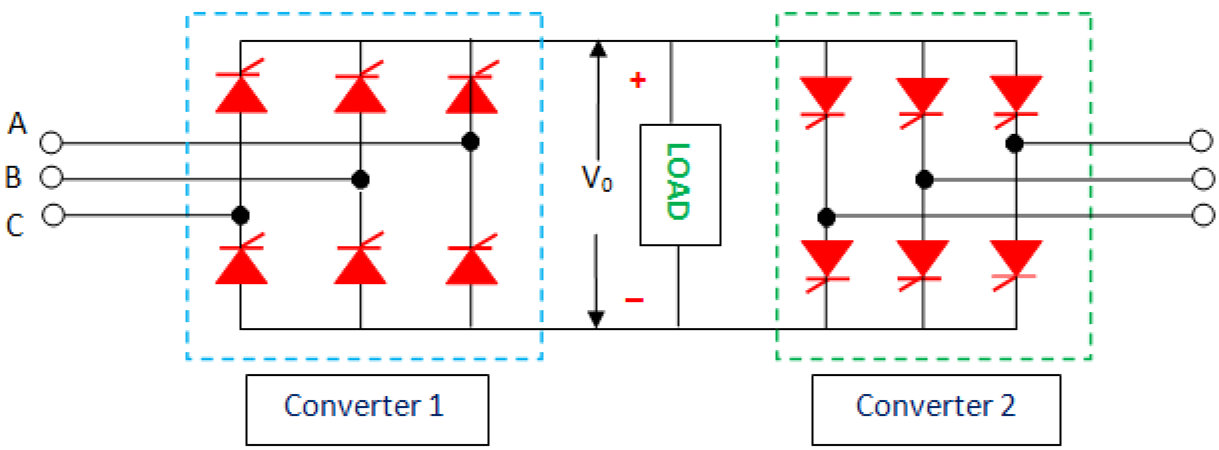
Single Phase Dual Converter

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.



Three Phase Dual Converter

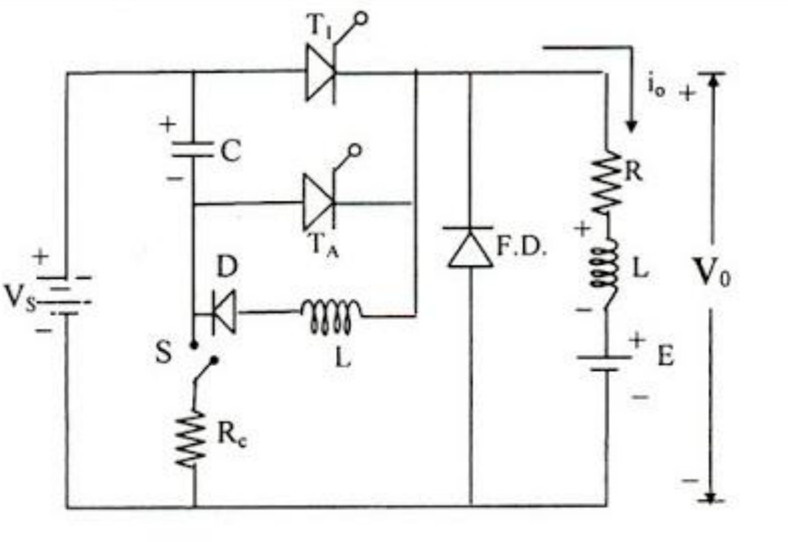
Here, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second converter. It will do the DC to AC 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.



UNIT -3

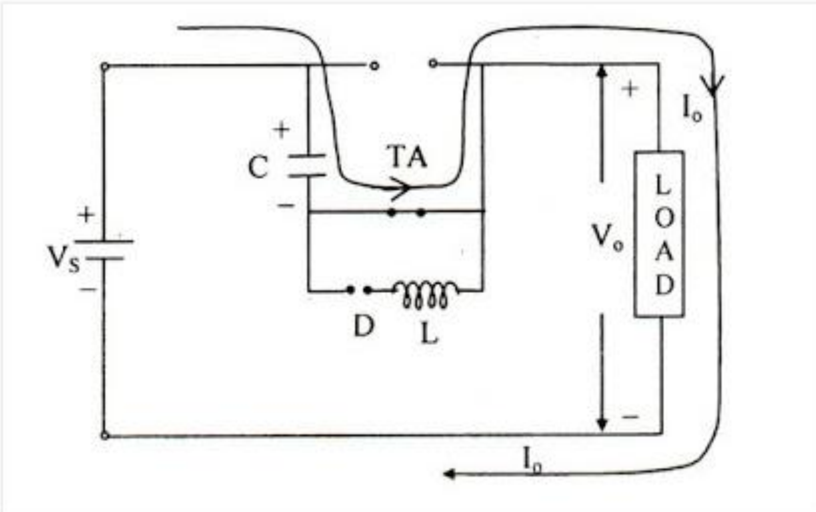
DC TO DC CHOPPER

Voltage Commutated Chopper



Voltage Commutated Chopper circuit diagram

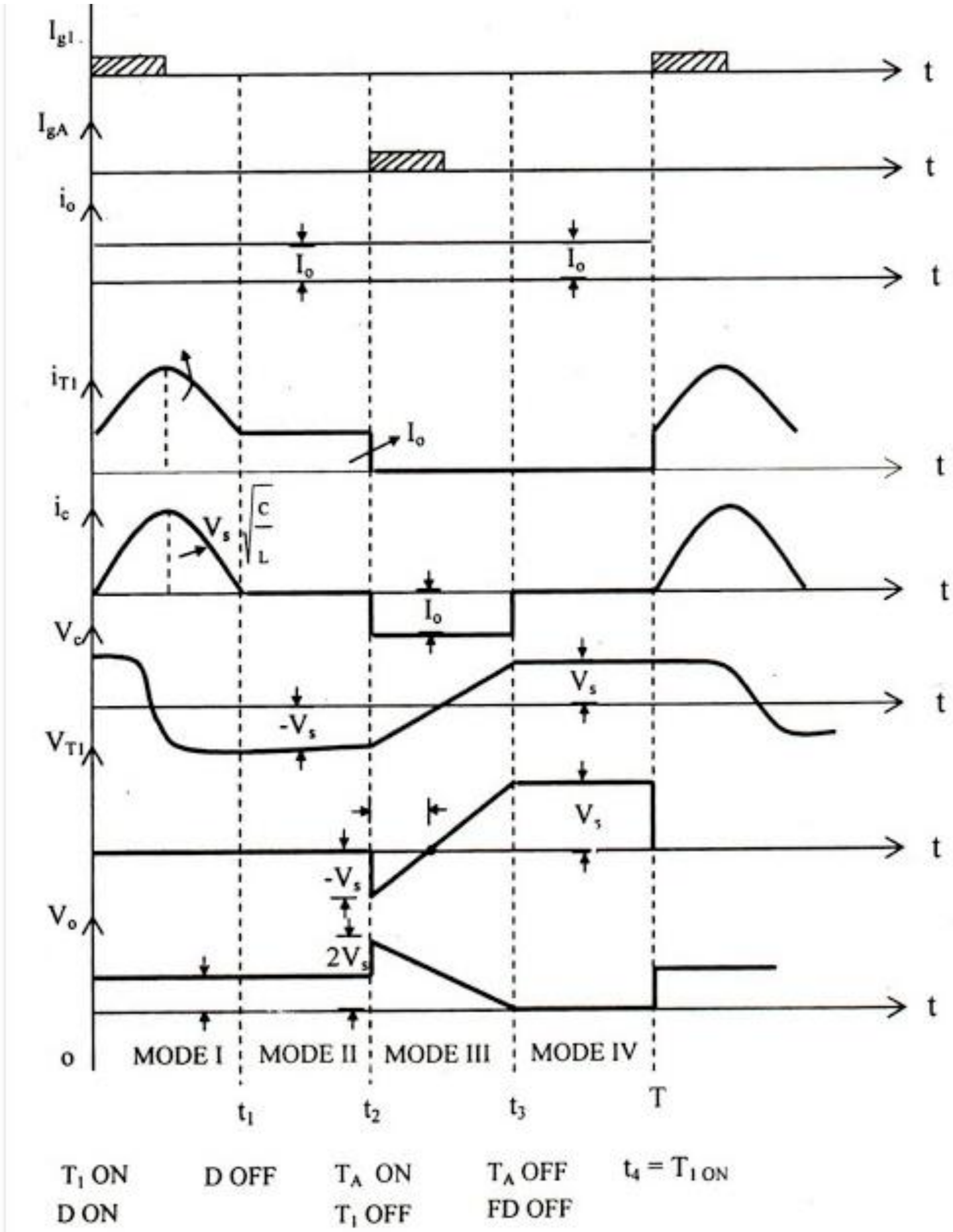
- Similar to step down chopper.
- T1 = Main thyristor, TA = Auxiliary thyristor, L,C = commutating components, Rc = charging resistor
- Assume output current is constant.
- Close the switch, initially capacitor short circuited, after 4 - 5 time constants, Vc = Vs.
- At t = 0, T1 is on, load is connected across the supply Vo = Vs.
- Tank circuit starts conduction (diode forward bias).
- After conduction polarities across capacitor are changed.
- D is reverse biased polarities across capacitor are changed.
- Upto t2 we completed now we have to turn off the main thyristor.



- Make TA on, T1 to be off (applying reverse voltage).
- To make the conduction continues use free wheeling diode.
- In order to make the output continuous, the existing path will be changed as Vs, C, TA and the load.
- Voltage across the capacitor changes.
- Now make the voltage across capacitor > Vs.
- Free wheeling diode conducts, output voltage becomes zero.
- To start next cycle, no need to close switch 's'.
- A reverse voltage is applied across conducting SCR due to which current through SCR becomes zero and it is getting off. Hence it is called voltage commutation.
- Other name of this is impulse commutation. It is because a high reverse voltage will turn off the SCR.

Limitations of voltage commutated chopper:

1. A starting circuit is required.
2. load voltage at once rises to 2Vs at the instant commutation of main SCR is initiated.
3. It can't work at no load. It is because at no load, capacitor would not get charged frm -Vs to Vs when auxiliary SCR is triggered for commutating the main SCr.
4. Main thyristor is required to carry current more than load current. So, it is to be over rated.



- The values of commutating components C and L can be obtained.
- The values depend upon turn off time of main thyristor T1. during tc capacitor voltage changes from -Vs to zero linearly.

$$ic = C\, dV / dt \quad \text{for a constant load current Io.}$$

$$Io = C \,.\, Vs / tc$$

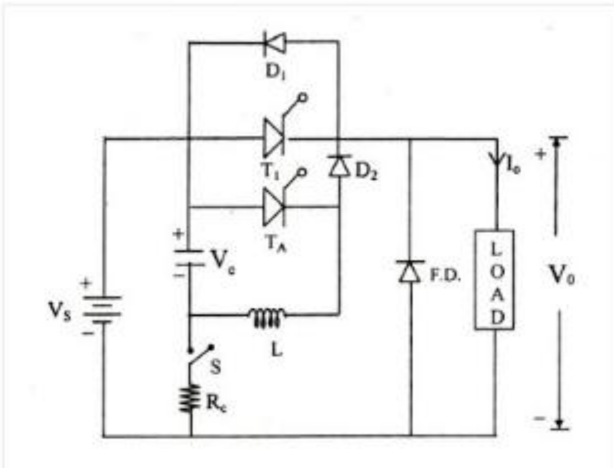
$$C = Io \,.\, tc / Vs$$

- The commutation circuit turn off time tc must be greater than thyristor turn off time.

- Load current should not be too large.

$$T_{om}' = T_{ON} + \frac{2CV_S}{I_o}$$

Current Commutated Chopper:



- Capacitor is charged to Vs, main thyristor T1 is fired at t = 0. So that load voltage Vo = Vs.
- At t = t1, auxiliary thyristor is turned on to commutate main thyristor.
- With turning on of TA, an oscillatory current ic is set up in the circuit.

$$i_c = \frac{V_s}{\omega_o L} \sin \omega_o t = V_s \sqrt{\frac{C}{L}} \sin \omega_o t.$$

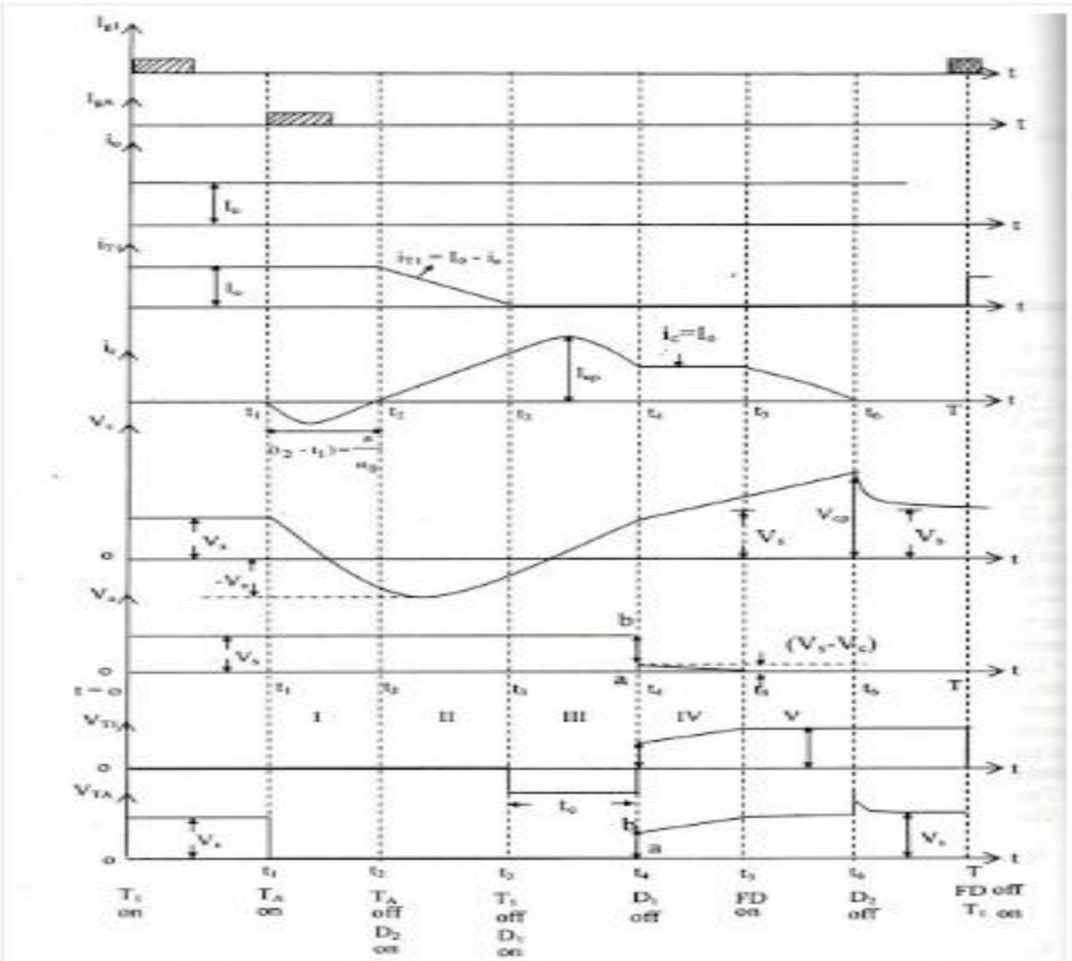
- At t2, Vc = - Vs and ic tends to reverse in the auxiliary thyristor TA, it gets naturally commutated.
- As TA is reverse biased and turned off at t2. Oscillatory current ic begins to flow through C, L, D2 and T1.
- At t3 ic rises to io so that iT1 = 0. As a result main SCR T1 is turned off at t3. Since oscillating current through T1 turns it off it is called current commutated chopper.
- After t3 ic supplies load current io and the excess current. iD1 = ic - Io is conducted through diode D1.
- Afetr t4, a constant current equal to Io flows through Vs, C, L, D2 and load.
- Capacitor c is charged linearly to source voltage Vs at t5, so during time (t5 - t4) ic= Io.
- In this commutation an opposite current pulse will be injected through SCR. As a result currents decreases and finally comes to zero if both the currents would be equal and opposite.

- Anti parallel diode is useful to apply the reverse voltage after current through SCR becomes to zero. The value of reverse voltage is low. So
    1. Turn off time increases.
    2. Turn off power loss increases.

$$L = \frac{V_s . t_c}{(x I_0)\left[\pi - 2 \sin^{-1}\left(\frac{1}{x}\right)\right]} \qquad \text{where } x = \frac{I_{cp}}{I_o}$$

$$C = \frac{(x\ I_o) t_c}{V_s\left[\pi - 2 \sin^{-1}\left(\frac{1}{x}\right)\right]}$$

- Jones chopper employes the principle of voltage commutation.
- Morgan's chopper based on the principle of current commutation.



Current and Voltage waveforms for current commutated chopper

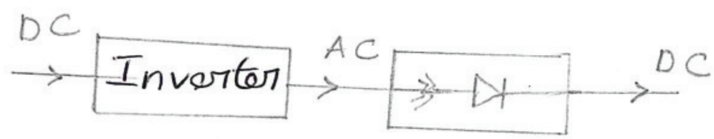
UNIT - 3

DC TO DC CHOPPER

* Many Industrial Applns. require power from dc voltage source.
⇒ Subway cars, trolley buses

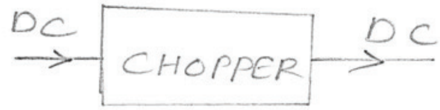
Two types of dc to dc converters :-

(i) Ac Link chopper



→ dc is first converted to ac by an inverter (dc to ac converter)
→ Ac is then stepped-up or stepped-down by a transformer which is converted back to dc by a diode rectifier.
* Conversion takes place in two steps so this ac link chopper is
→ Costly
→ bulky
→ less efficient

(ii) DC CHOPPER :-

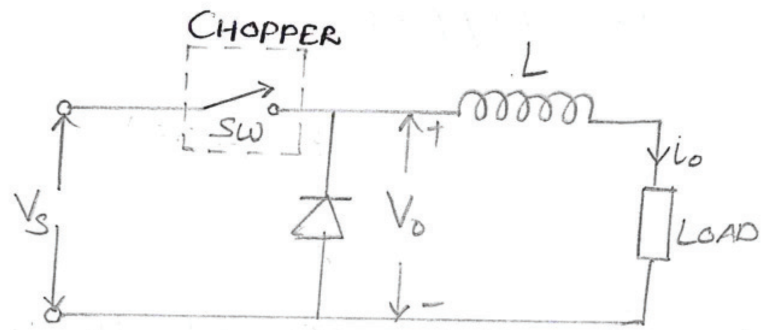


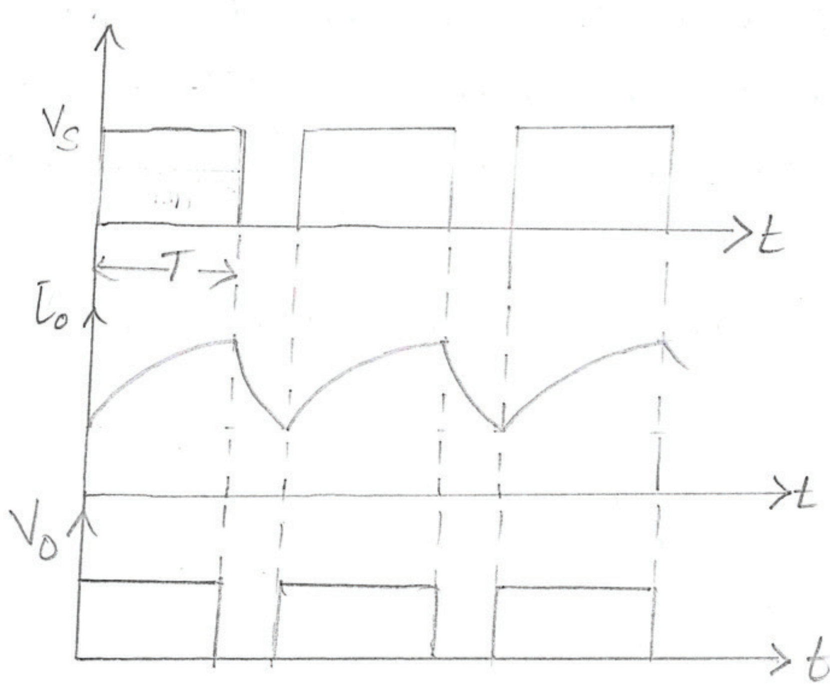
→ Direct Conversion (one stage Conversion)

* Fixed dc input voltage to a variable dc o/p voltage directly.

→ Power BJT, Power MOSFET, GTO or IGB

STEP DOWN CHOPPERS :-





* A chopper is a high speed on/off Semiconductor switch.

* It connects source to load & disconnects the load from source at a fast speed.

* Chopper (switch) may be turned ON or OFF as desired.

* During the period T_{ON}, the chopper is ON and the load vge is equal to the source voltage V_S.

* During the period T_{OFF}, the chopper is OFF & the load current flows through the freewheeling diode FD.

* During T_{OFF}, the load terminals are short circuited by FD & load vge is therefore zero.

⇒ During T_{ON} → load current rises
T_{OFF} → load current decays.

Avg. load voltage, $V_o = \frac{T_{on}}{T_{on} + T_{OFF}} V_s$

$$V_o = \frac{T_{on}}{T} V_s = \alpha V_s$$

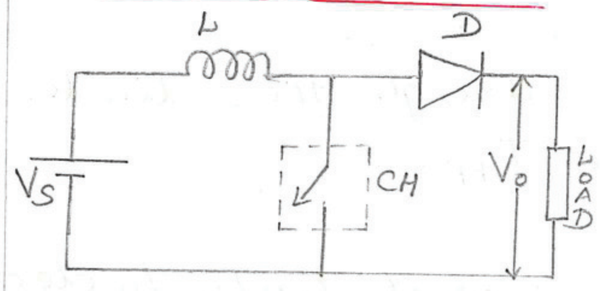
$T_{on} \rightarrow$ on-time

$T_{OFF} \rightarrow$ Off-time

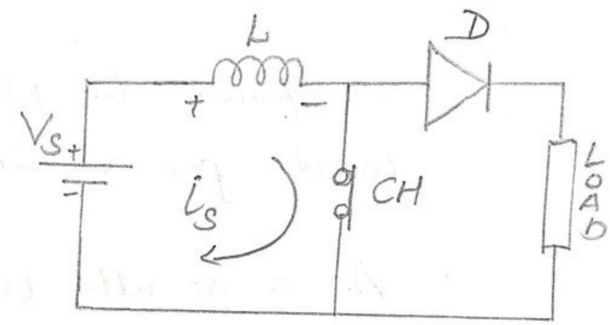
$T = T_{on} + T_{OFF}$ (Chopping Period)

$\alpha = \frac{T_{on}}{T}$ (Duty cycle)

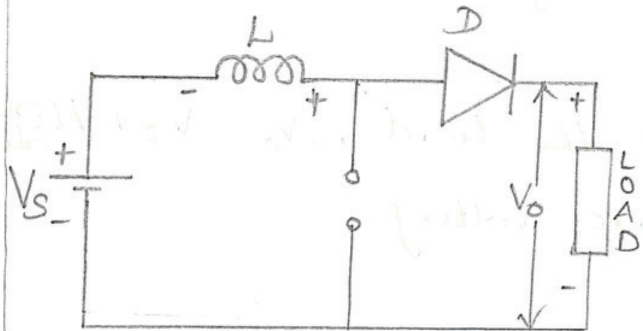
STEP UP CHOPPERS :-



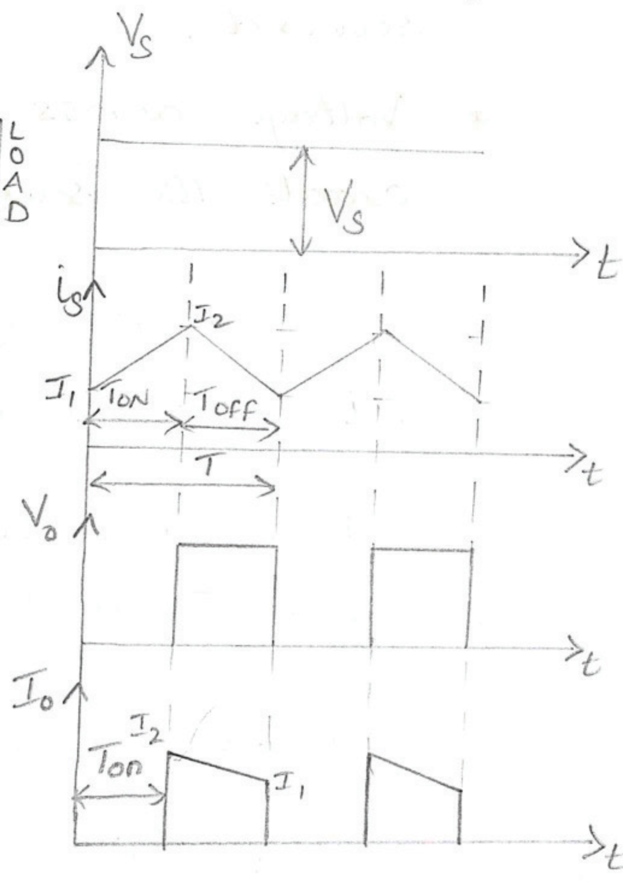
(a) Step-up chopper



(b) L stores charge



$L\frac{di}{dt}$ is added to V_s.



* Avg. o/p voltage V_o greater than the input voltage V_S.

$$V_o > V_S.$$

⇒ Called as step-up chopper.

* Inductor 'L' in series with source vge V_s.
* When CH is ON, the inductor stores the energy.
* During T_{ON} → L stores the energy.

* When chopper CH is off inductor current can't die down instantaneously, the current is forced to flow through the diode & load for a time T_{OFF}.

* As a result the current tends to decrease, polarity of the emf induced in L is reversed.

* Voltage across the load, $V_o = V_S + L\left(\frac{di}{dt}\right)$ exceeds the source voltage.

⇒ When CH is ON, the current thru. the inductance L would ↑se from I_1 to I_2.

⇒ When CH is OFF, current would fall from I_2 to I_1.

⇒ CH → ON → $V_S = V_L$

CH → OFF → $V_L = V_0 - V_S$

V_L → Vge across L.

Avg. o/p vge, $V_o = V_S\left(T/T_{OFF}\right)$

$$V_o = V_S\left(\frac{1}{1-\alpha}\right)$$

Types Of CHOPPERS

(i) First quadrant (or) Type-A chopper

(ii) Second quadrant (or) Type-B chopper

(iii) Two quadrant type A chopper (or) Type C chopper

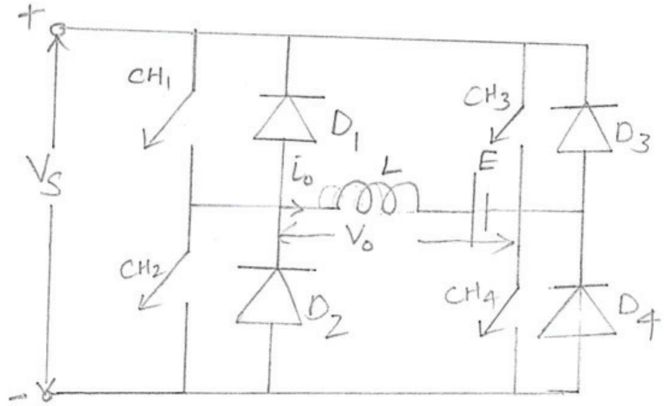
(iv) Two-quadrant Type B chopper (or) Type D chopper

(V) Four quadrant chopper (or) Type E chopper.

Four Quadrant Chopper (or) Type E chopper:-

→ 4 Semiconductor switches CH_1 to CH_4

→ 4 Diodes D_1 to D_4 is antiparallel.



TYPE-E CHOPPER load emf E

First Quadrant :-

For first quadrant operation,

CH_4 kept ON
CH_3 kept OFF & CH_1 is operated.

* CH_1 & CH_4 → ON → $V_o = V_S$; load current i_o begins to flow.

* V_o & I_o are +ve (I quadrant)

⇒ When CH_1 is turned off, positive current freewheels through CH_4, D_2.

Second Quadrant :-

* CH_2 is operated
* CH_1, CH_3 & CH_4 kept off.
* With CH_2 ON reverse (or negative) current flows through L, CH_2, D_4 & E
* L stores energy during the time CH_2 is ON
* When CH_2 is turned OFF, current is fed back to sources thru. diodes D_1, D_4.
* $(E + L\frac{di}{dt})$ is more than source voltage V_s.

* Load Voltage V_0 is positive
I_0 is negative

⇒ Second quadrant operation of chopper.

* Power is feed back from load to source.
* "Step-up chopper"

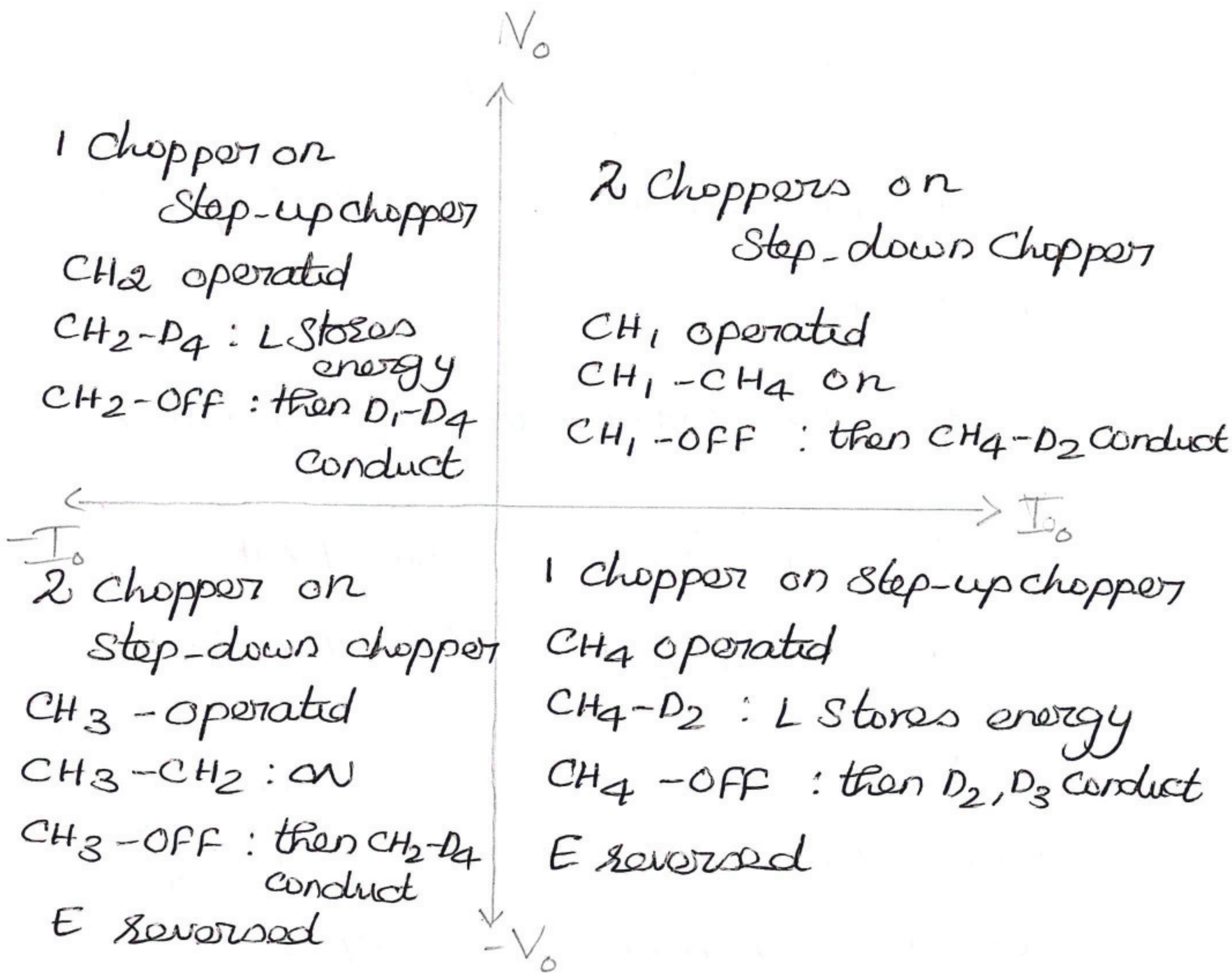
Third Quadrant :-

* CH_1 is kept off, CH_2 is kept on & CH_3 is operated.
* CH_3 is ON, load gets connected to source V_S, Both V_0, I_0 are negative

⇒ Third Quadrant operation.

* CH_3 → turned off, negative current freewheels through CH_2, D_4.
* Load Voltage V_0 is negative
I_0 is negative

"Step-down chopper".



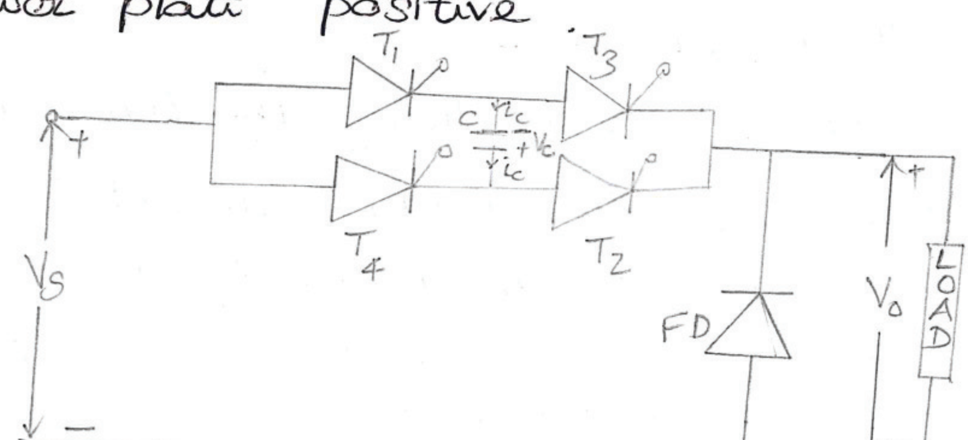
Fourth Quadrant :-

* CH_4 is operated & other devices are OFF.
* CH_4 is ON, Positive current flows through CH_4, D_2, L & E.
* L stores energy during the time CH_4 is ON.
* When CH_4 → turned OFF, current is fed back to source through diodes D_2, D_3.
* V_o → negative & I_o → Positive
* Power is fed back from Load to source

⇒ Chopper Operates as "Step Up Chopper".

Load Commutated Chopper :-

* It consists of 4 thyristors T_1, T_2, T_3 & T_4
* One Commutating capacitor c.
* T_1, T_2 ⇒ ONE PAIR
* T_3, T_4 ⇒ ANOTHER PAIR
* When T_1 T_2 are conducting they are main thyristors, whereas T_3 T_4 & c act as commutating components.
* FD is the freewheeling diode across the load.
* Initially capacitor 'c' is charged to a voltage V_s with upper plate negative & lower plate positive.



Load Commutated Chopper

Working Of Load-Commutated Chopper can be explained in various modes.

Mode I :-

* 'C' charged with lower plate p...

the load commutated chopper is ready for operation.

* At $\underline{t=0}$, the thyristor pair T_1, T_2 is triggered. the load current flows through V_S, T_1, C, T_2 & load, so the load voltage atonce shoots to $V_0 = V_S + V_C = 2V_S$.

* Load current now flows from source to load.

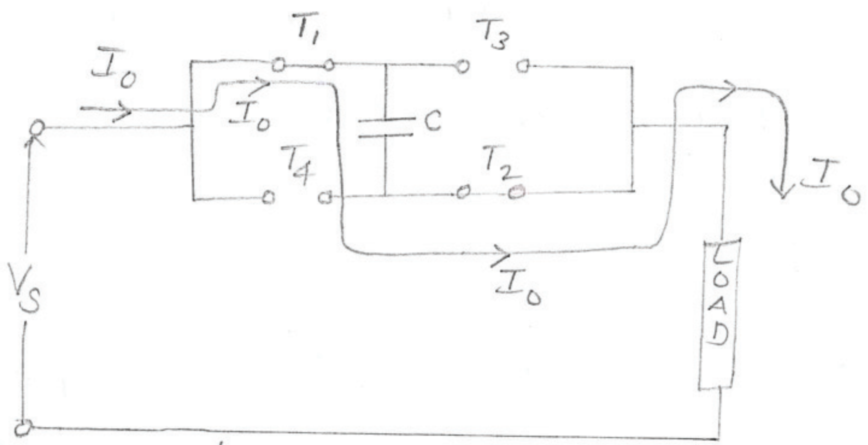
* The capacitor 'C' is charged linearly by constant load current I_0 from V_S at $t=0$ to $(-V_S)$ at t_1.

* When the capacitor voltage becomes $(-V_S)$, the load voltage falls from $2V_S$ to $\boxed{V_0 = V_S - V_S = 0}$

* At $t=0$, when T_1, T_2 are turned ON, T_3 & T_4 are reverse biased by capacitor voltage.

ie) at $t=0$, $V_{T3} = V_{T4} = -V_S$.

at $t = t_1$, $V_{T3} = V_{T4} = V_S$ (T_3, T_4 forward biased at t_1).



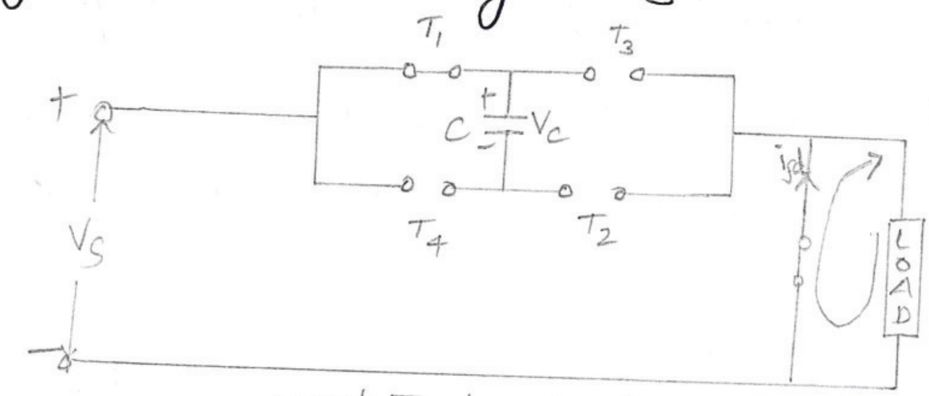
mode I , $0<t<t_1$

Mode II :-

* At t_1, Capacitor C is slightly overcharged as a result freewheeling diode gets forward biased & load current is transferred from T_1, T_2 to FD.

* From t_1 onwards load current freewheels through FD.

* During $(t_2 - t_1)$, $V_c = -V_S$, $V_0 = 0$, $i_c = 0$, $i_{fd} = I_0$, $i_{T_1} = i_{T_2} = 0$; $V_{T_3} = V_{T_4} = V_S$ & $V_{T_1} = V_{T_2} = -\Delta V_S$ as capacitor is overcharged by a small voltage ΔV_S.



mode II $t_1 < t < t_2$

Mode III :-

* At t_2 , T_3 & T_4 is triggered load voltage $V_0 = V_S + V_C = 2V_S$.

* T_1 & T_2 ⇒ reverse biased by V_C , this pair is turned off at t_2 .

* load current flows through V_S , T_4 , C, T_3 & load charges capacitor linearly from $(-V_S)$ at t_2 to V_S at t_3 .

⇒ Load voltage falls from $2V_S$ at $t_2 = 0$ at t_3

* $t_3 - t_2$ ⇒ $i_c = -I_0$

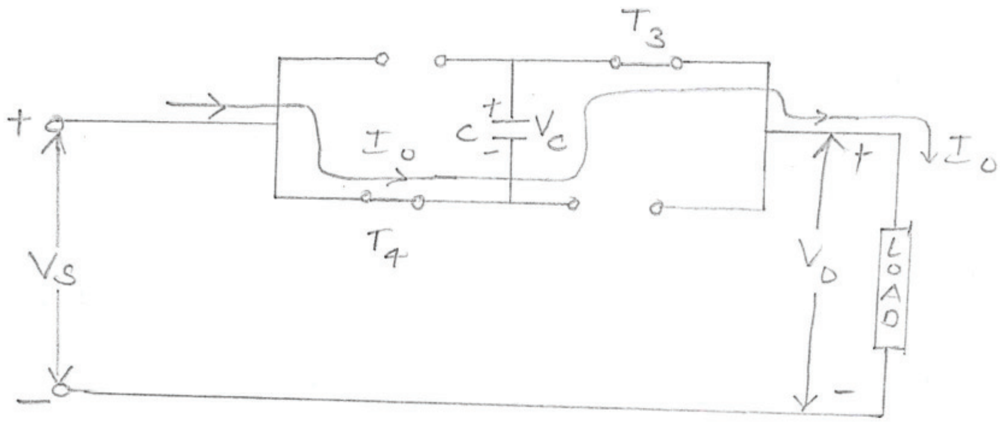
$$i_{T_3} = i_{T_4} = I_0$$

But $V_{T_1} = V_{T_2} = -V_S$ at t_2 & V_S at t_3

∴ T_1 , T_2 gets forward biased at t_3 .

* At t_3 capacitor 'c' is overcharged, FD gets forward biased & therefore after t_3 , load current freewheels through FD & load.

⇒ When T_1 , T_2 are turned on at t_4 mode I repeats.



mode III $t_2 < t < t_3$

Design Of Commutating Capacitance :-

* For a constant load current I_o, Capacitor voltage changes from $-V_s$ to V_s in time T_{on} i.e) total change in vge is $2V_s$ in time T_{on}.

$$I_o = C \frac{2V_s}{T_{on}}$$

(or) $$C = \frac{I_o T_{on}}{2V_s} \longrightarrow (1)$$

O/P voltage, $V_o = \frac{1}{2}(2V_s) T_{on} \cdot \frac{1}{T}$

$$V_o = V_s T_{on} f \cdot \longrightarrow (2)$$

Sub $T_{on} = \frac{2V_s C}{I_0}$ in eqn (2)

$$V_o = V_s f \cdot \frac{2CV_s}{I_0}$$

$$V_o = \frac{2V_s^2 C f}{I_0}$$

Min. chopping period, $T_{min} = T_{on}$

∴ Max. chopping freq,

$$f_{max} = \frac{1}{T_{min}} = \frac{1}{T_{on}}$$

From eqn ① ⇒ $C = \frac{I_0}{2V_s} \cdot \frac{1}{f_{max}}$

The circuit turn off time

$$t_c = \frac{1}{2} T_{on} = \frac{1}{2} C \frac{2V_s}{I_0}$$

$$t_c = \frac{CV_s}{I_0}$$

Total commutation interval, $T_{on} = \frac{2CV_s}{I_0}$.

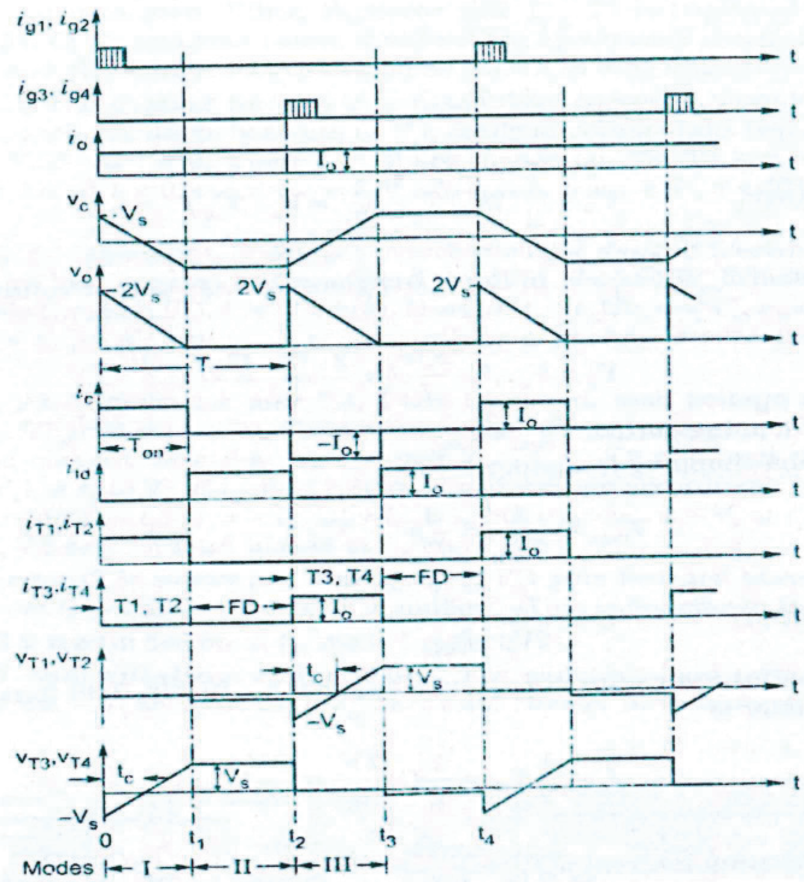


Fig. 7.33. Voltage and current waveforms for a load-commutated chopper.

Merits :-

(i) Capable of commutating any amount of load current.

(ii) No commutating inductor is required

(iii) Can work at high frequency so filtering requirements are minimal.

Demerits :-

(i) Peak load Voltage is equal is twice the supply voltage. This can be re[illegible] by filtering.

(ii) For high power applications, efficiency may become low becoz. of higher switching losses at high operating freq.

(iii) Freewheeling diode is subjected to twice the supply voltage.

(iv) Commutating capacitor has to carry full load current at a freq. of half the chopping freq.

(v) One pair of SCRs should be turned on only when the other pair is commutated.

PROBLEM :-

For a type A chopper a dc vge source = 230 V, load resistance = 10 Ω. Take a voltage drop of 2 V across chopper when it is on. For a duty cycle of 0.4. Calculate

a) Average & rms values of o/p vge

b) Chopper efficiency.

Soln :-

* When chopper is on, o/p voltage is $(V_s - 2)$ volts & during the time chopper is OFF, o/p vge = 0.

$\therefore$ Avg. o/p vge $= \dfrac{(V_s - 2)T_{on}}{T} = \alpha(V_s - 2)$

$= 0.4(230-2) = 91.2V$

RMS value of o/p voltage,

$$V_{rms} = \left[(V_s - 2)^2 \frac{T_{on}}{T}\right]^{1/2} = \sqrt{\alpha}\,(V_s - 2)$$

$= \sqrt{0.4}\,(230-2)$

$= 144.2$ V

(b) Power o/p (or) Power delivered to load,

$$P_o = \frac{V_{rms}^2}{R} = \frac{(144.2)^2}{10} = 2079.364W$$

Power i/p to chopper, $P_i = V_S I_o$

$$= 230 \times \frac{91.2}{10}$$

$$P_i = 2097.6W$$

$$\text{Chopper efficiency} = \frac{P_o}{P_i} = \frac{2079.364}{2097.6} \times 100$$

$$= 99.13\%$$

UNIT - 4

INVERTERS

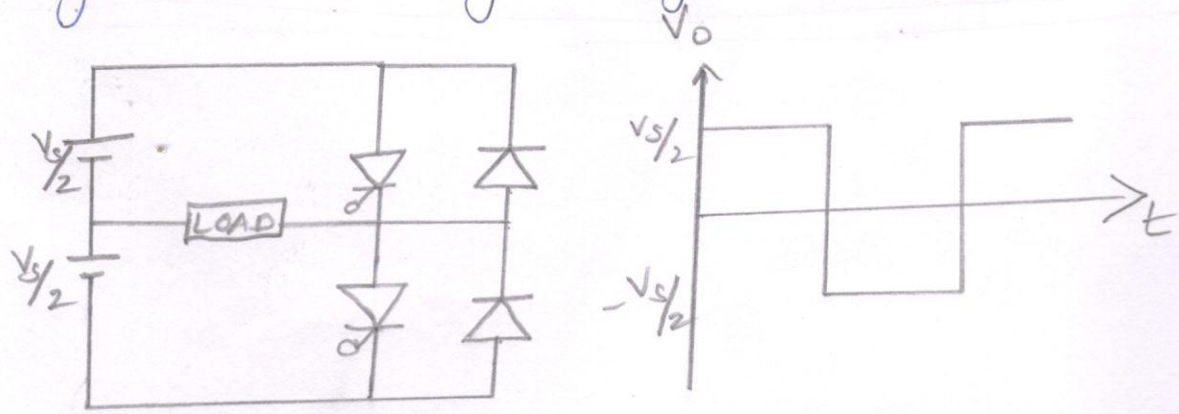
A device that converts dc power into ac power at desired o/p vge & freq. is called as an INVERTER.

- Classification
  - (i) Bridge Inverter
  - (2) Series Inverter
  - (3) Parallel Inverter.

1, (1) Single-Phase Vge Source Inverters:-

- * 1φ Half-bridge inverter
- * 1φ Full bridge inverter.

Single Phase Half-bridge Inverter :-



* 2 SCRs, 2 diodes & three-wire supply
* $0 < t \leq T/2 \Rightarrow T_1$ conducts & load is subjected to a vge $V_s/2$ due to the upper vge source $V_s/2$.
* At $t = T/2$ thyristor T_1 is commutated & T_2 gated on.
* $T/2 < t \leq T$, T_2 conducts & the load is subjected to a vge $(-V_s/2)$ due to lower vge source.

Disadvantage :-

→ requires 3-wire dc supply.

$$V_0 = \begin{cases} V_s/2 & 0 < t << T/2 \\ -V_s/2 & T/2 < t < T \end{cases}$$

2, Voltage Control In Single Phase Inverters :-

* Ac loads may require constant or adjustable vge at their i/p terminals.

Various Methods :-

(a) External control of ac o/p vge.

(b) External control of dc i/p vge

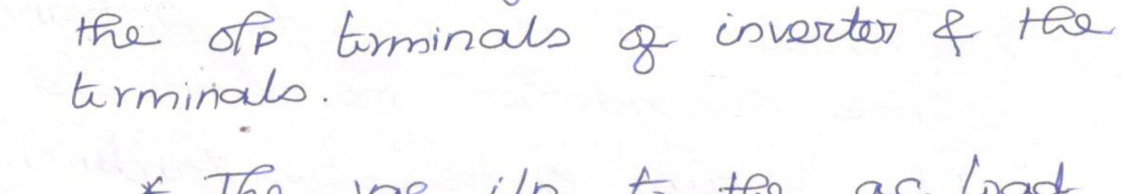
(c) Internal control of inverter.

(a) External Control of AC o/p vge

(i) AC vge control

(ii) Series - inverter control.

(i) Ac Vge Control :-



* An ac vge controller is inserted b/w the o/p terminals of inverter & the load terminals.

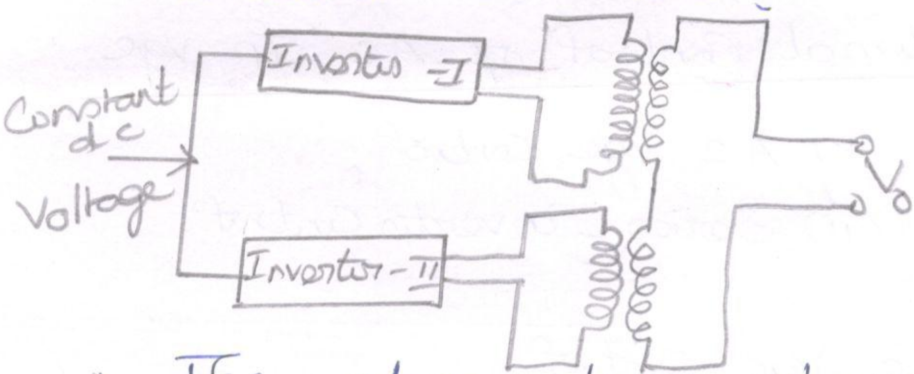
* The vge i/p to the ac load is regulated thru. the firing angle control of ac vge controller.

* This method gives rise to higher harmonic content in the o/p vge; particularly when o/p vge from the ac vge controller is at low level.

→ rarely employed except for low power applns.

(ii) Series - inverter Control :-

* Involves the use of two or more inverters in series



* The above diag. shows how the o/p vge of two inverters can be summed up with the help of transformers whose o/p vge can be adjusted.

⇒ Inverter o/p is fed to 2 transformers whose secondaries are connected in series.

* Phasor sum of the two fundamental vge V_{01}, V_{02} gives the resultant fundamental vge V_0.

$$V_0 = \left[V_{01}^2 + V_{02}^2 + 2 V_{01} V_{02} \cos\theta\right]^{1/2}$$

Advantages :-

(i) o/p vge w/f & its harmonic content are not affected appreciably as the inverter o/p vge is controlled thru. the adjustment of dc i/p vge to the inverter

Disadvantages :-

(i) The no. of power converters used for the control of inverter o/p vge varies from two or three. More power handling stages result in more losses & reduced η of the entire scheme.

(ii) Filter circuit is required in all types of schemes, which ↑ses the cost, weight & size & at the same time reduces the η & makes the transient response sluggish.

(iii) As the dc i/p is ↓sed, the commutating capacitor vge also ↓ses. This has the effect of reducing the ckt turn-off time $\left(t = C\frac{V}{I}\right)$ for the SCR for a constant load current.

* Control of dc i/p vge is not conductive for a large variation of o/p vge for a constant load current.

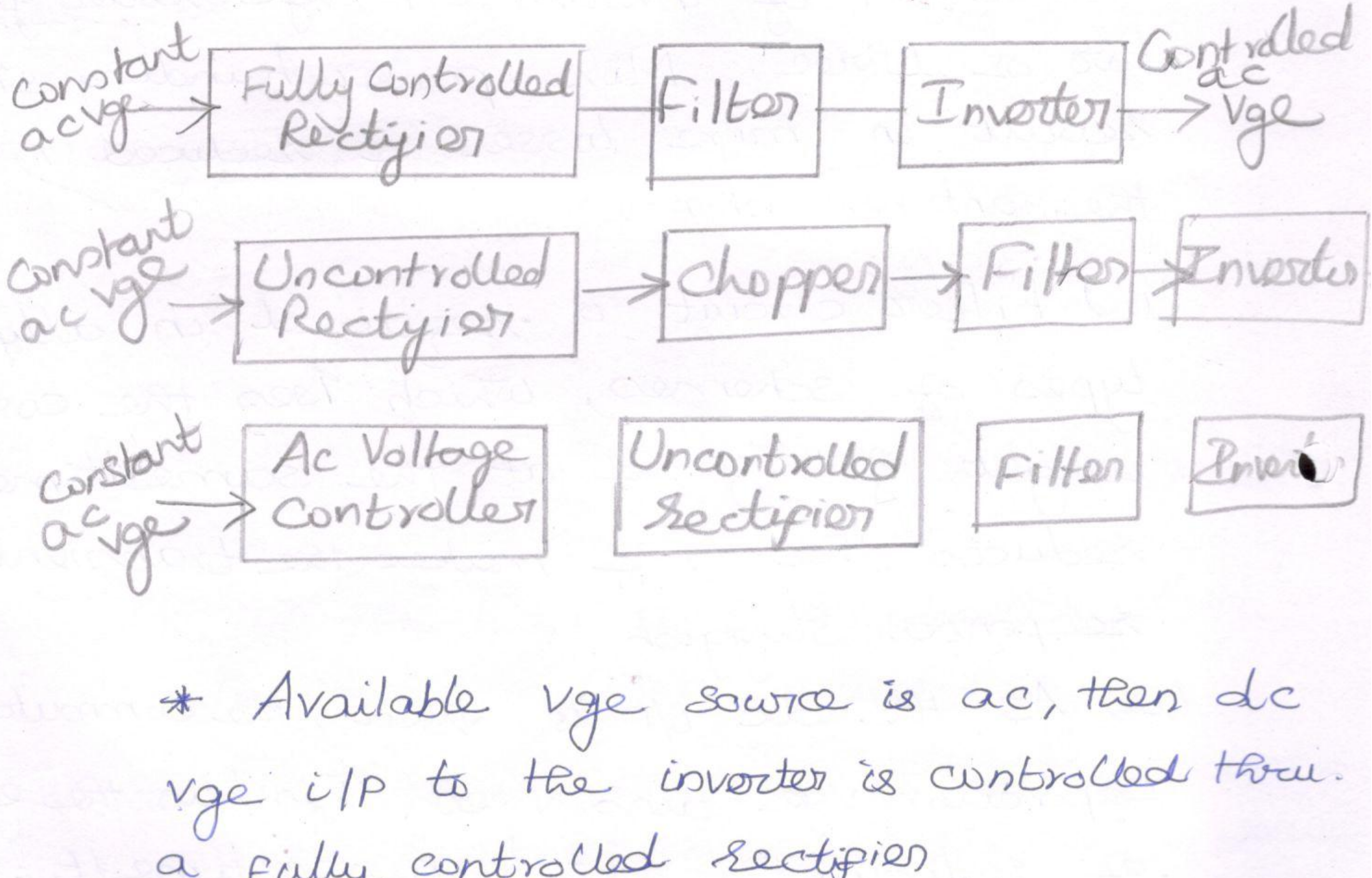
* Freq. of o/p vges V_{01}, V_{02} from the two inverters is the same.

=> when $\theta = 0$; $V_0 = V_{01} + V_{02}$ &

$\theta = \pi$ $V_0 = 0$ in case $V_{01} = V_{02}$

* Angle θ can be varied by the firing angle control of 2 inverters.

(b) External Control of DC i/p vge :-



* Available vge source is ac, then dc vge i/p to the inverter is controlled thru. a fully controlled rectifier.

(c) Internal Control of Inverters :-

→ The most efficient method of doing this is by pulse-width modln. control used within an inverter.

Pulse Width modln. Control

→ In this method, a fixed dc i/p vge is given to the inverter & a controlled ac o/p vge is obtained by adjusting the ON & OFF periods of the inverter components.

* Most popular method of controlling the o/p vge & termed as PWM control.

Advantages :-

→ o/p control can be obtained without any additional components.

→ Lower order harmonics can be eliminated or minimised along with its o/p vge control.

→ As higher order harmonics can be eliminated or minimised or filtered easily.

Disadvantage :-

* SCRs are expensive as they must possess low turn-on & turn-off times.

3, Current Source Inverters :-

* i/p current -> constant but adjustable
* Amp. of o/p current from CSI is independent of the load.
* mag. of o/p vge is dependent upon the nature of load.

⟹ CSI converts the i/p dc current to an ac current at its o/p terminals.

* O/P freq. depends upon the rate of triggering the SCR.

Applns :-

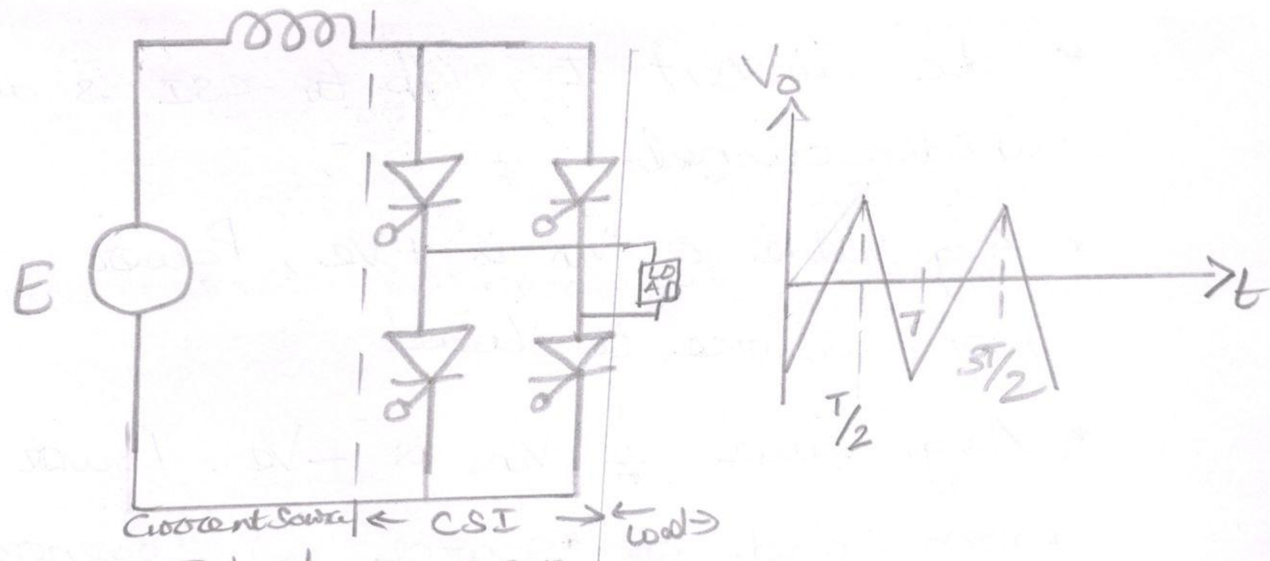
(i) Speed Control of ac motors
(ii) Induction heating
(iii) Lagging VAr Compensation
(iv) Synchronous motor starting

Single-phase CSI with Ideal Switches:-

→ A thyristor is assumed as an ideal switch with zero commutation time.

* Source consits of a vge source E & large inductance 'L' in series with it.

* Function of high-impedance reactor in series with vge source is to maintain a constant current source at the i/p terminals of CSI.



Ideal 1φ CSI

* $T_1 T_2$ → ON, i_0 is +ve $i_0 = I$.

$T_3 T_4$ → ON, i_0 is −Ve & $i_0 = -I$.

* O/P current i_o is a square w/f of amplitude equal to dc i/p current I.

* Assume load consists of a capacitor 'C'

$$i_o = C\frac{dv_o}{dt}$$

$i_o \rightarrow$ constant & slope must be constant over every half cycle.

* This slope is +Ve from 0 to T/2
  & -Ve from T/2 to T.

* dc current I, i/p to CSI is always unidirectional.

* Avg. value of V_{in} is +Ve, Power flows from source to load.

* Avg. Value of V_{in} is -Ve, Power flows from load to source i.e) regeneration of power takes place.

⇒ CSI may be load or force commutated.

* Load commutation possible when load pf is leading.

* Forced commutation for load pf lagging

4) Series Inverters :-

* Inverters in which commutating components are permanently connected in series with the load are called series inverters.

* The series ckt should be underdamped.

* Self commutated (or) Load commutated inverters.

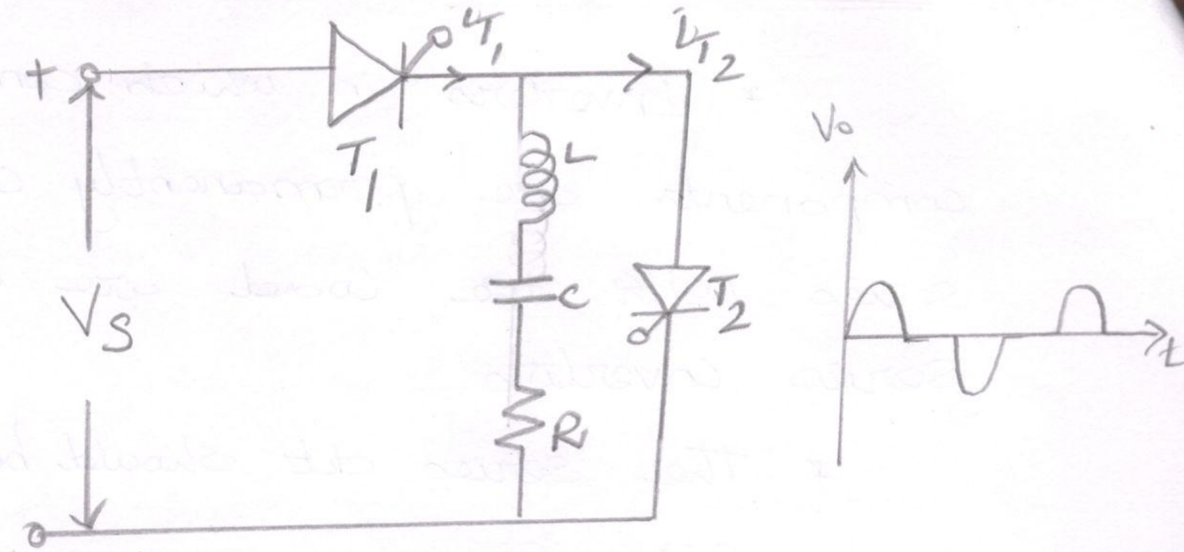
* Operate at HF (200 Hz to 100 kHz).

Basic Series Inverter :-

* Consists of load resistance R in series with components i.e. commutating components L & C.

* Values of L & C are chosen so that it forms underdamped ckt.

* T_1 T_2 turned on appropriately so that o/p vge. of desired freq. can be obtained.



* When T_1 turned ON, with T_2 turned off current i starts builing up in the RLC ckt.

* Since ckt is underdamped load current after reaching some peak value decays to zero at point a.

* At point 'a' load current tends to reverse, SCR T_1 is turned off.

* After instant a, some min. time $t_{q,min}$ must elapse for T_1 to regain its f/d blocking capability.

$$t_{q,min} = \frac{\pi}{\omega} - \frac{\pi}{\omega_r} = \frac{1}{2}\left(\frac{1}{f} - \frac{1}{f_r}\right)$$

$\omega \rightarrow$ o/p freq. in rad/sec

$\omega_r \rightarrow$ ckt ringing freq. in rad/sec.

* time interval b/w T_2 turned ~~off~~ ON & T_1 turned off is indicated by $T_{off} = ab$

$T_{off} > t_{q\text{-}min}$.

* After T_1 has commutated, upper plate of capacitor attains +ve polarity.

* When T_2 is turned on at instant b, capacitor begins to discharge & load current in the reversed direction builds up to some peak negative value & then decay to zero at instant c.

* After this time $T_{off} = cd$ must elapse for T_2 to recover.

* At d, T_1 is again turned on & the process repeats.

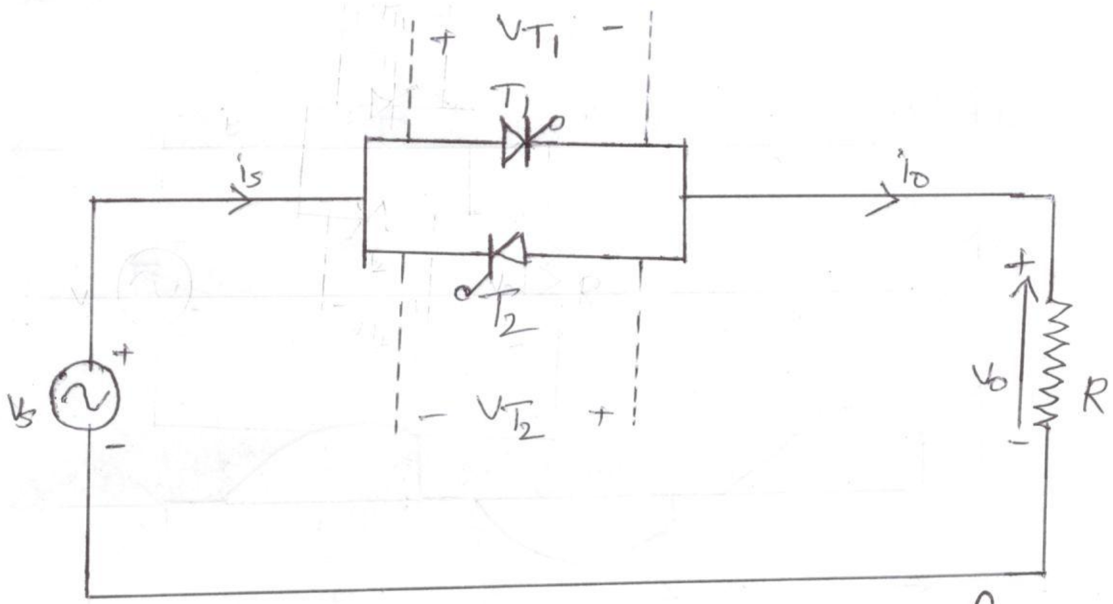
⟹ In this way, dc is converted to ac with the help of series inverter.

* C stores charge in one half cycle & releases the same amt during next half cycle.

UNIT – V

Single Phase full wave AC voltage controller with R-Load.

⇒ In a single Phase full wave AC voltage controller, two thyristors are connected in antiparallel.

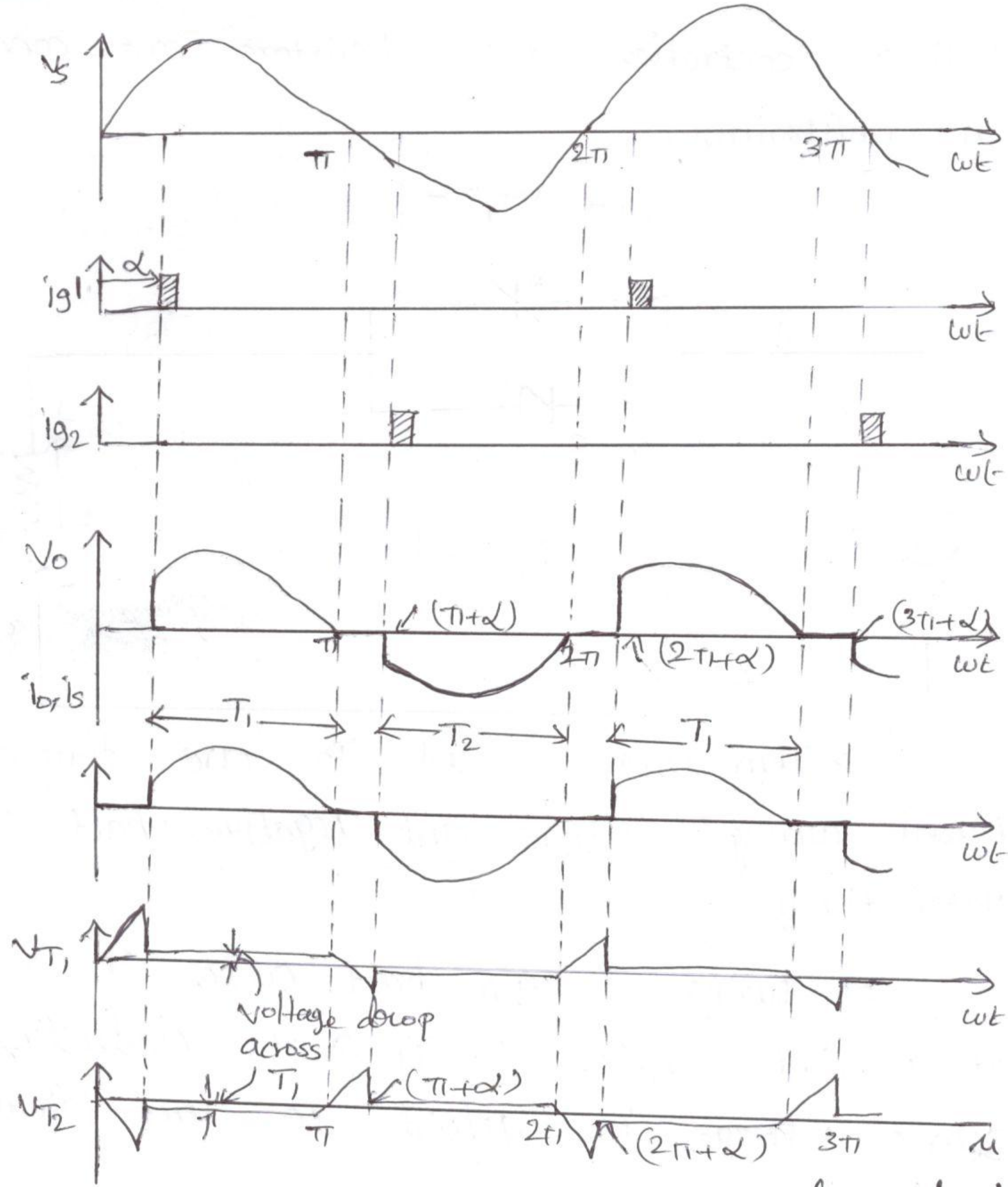


⇒ Thyristors T_1 and T_2 are forward biased during Positive and negative half cycles respectively.

⇒ During positive half cycle, T_1 is triggered at a firing angle α. T_1 starts conducting and source voltage is applied to load from α to π.

⇒ At π, both V_o, i_o falls to zero. Just After π, T_1 is subjected to reverse bias, it is therefore turned off.

⇒ During negative half cycle, T_2 is triggered at $(\pi+\alpha)$. T_2 conducts from $\pi+\alpha$ to 2π. Soon after 2π, T_2 is subjected to a reverse bias, it is therefore turned off.



⇒ From zero to α, T_1 is forward biased, V_{T_1} is therefore $V_{T1} = V_s$. From α, T_1 conducts, V_{T_1} is reverse biased by about 1V. After π, T_1 is source voltage, therefore $V_{T1} = V_s$ from π to $\pi+\alpha$.

⇒ From $\pi+\alpha$ to 2π, T_2 conducts; T_1 is therefore reverse biased by voltage drop across T_2 which is about 1V. The variation of voltage V_{T2} across T_2 is same as that of voltage variation V_{T1} across T_1.

⇒ If $V_s = \sqrt{2}\, V_s \sin\omega t$ is the input voltage, and the firing angles of thyristors T_1 and T_2 are equal ($\alpha_1 = \alpha_2 = \alpha$), the RMS output voltage is,

$$V_0 = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi} 2V_s^2 \sin^2\omega t \, d\omega t\right]^{1/2}$$

$$= \left[\frac{4V_s^2}{4\pi}\int_{\alpha}^{\pi}\left[1-\cos 2\omega t\right] d\omega t\right]^{1/2}$$

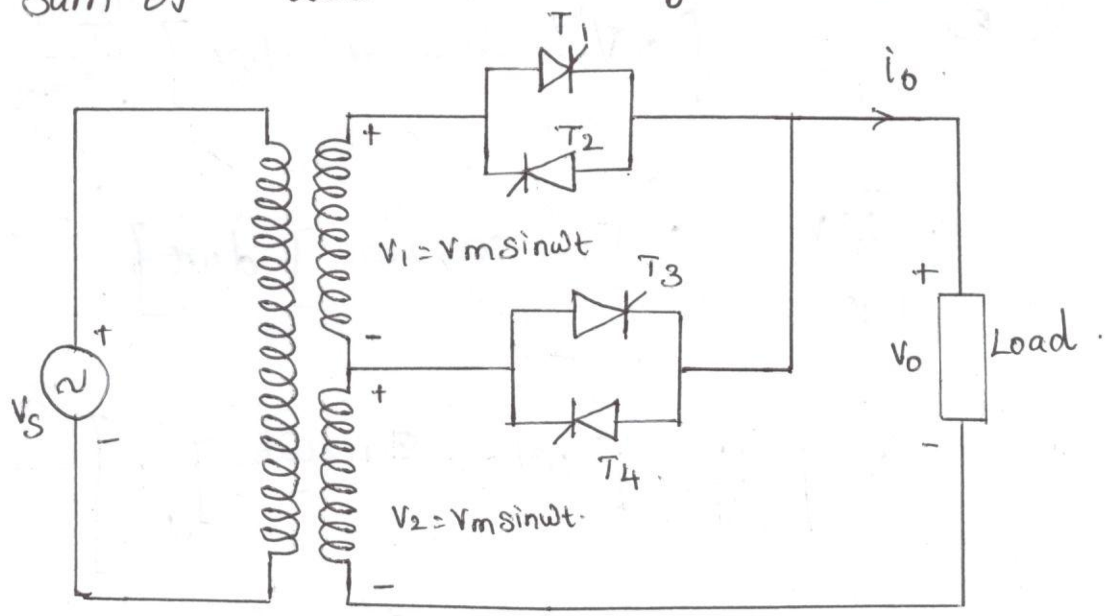
$$= V_s\left[\frac{1}{\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right]^{1/2}$$

$$= V_s\left[\frac{1}{\pi}\left[\pi - \frac{\sin 2\pi}{2}^{\,\nearrow 0} - \alpha + \frac{\sin 2\alpha}{2}\right]\right]^{1/2}$$

$$\boxed{V_0 = V_s\left[\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right]^{1/2}}$$

Two Stage Sequence control of voltage controller with R-Load.

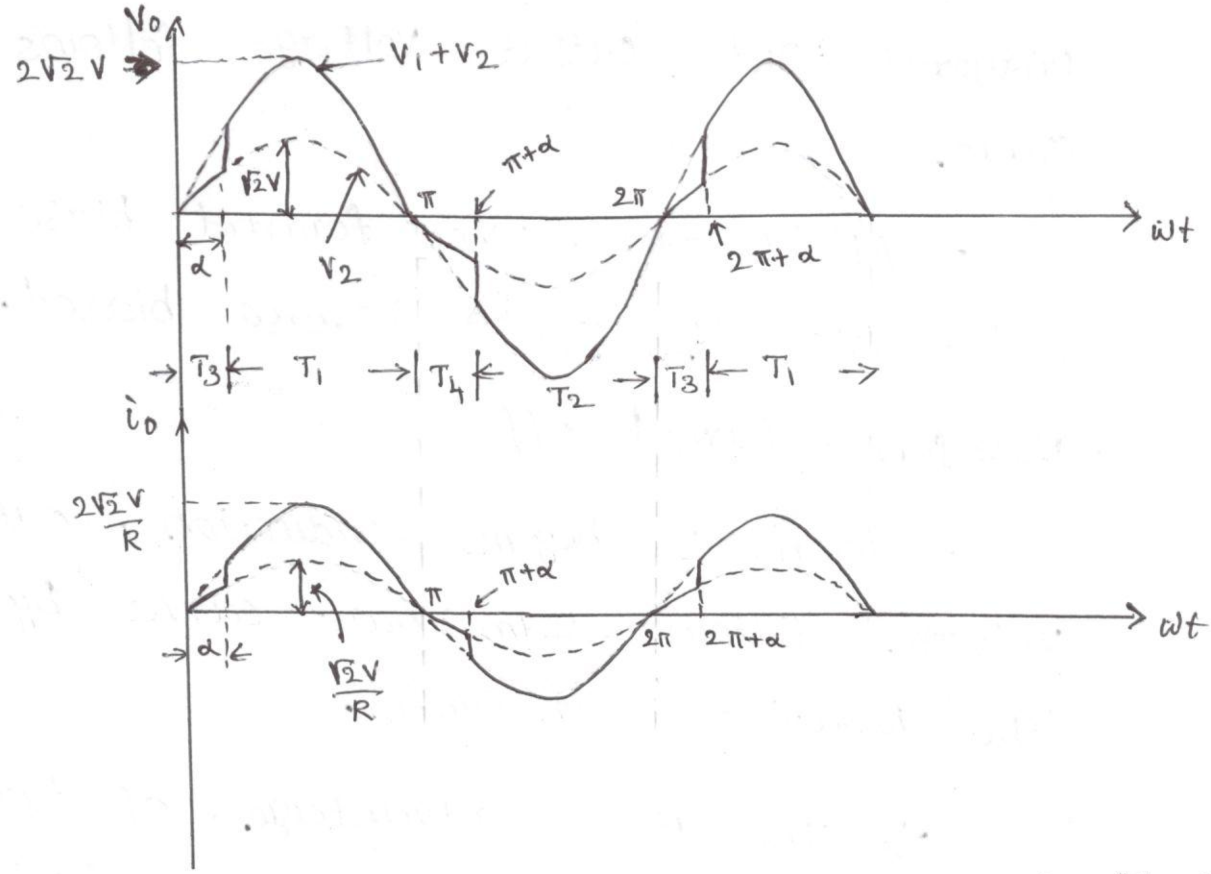
⇒ A two stage sequence control of ac voltage controller employs two stages in parallel as shown in fig. The turns ratio from primary to each secondary is taken as unity. This means that for source voltage $V_S = V_m \sin\omega t$, $V_1 = V_2 = V_m \sin\omega t$ and sum of two secondary voltage is $2V_m \sin\omega t$.



⇒ For obtaining output voltage control from zero to rms value V, use only thyristor pair T_3, T_4.

⇒ For zero output voltage, α is 180° for T_3, T_4 and for V, α is zero.

⇒ For output voltage control from V to 2V, α for thyristor pair T_3, T_4 is always zero and for thyristor pair T_1, T_2 ; α is varied from zero to 180°



⇒ When both pairs, T_1, T_2 and T_3, T_4 are in operation, then firing angle for T_3, T_4 is always zero whereas firing angle for pair T_1, T_2 is varies from 180° to zero for obtaining output voltage from V to 2V

⇒ The output voltage, when thyristor T_3 is triggered at $\omega t = 0$, follows $v_2 = V_m \sin\omega t$ curve. When T_1 is triggered at $\omega t = \alpha$, voltage V_1 reverse biases T_3, it is therefore turned off.

⇒ After this, T_1 begins conduction and the output voltage jumps from V_2 to (V_1+V_2) and follows $2V_m \sin\omega t$ curve.

⇒ At $\omega t = \pi$, output voltage and current are zero. At this instant, T_4 is triggered and output voltage follows $V_m \sin\omega t$ curve.

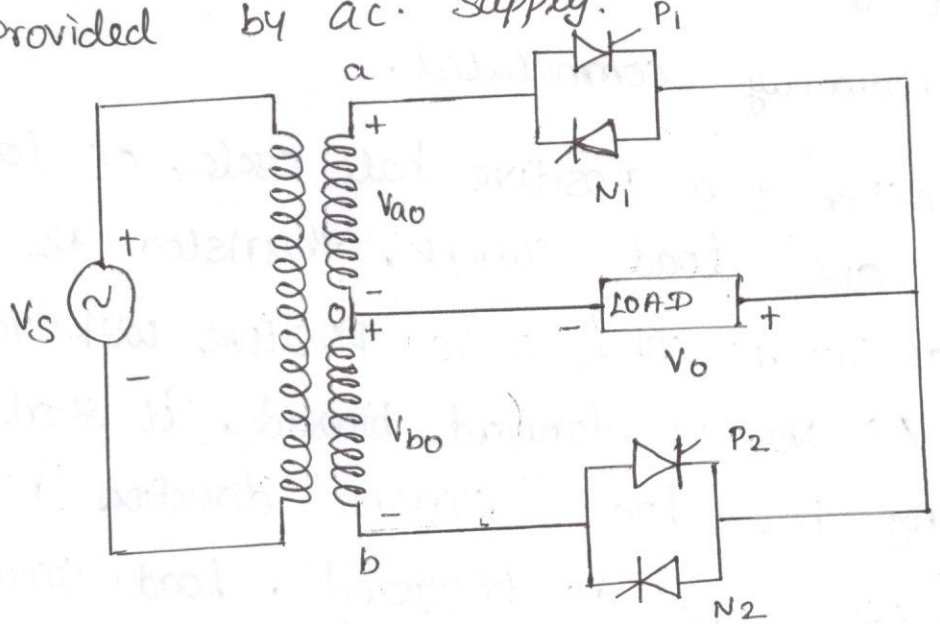
⇒ At $\omega t = \pi + \alpha$, when forward biased SCR T_2 is triggered, T_4 is reverse biased, it is therefore turned off.

⇒ when T_2 begins conduction, output voltage follows $2V_m \sin\omega t$ curve by the negative half cycle.

⇒ The main advantage of two stage sequence control of Ac voltage controller over single phase full wave ac voltage controller is the reduction of harmonics in the load and line currents.

Single Phase mid point Step down cycloconverter:-

⇒ A Step down cycloconverter does not require forced commutation. These converters need only line, or natural commutation which is Provided by ac. Supply.



⇒ This type of cycloconverter will be described both for discontinuous as well as continuous load current.

Discontinuous load Current:-

⇒ When α is Positive with respect to O, forward biased SCR P_1 is triggered at $\omega t = \alpha$. with this, load current i_0 starts building up in the positive direction A to O.

⇒ Load current i_0 becomes zero at $\omega t = \beta > \pi$ but less than $(\pi + \alpha)$. Thus P_1 is naturally commutated at $\omega t = \pi$ which is already Reverse biased after π.

⇒ After half cycle, b is positive with respect to 0. Now forward biased thyristor P_2 is triggered at $\omega t = \pi + \alpha$. Load current is again positive from A to O and builds up from zero.

⇒ At $\omega t = \pi + \beta$, i_o decays to zero and P_2 is naturally commutated.

⇒ After four positive half cycles of load voltage and load current, thyristor N_2 is gated at $(4\pi + \alpha)$ when O is positive with respect to b. As N_2 is forward biased, it starts conducting but load current direction is reversed.

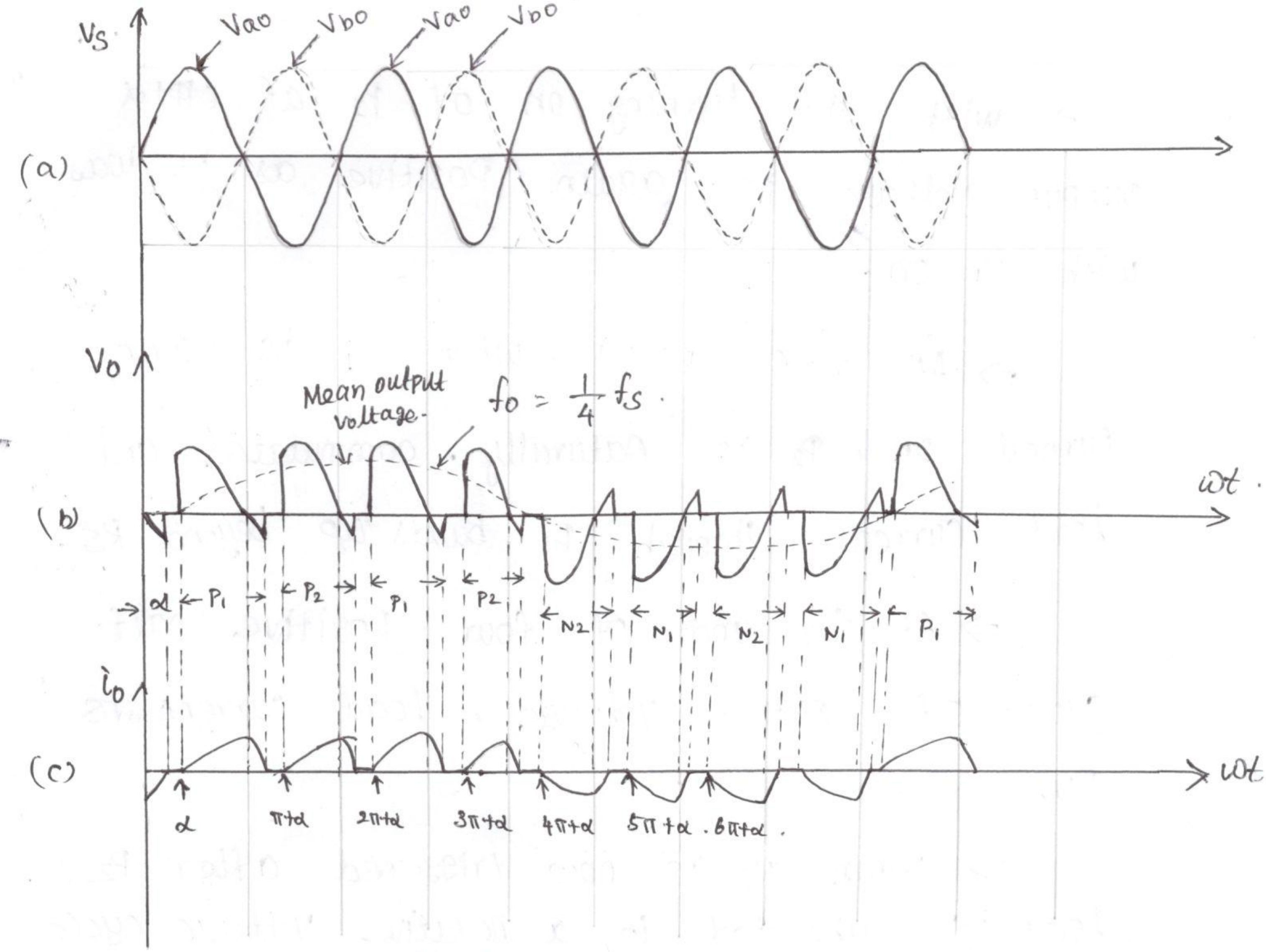
⇒ After N_2 is triggered, load current builds up in the negative direction.

⇒ In the next half cycle, O is positive with respect to a but before N_1 is fired i_o decays to zero and N_2 is naturally commutated.

⇒ Now when N_1 is gated $(5\pi + \alpha)$, i_o again builds up but it decays to zero before N_2 in sequence is again gated.

⇒ In this manner, four negative half cycles of load voltage and load current equal to number of four positive half cycles are generated.

⇒ In is seen from this, that frequency of o/p voltage & current is $f_o = \frac{1}{4} f_s$.



continuous load current:

⇒ when a is positive with respect to 0, P_1 is triggered at $\omega t=\alpha$, positive output voltage appears across load and load current starts building up.

⇒ At $\omega t=\pi$, supply and load voltages are zero. After $\omega t=\pi$, P_1 is reverse biased.

⇒ As load current is continuous, P_1 is not turned off at $\omega t=\pi$. when P_2 is triggered in sequence at $\pi+\alpha$, reverse voltage appears across P_1, therefore turned it off by natural commutation.

⇒ with the turning on of P_2 at $(\pi+\alpha)$, output voltage is again Positive as it was with P_1 on.

⇒ At $\omega t \leq 2\pi+\alpha)$, when P_1 is again turned on, P_2 is naturally. commulated and load current through P_1 builds up beyond Rs.

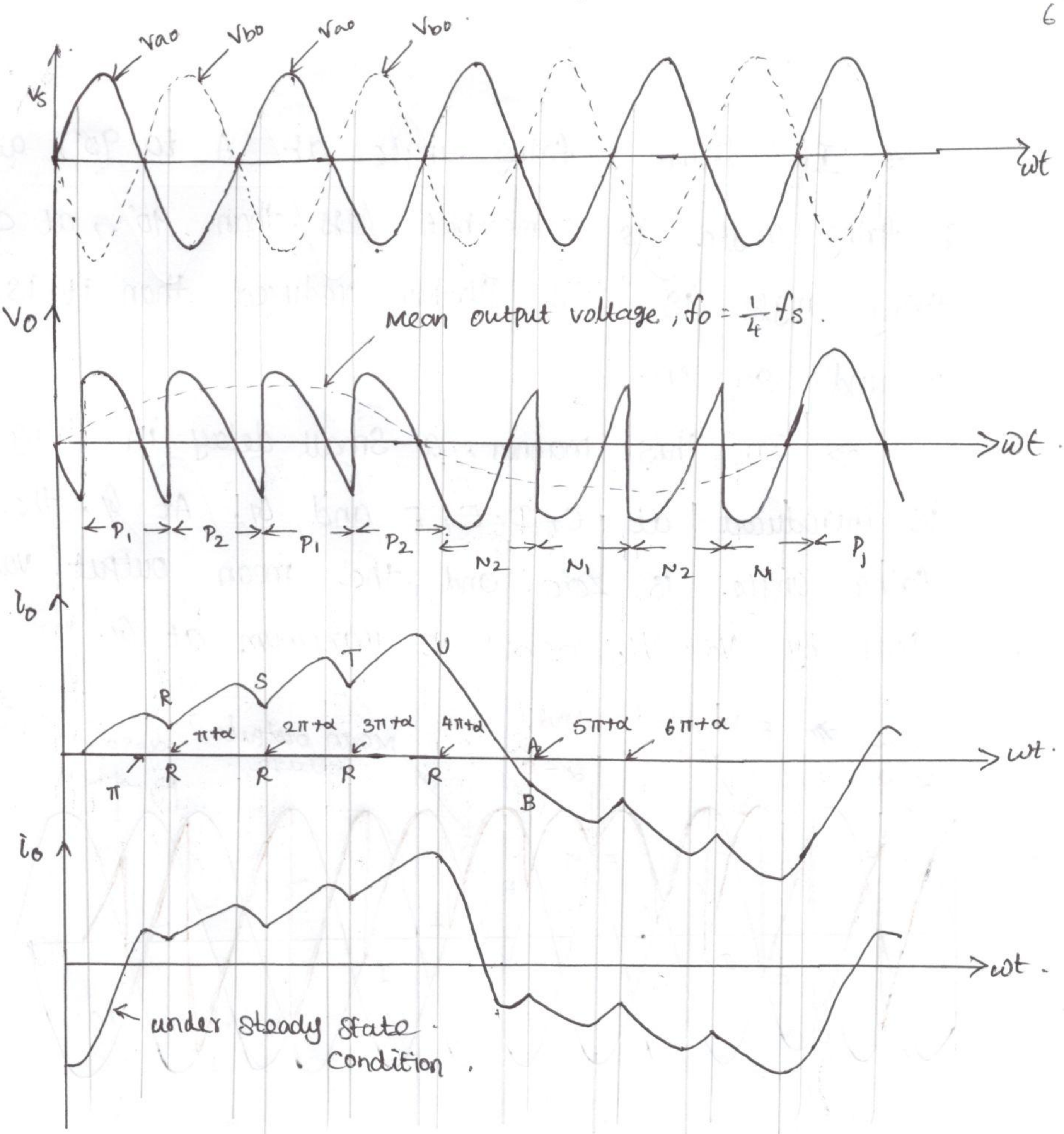
⇒ At the end of four Positive half cycles of output voltage, load current is RU.

⇒ When N_2 is now triggered after P_2 load is subjected to a negative voltage cycle and load current i_0 decreases from Positive RU to negative AB.

⇒ Now N_2 is commutated and N_1 is gated at $(5\pi+\alpha)$. Load current i_0 becomes more negative than AB at $(6\pi+\alpha)$, this is because with N_1 on, load voltage is negative.

⇒ The Positive group of voltage group and current wave consists of four pulses and same is true for negative group.

⇒ The supply voltage has, however, gone through four cycles. The output frequency is, therefore $f_0 = 1/4 \ f_s$.

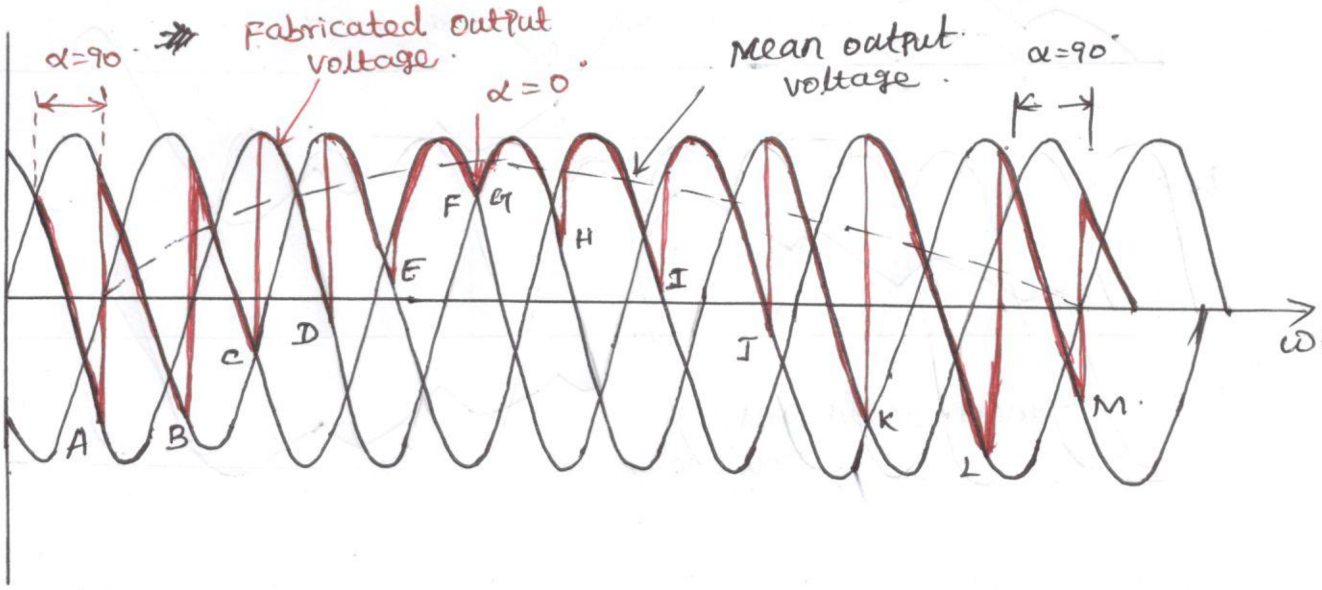


Three Phase to Single Phase Cycloconverter:

⇒ For converting three phase supply at one frequency to single phase supply at lower frequency, the basic principle is to vary progressively the firing angle of the three thyristors of a 3-phase half-wave circuit.

⇒ In figure, firing angle at A to 90°, at B firing angle is somewhat less than 90°, at C firing angle is still further reduced than it is at B and so on.

⇒ In this manner, a small delay in firing angle is introduced at C, D, E, F and G. At G, the firing angle is zero and the mean output voltage, given by $V_0 = V_{do} \cos\alpha$ is maximum at G.



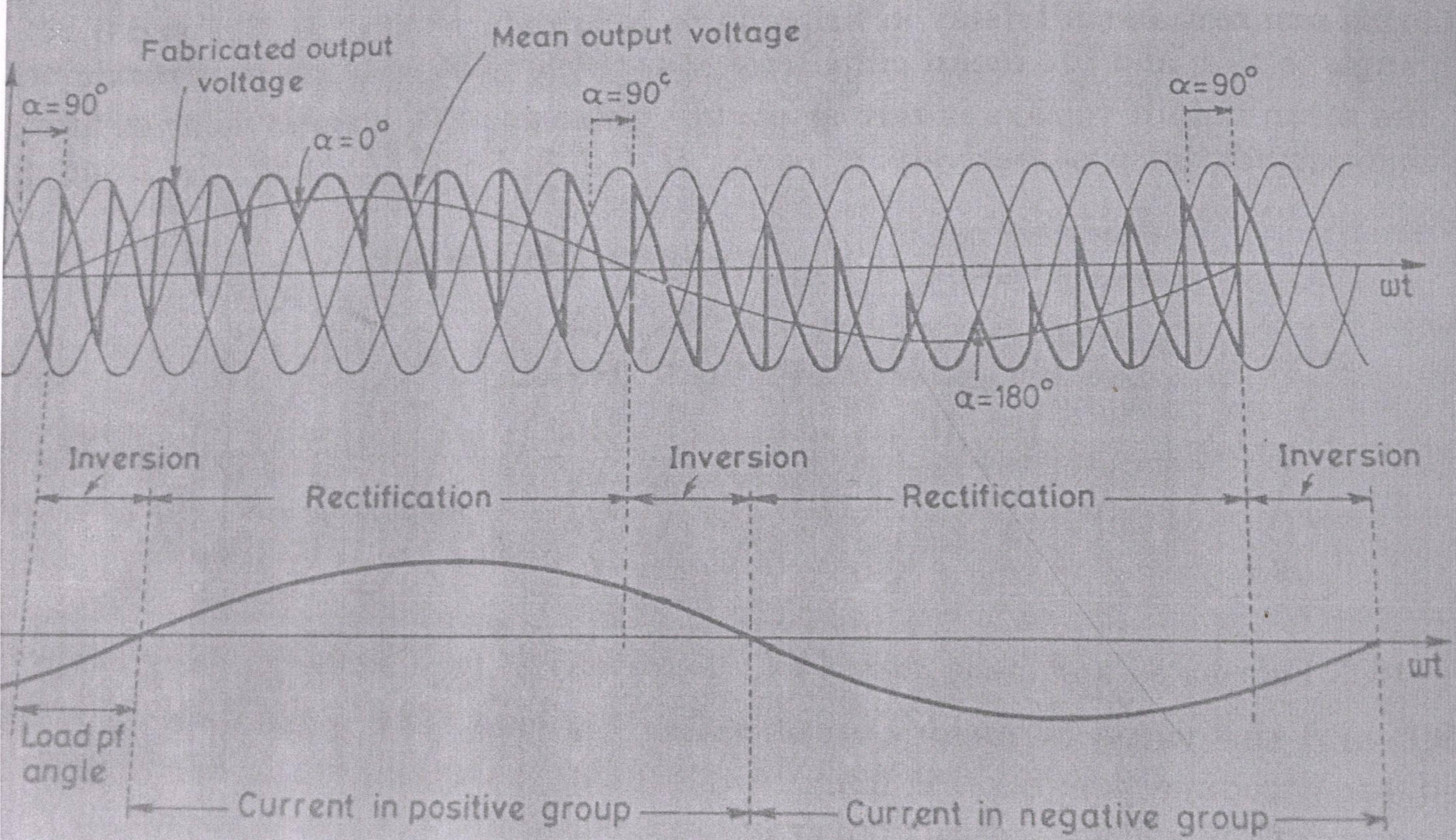
⇒ At A, the mean output voltage is zero as $\alpha = 90°$. After point G, a small delay in firing is further introduced progressively at points H, I, J, K, L and M. At M, the firing angle is again 90° and the value of mean output voltage is zero.

⇒ The Single Phase output voltage fabricated from 3-phase input voltage is shown by thick Curve.

⇒ For one half cycle of fundamental frequency output voltage, there are eight half cycles of supply frequency voltage. This shows that output frequency $f_o = \frac{1}{8} f_s$ where fs is the supply frequency.

⇒ For obtaining one cycle of low frequency output voltage, the firing angle should be varied from 90° to zero degree to 90° for positive half cycle and from 90° to 180° and back to 90° for negative half cycle

⇒ In a thyristor converter circuit, current can only flow in one direction. For allowing the flow of current in both the directions during one complete cycle of load current, ~~th~~ two three phase half-wave converters connected in anti parallel.

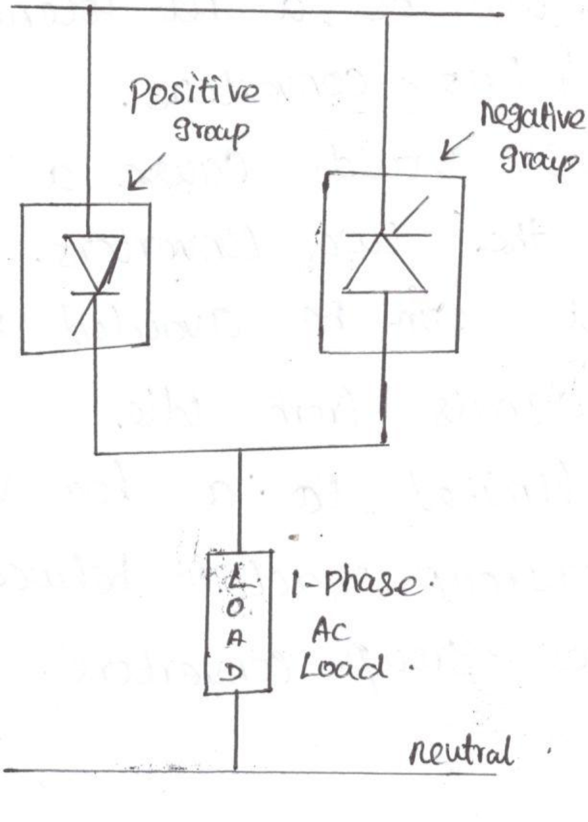


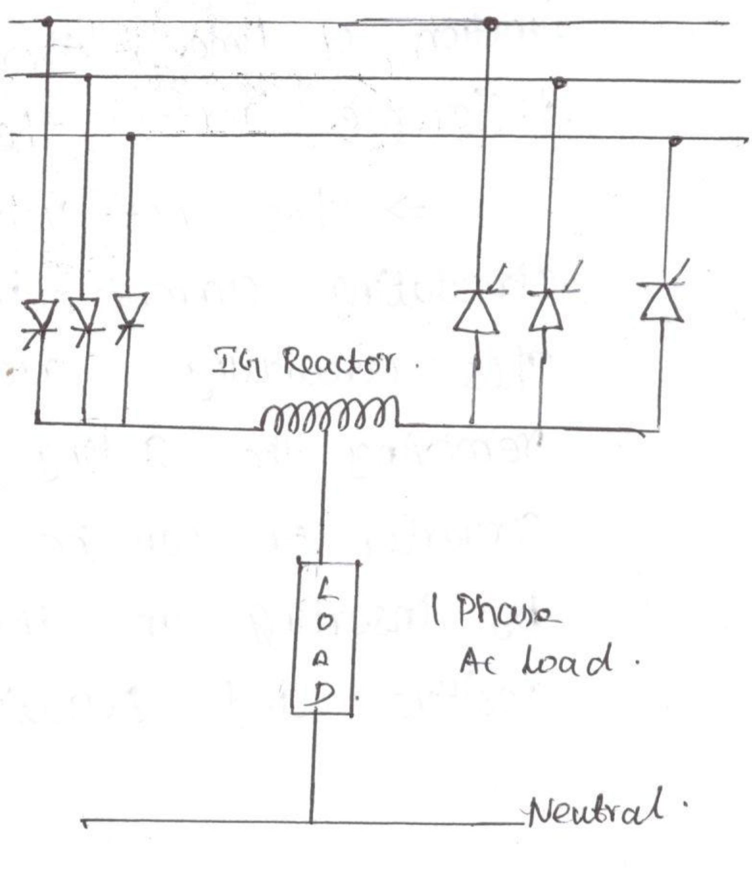
Fabricated output voltage
Mean output voltage
α=90°
α=0°
α=90°
α=90°
α=180°
ωt
Inversion
Rectification
Inversion
Rectification
Inversion
Load pf angle
Current in positive group
Current in negative group
ωt

⇒ The converter circuits that permits the flow of current during one positive half cycle of low frequency output current is called positive converter group.

⇒ The other group permitting the flow of current during the negative half cycle of output current is called negative converter group.

⇒ For a three phase to single phase cycloconverter, schematic diagram and basic circuit configuration is shown in below.





⇒ when output current is positive, positive converter conducts. Under this condition, positive converter acts as a rectifier when output voltage is positive and as an inverter when output voltage negative.

⇒ when output current is negative, the negative converter conducts; under this condition, negative converter acts as a rectifier when output voltage is negative and as an inverter when output voltage is positive.

⇒ The output voltages of the two converters in the same phase ~~value~~ have the same average value, their output voltage waveforms as a function of time, there will be a net potential difference across the two converters.

⇒ This net voltage would cause a circulating current in the two converters. This circulating current can be avoided by removing the gating signals from idle converter or can be limited to a low value by inserting an intergroup reactor between positive and negative group converters.

⇒ If α_p and α_n are the firing angles for positive and negative group converters respectively, then these firing angles should be so controlled as to satisfy the relation $\alpha_p + \alpha_n = 180°$.

A single phase voltage controller is employed for controlling the power flow from 230V, 50Hz source into a load circuit consisting of $R = 3\Omega$ and $\omega L = 4\Omega$. Calculate.

(a) The control range of firing angle.

(b) The maximum value (or) rms load current

(c) The maximum power and power factor.

(d) The maximum values of average and rms thyristor currents.

Given.

$V_s = 230V$; $R = 3\Omega$; $\omega L = 4\Omega$.

Solution:

(a) The ~~maximum~~ minimum value of firing angle α = load phase angle, $\phi = \tan^{-1}\frac{\omega L}{R}$.

$$\phi = \tan^{-1}(4/3) = 53.13°$$

The maximum value of firing angle is 180°

∴ The firing angle control Range is

$$53.13° \le \alpha \le 180$$

(b)

The maximum value of rms load current is

$$I_0 = \frac{V_S}{\sqrt{R^2 + (\omega L)^2}} = \frac{230}{\sqrt{3^2+4^2}}$$

$$I_0 = 46\,A$$

(c) The maximum power $= I_0^2 R$.

$$= 46^2 \times 3$$

$$P_0 = 6348\,W$$

Power factor, $Pf = \dfrac{I_0^2 R}{V_S I_0}$

$$= \frac{46^2 \times 3}{230 \times 46}$$

$$Pf = 0.6$$

(d) Maximum value of Average thyristor current,

$$I_{TAVM} = \frac{V_m}{\pi Z} = \frac{\sqrt{2} \times 230}{\pi \times \sqrt{3^2+4^2}}$$

$$\boxed{I_{TAV} = 20.707\,A.}$$

Maximum value of RMS thyristor current is,

$$I_{TM} = \frac{V_m}{2Z} = \frac{\sqrt{2} \times 230}{2\sqrt{3^2+4^2}}$$

$$\boxed{I_{TM} = 32.527\,A.}$$