



KALINGA NAGAR POLYTECHNIC, JAJPUR ROAD

POWER ELECTRONICS & PLC



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## **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.

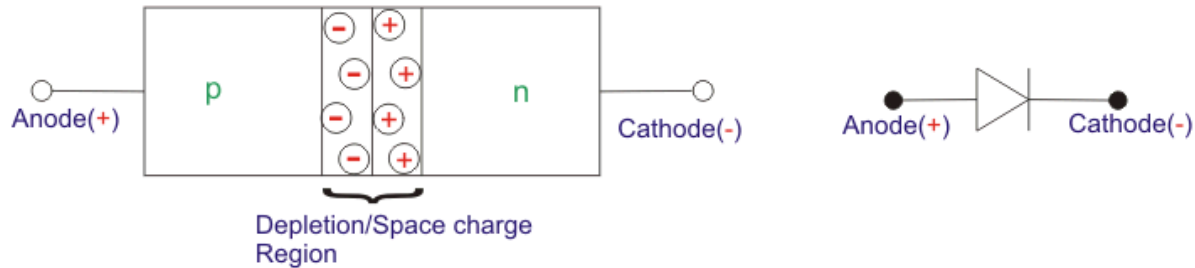
### **UNIT V AC CHOPPER,CYCLOCONVERTER&VOLTAGE CONTROLLER :**

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:

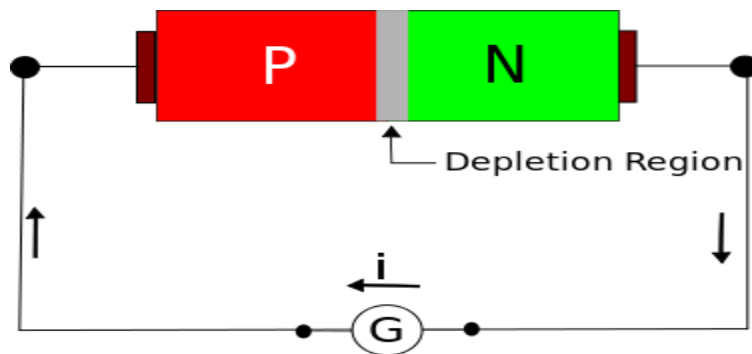
Diodes are the simplest semiconductor device having only two layers, two terminals and one junction. The ordinary signal diodes have a junction formed by p type semiconductor and n type semiconductor, the lead joining p type is called anode and the other side lead joining the n type is called cathode.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

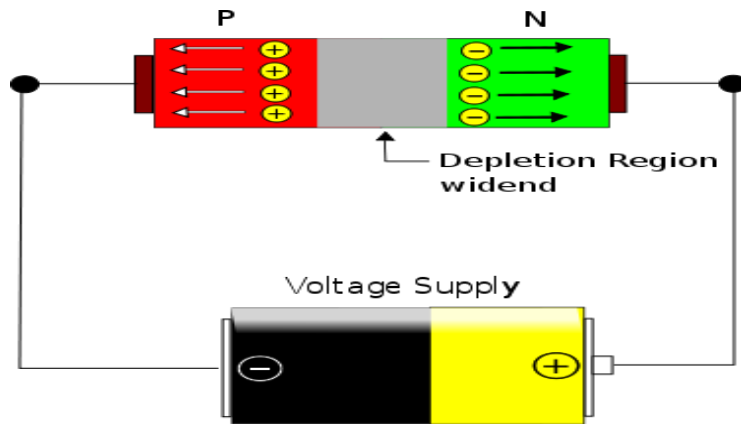
### DIODE BIASED VOLTAGE:

#### ZERO BIAS:



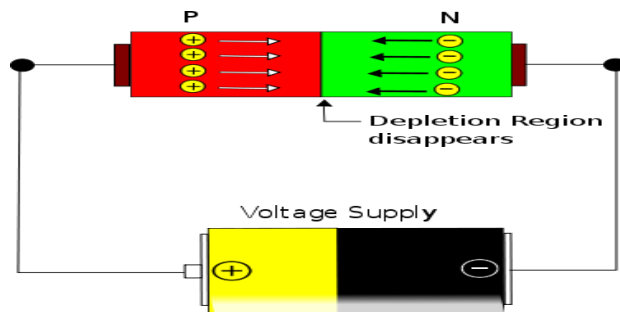
When a diode is zero biased, that is has no bias, it just stays. Almost no current passes through the diode. However if you connect the anode and cathode of the diode you might be able to observe small voltage or current that is insignificant. This is because the electromagnetic spectrum that's present 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:



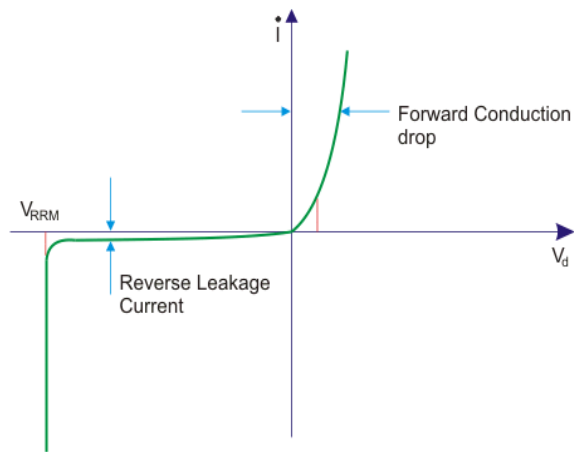
In forward bias the P-Region of the diode is connected with the positive terminal of the battery and N-region is connected with the negative region. During the forward bias the following process occurs. The positive of the battery pumps more holes into the P-region of the diode. The negative terminal 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  $V_f$  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:

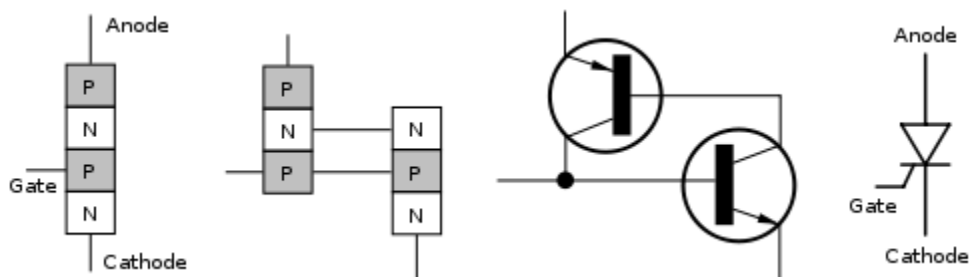
A **silicon controlled rectifier** or **semiconductor-controlled rectifier** is a four-layer solid-state current-controlling device. SCRs are unidirectional devices (i.e. can conduct current only in one direction) as opposed to TRIACs, which are bidirectional (i.e. current can flow through them in either 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.<sup>[9]</sup>

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

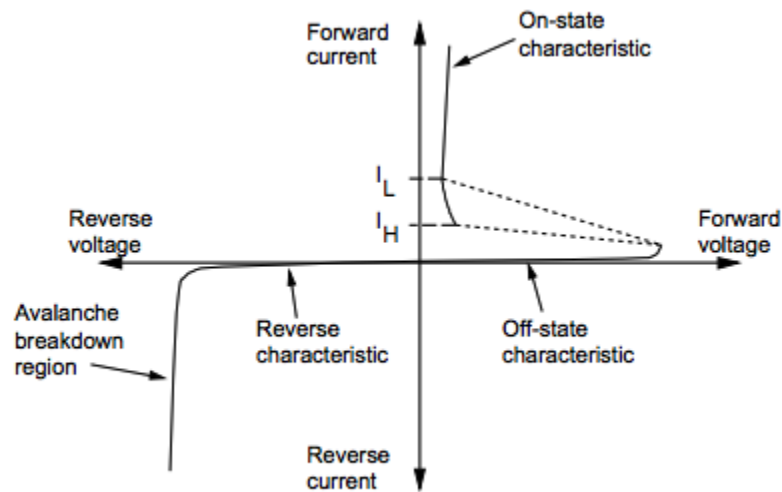
Forward-voltage triggering occurs when the anode–cathode forward voltage is increased with the gate circuit opened. This is known as avalanche breakdown, during which junction J2 will break down. At sufficient voltages, the thyristor changes to its on state with low voltage drop and large forward current.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

## V-I Characteristics of SCR

In this 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 is 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 the 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 SCR will 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 circuit 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<sup>2</sup>s. 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.

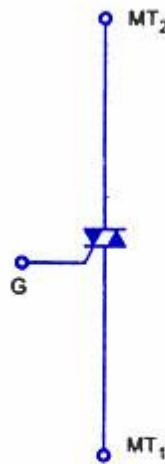
SCRs and similar devices are used for rectification of high-power AC in high-voltage direct-current power transmission. They are also used in the control of welding machines, mainly MTAW (metal tungsten arc welding) and GTAW (gas tungsten arc welding) processes similar.

## 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.



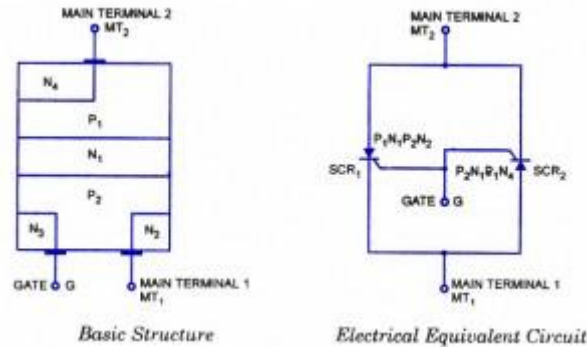
*Schematic Symbol*

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 breakdown 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.

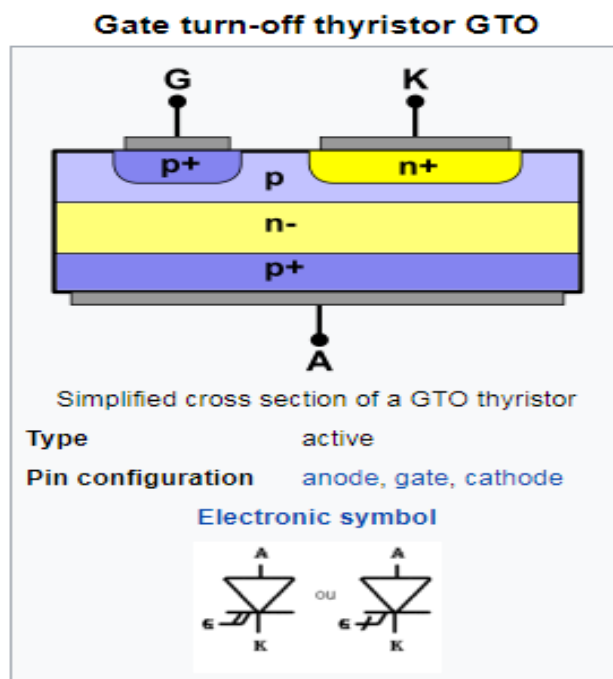
#### 4. Terminal $MT_2$ is negative but gate is positive with respect to terminal $MT_1$

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.<sup>[1]</sup> GTOs, as opposed to normal thyristors, are fully controllable switches which can be turned on and off by their third lead, the gate lead.



## 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.

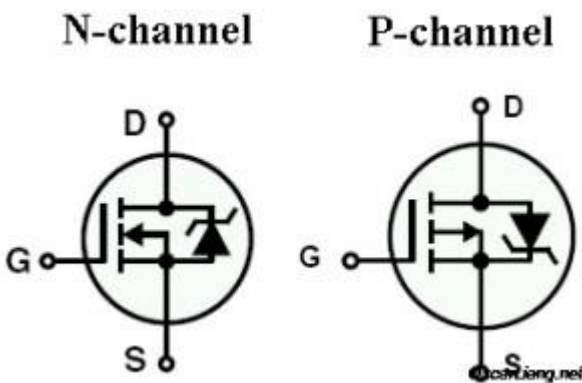
During turn off, the forward voltage of the device must be limited until the current tails off. The limit is usually around 20% of the forward blocking voltage rating. If the voltage rises too fast at turn off, not all of the device will turn off and the GTO will fail, often explosively, due to the high 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. Resetting 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

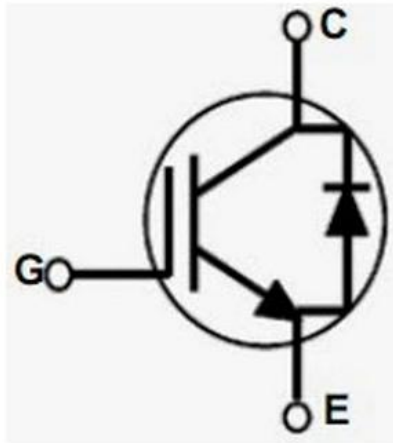
current flowing. Because of this property, FETs are great for large current flow, and the MOSFET is commonly used as a switch.

### **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 impedance
- 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:**

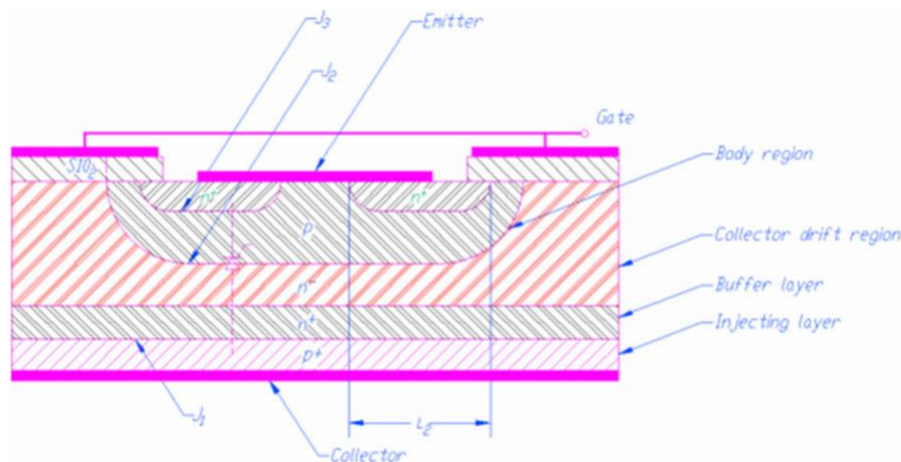
The IGBT (insulated gate bipolar transistor) is a three-terminal electronic component, and these terminals are termed as emitter, collector and gate. Two of its terminals namely collector and emitter are associated with a conductance path and the remaining terminal 'G' is associated with its control.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



IGBT Symbol

**Basic Structure of IGBT**

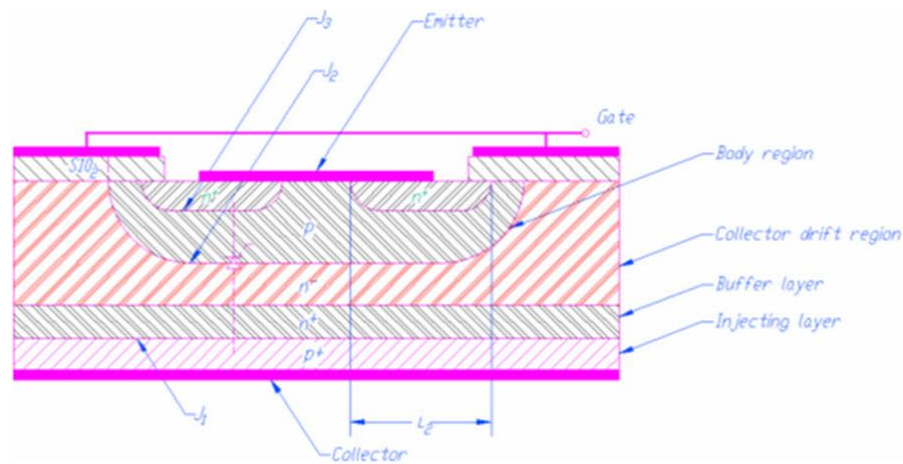
The basic structure of the N-channel IGBT is shown below. This structure is plain that the IGBTs silicon cross section is almost equal to that of a vertical power MOSFET except P+ injecting layer. It shares the same structure of MOS gate & P-wells with N+ source regions. In the following structure, the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

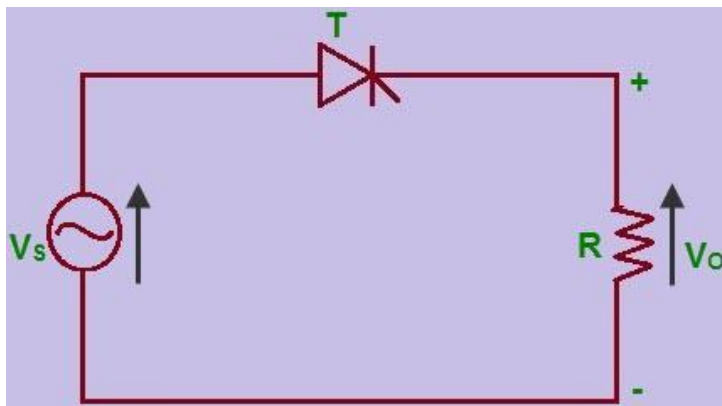
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Circuit Diagram of a IGBT

## 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

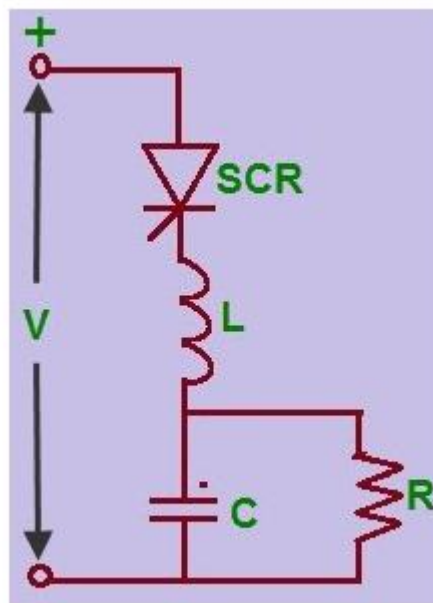
Natural commutation can be observed in AC voltage controllers, phase controlled rectifiers and cyclo converters

## 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.

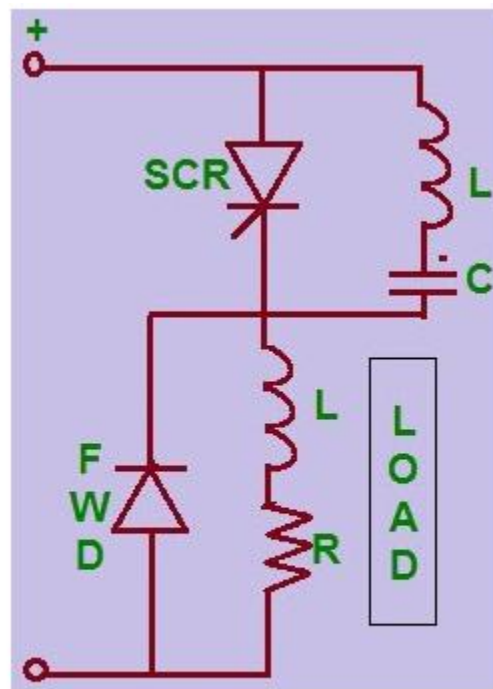


*Class A-Commutation*

### ***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.



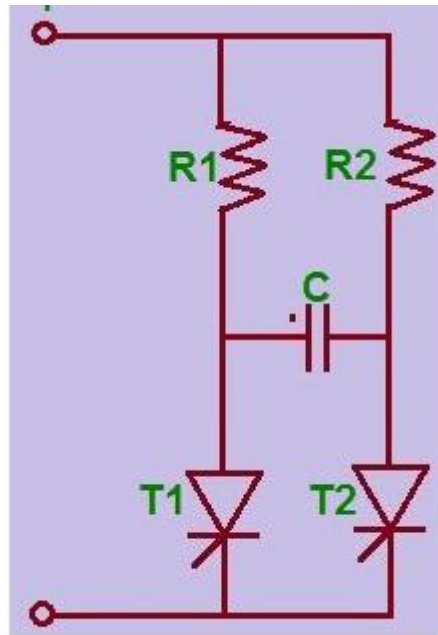


*Class B-Commutation*

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.

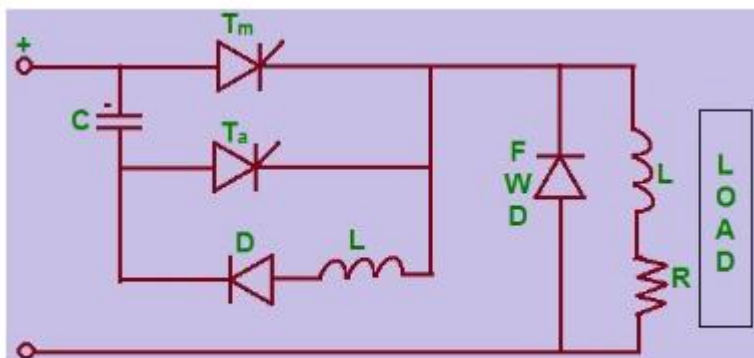


*Class C-Commutation*

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.

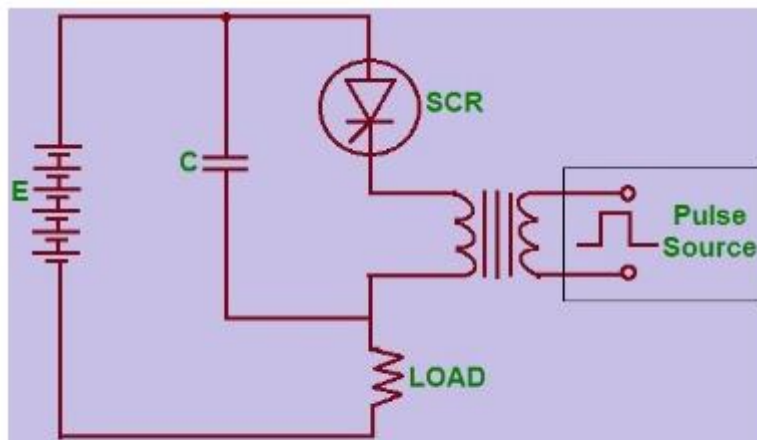


*Class D-Commutation*

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



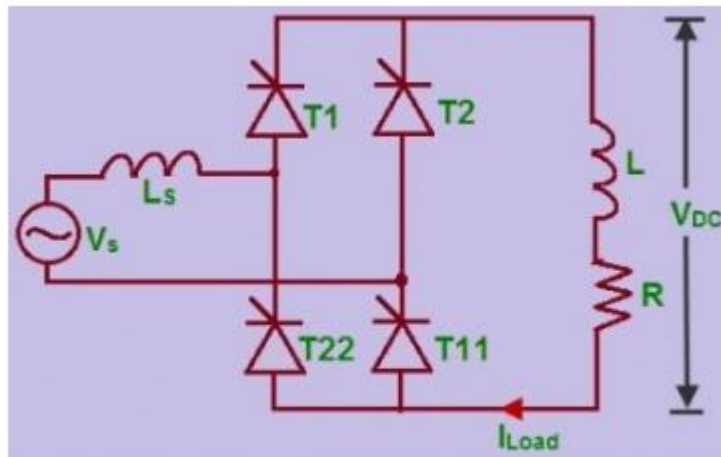
*Class E-Commutation*

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

#### APPLICATIONS

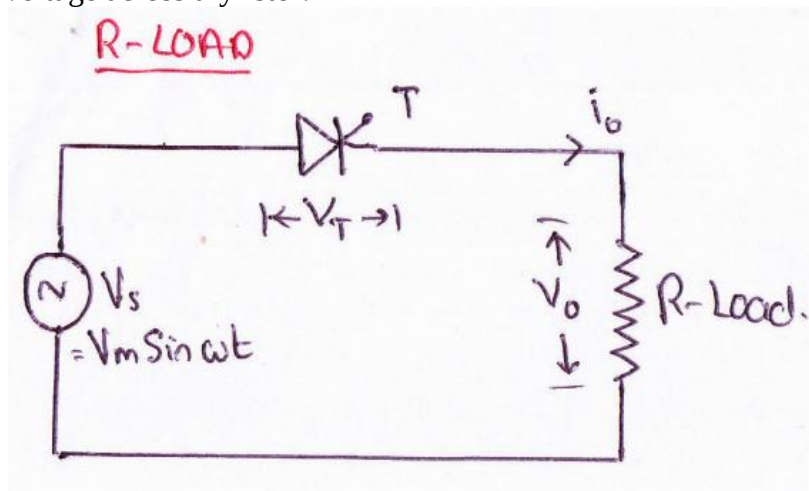
- Steel rolling mills, paper mills, textile mills where speed control of DC motors are necessary.
- Electric traction.
- High voltage DC transmission
- Electromagnet power supplies

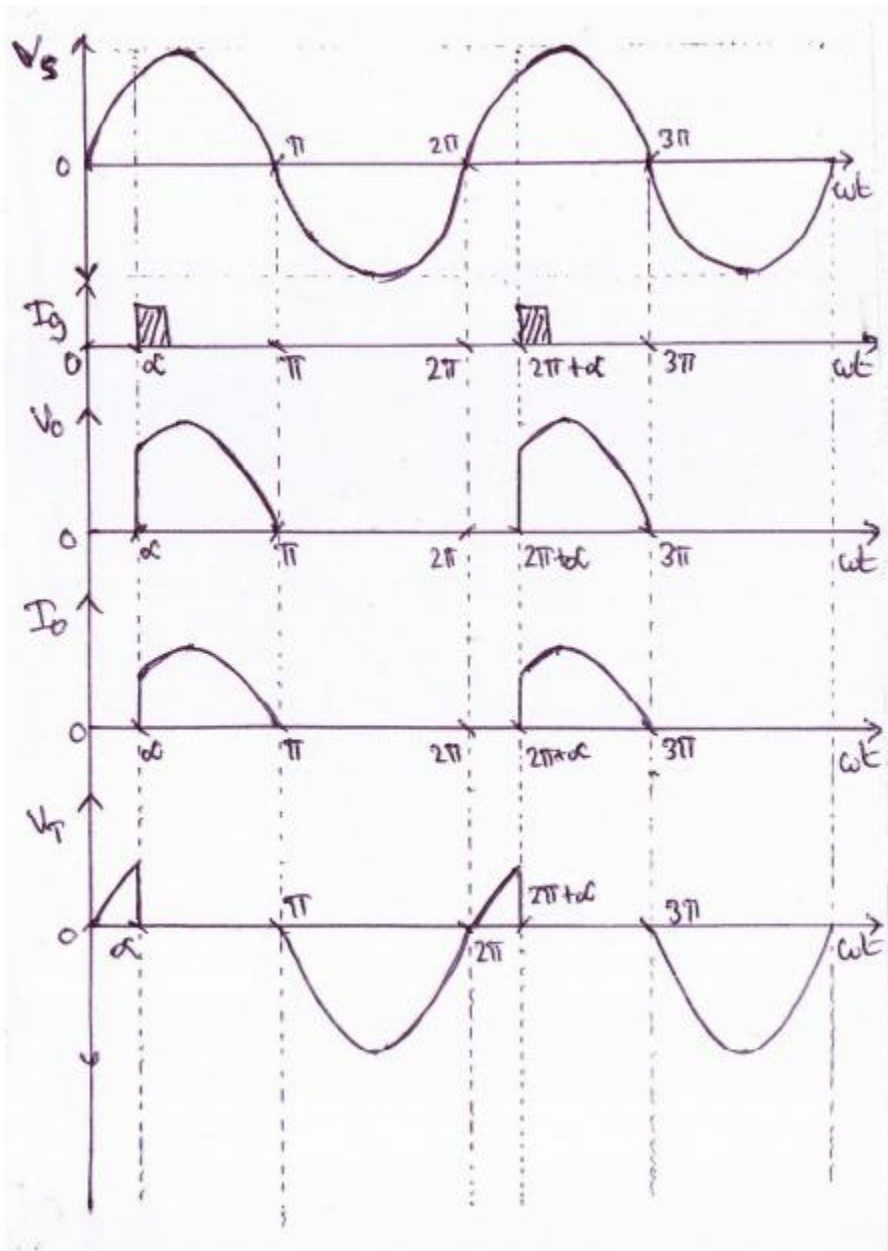
In this unit, the following categories of phase controlled rectifiers will be studied in detail.

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 consists of a thyristor T, a voltage source  $V_s$  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 turned 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.

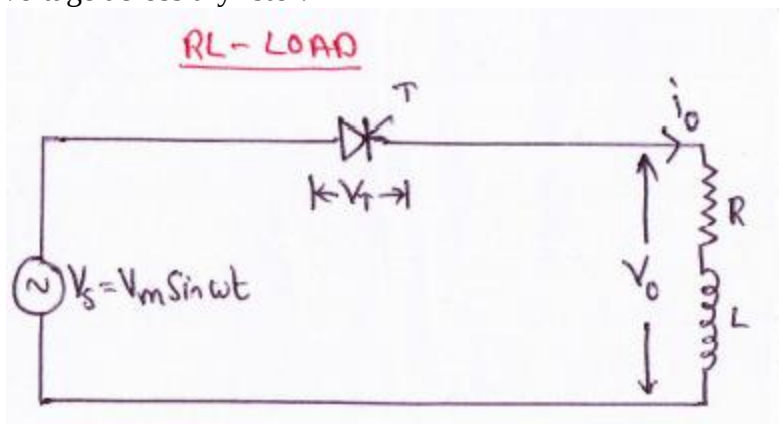




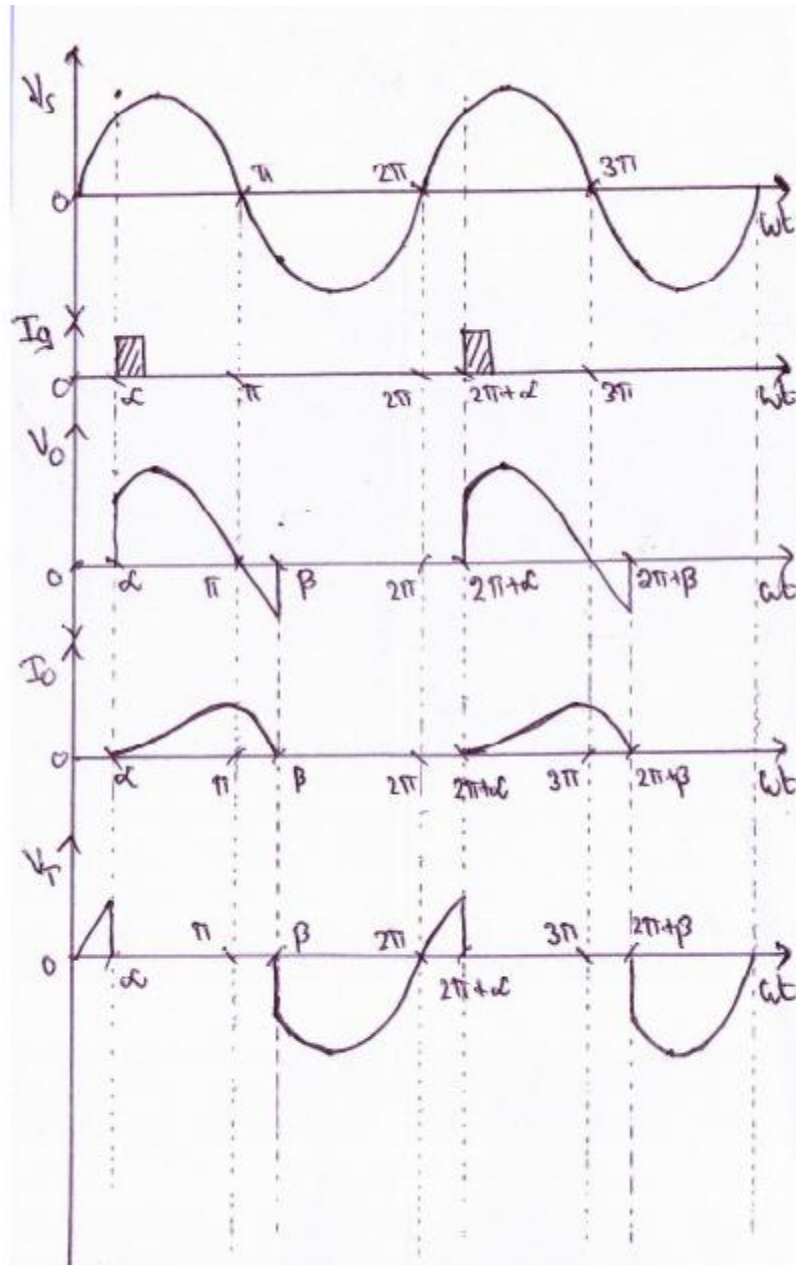
### Single Phase Half Wave Controlled Rectifier with RL Load

- The circuit consist of a thyristor T, a voltage source  $V_s$ , 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 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  $\omega t = \beta$ . The angle  $\beta$  is called extinction angle.
- The duration from  $\alpha$  to  $\beta$  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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



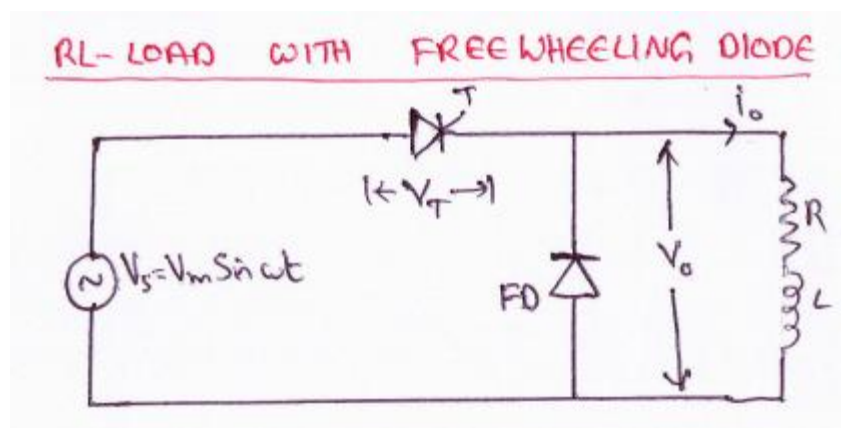


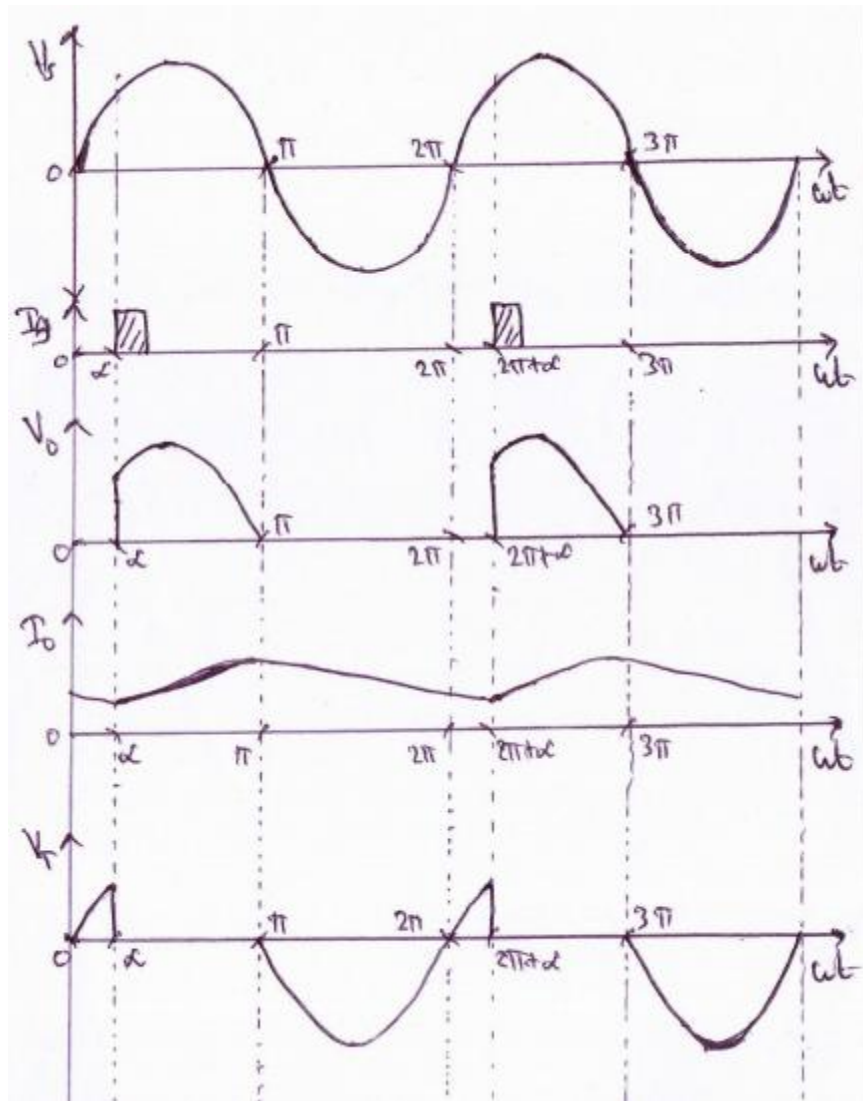


### Single Phase Half Wave Controlled Rectifier with RL Load and Freewheeling Diode

- The circuit consist of a thyristor T, a voltage source  $V_s$ , 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  $\omega t = \pi$ , 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  $\omega t = \pi$ .
- 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.

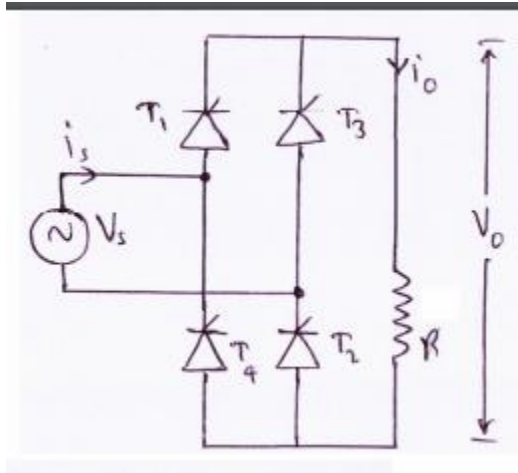


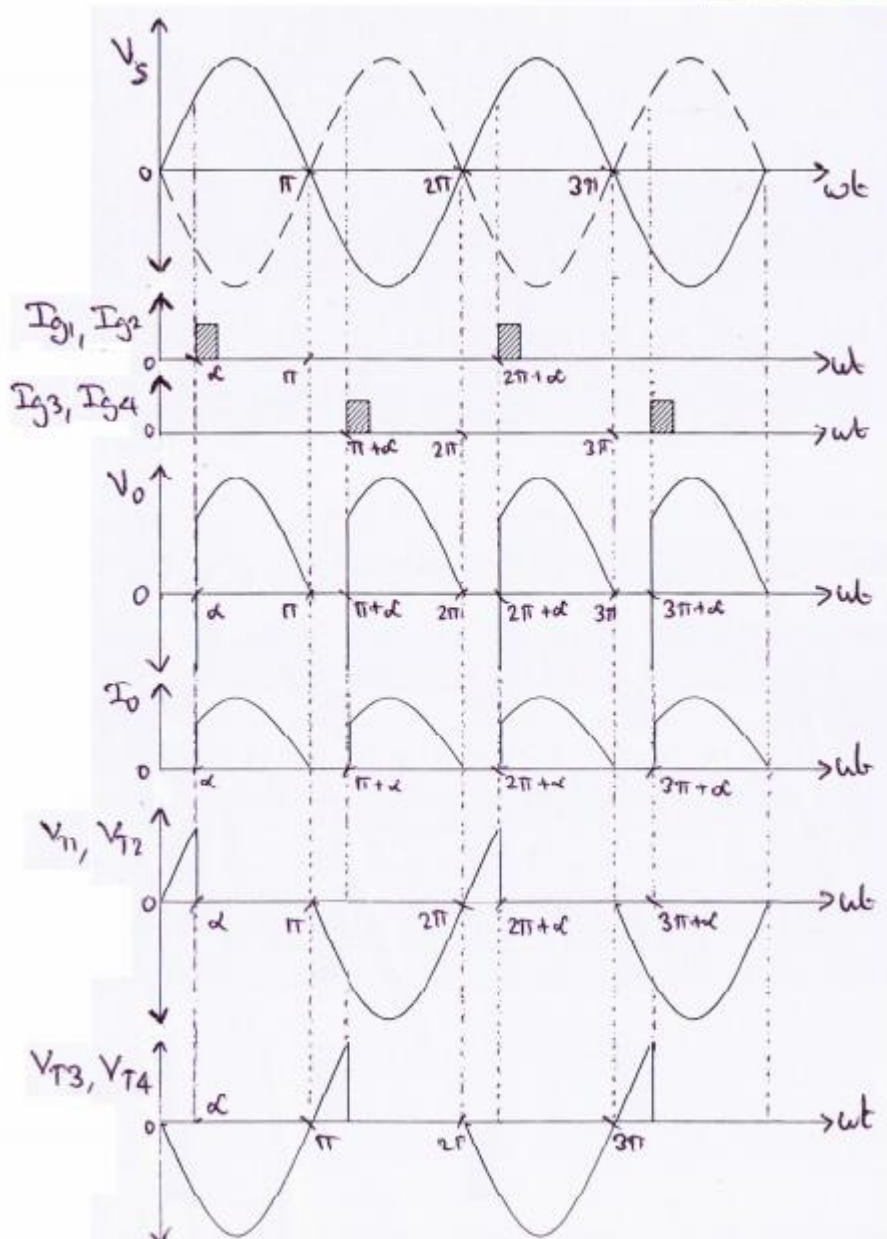


#### Single Phase Full Wave Controlled Rectifier with R Load

- The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source  $V_s$  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  $V_s$ T1-Load-T2- $V_s$ .
- 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  $V_s$ -T3-Load-T4- $V_s$ .
- Here the load receives voltage during both the half cycles.
- The average value of output voltage can be varied by varying the firing angle  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



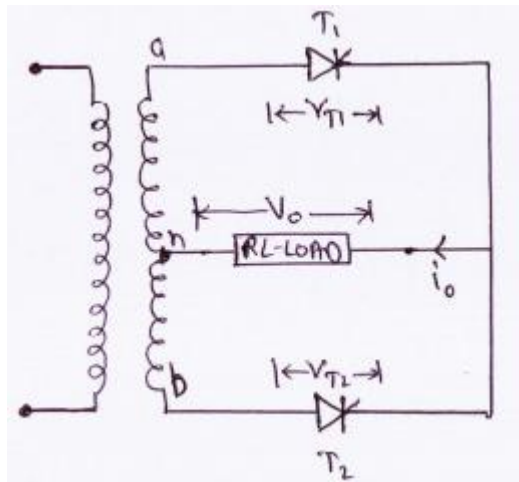


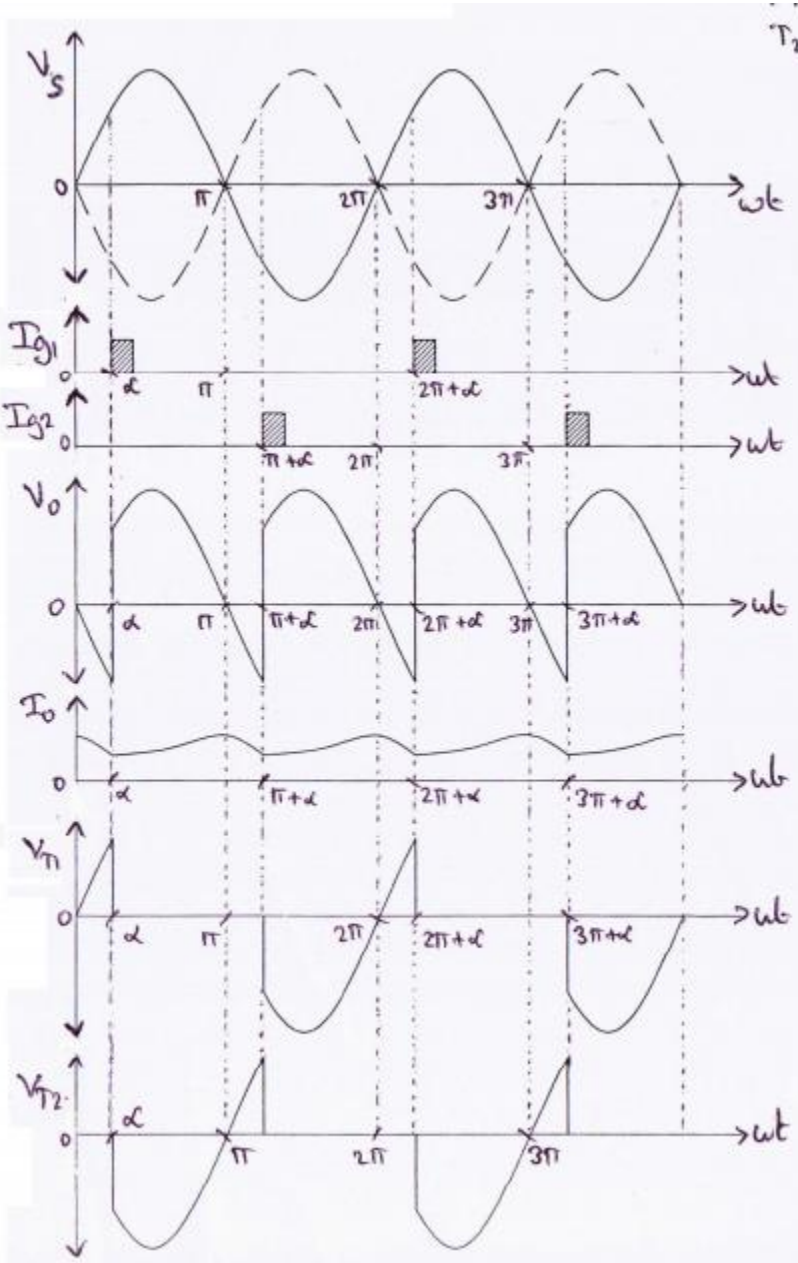
### Single Phase Full Wave Controlled Rectifier with RL Load

#### A. MID POINT CONVERTER

- The circuit consist of two thyristors T1 and T2, a center tap transformer, a voltage source  $V_s$  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 turn 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  $\omega t = \pi + \alpha$ , 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  $\omega t = \pi + \alpha$ .
- 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor

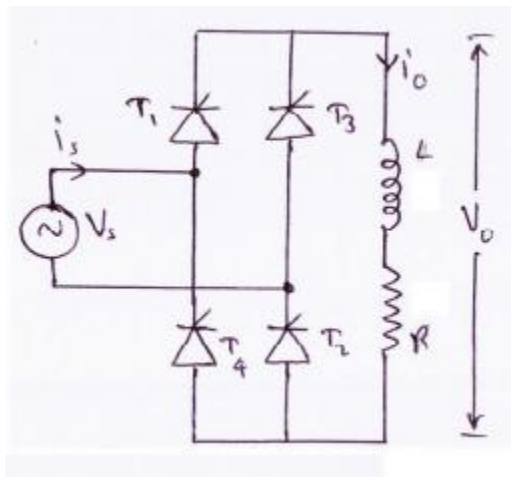




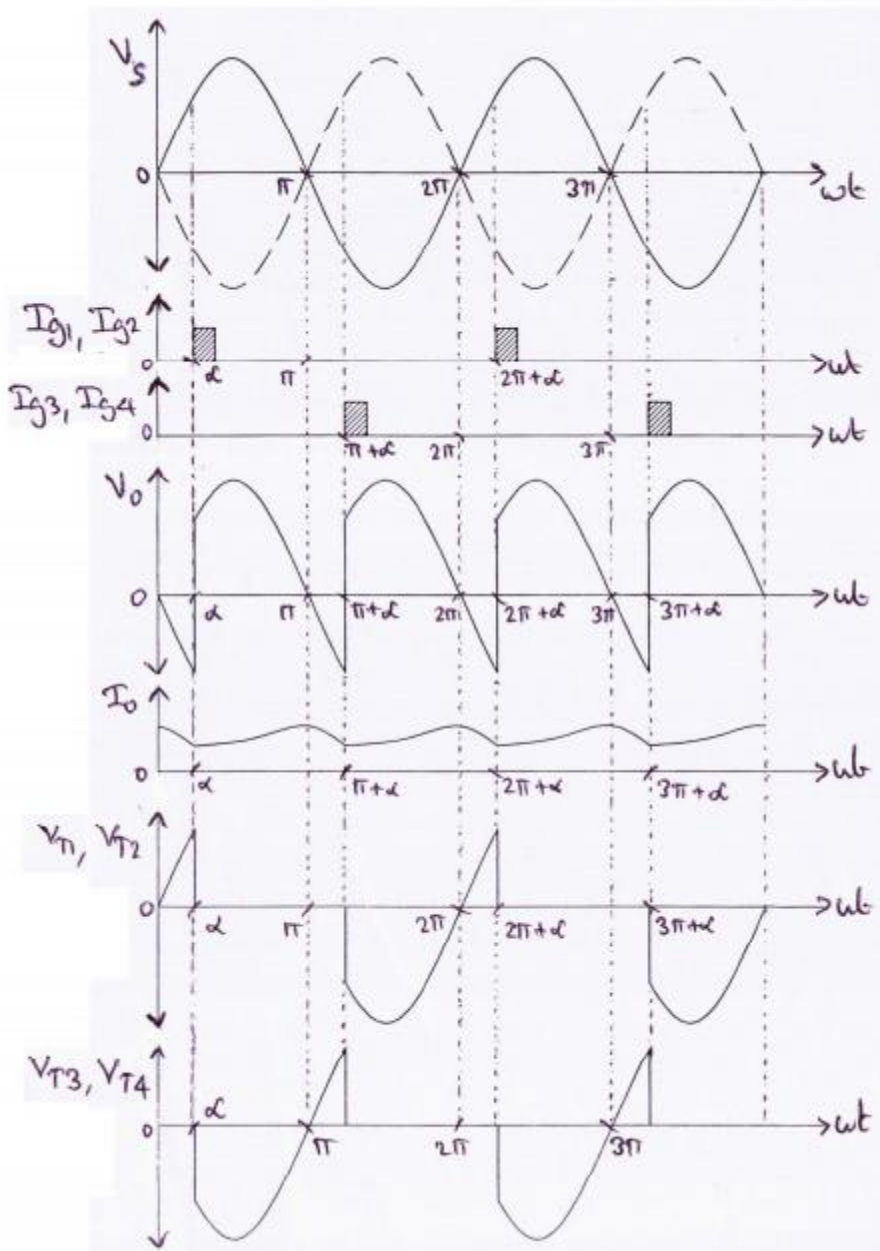
## B. BRIDGE CONVERTER

- The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source  $V_s$  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  $\omega t = \alpha$ , it gets turned ON and begins to conduct.
- When the T1 & T2 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly through the path  $V_s$ -T1-Load-T2- $V_s$ .
- 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  $\omega t = \pi + \alpha$ , 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  $\omega t = \pi + \alpha$ .
- When T3 & T4 is ON, the current through the load builds up slowly through the path  $V_s$ -T3-Load-T4- $V_s$ .
- 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



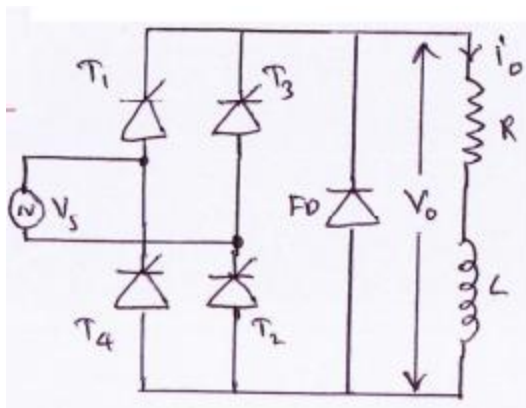


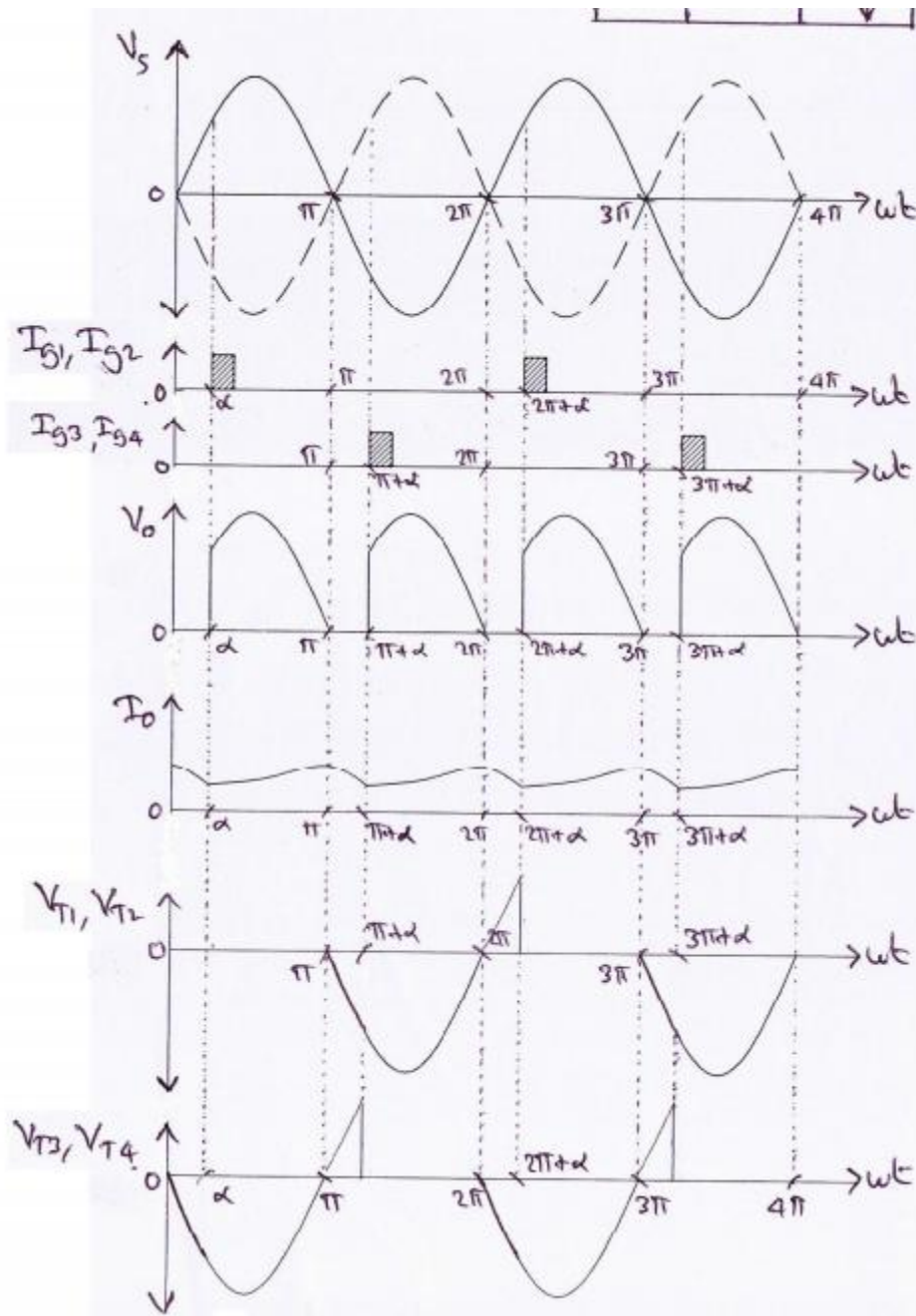


### Single Phase Full Wave Controlled Rectifier with RL Load and Freewheeling Diode.

- The circuit consist of four thyristors T1, T2, T3 and T4, a voltage source  $V_s$ , 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  $\omega t = \alpha$ , it gets turned ON and begins to conduct.
- When the T1 & T2 is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly through the path  $V_s$ -T1-Load-T2- $V_s$ .

- During the negative half cycle (at  $\omega t = \pi$ ), 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  $\omega t = \pi$
- 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 current through the load builds up slowly through the path  $V_s$ -T3-Load-T4- $V_s$ .
- During the next positive half cycle (at  $\omega t = 2\pi$ ), 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  $\omega t = 2\pi$
- 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



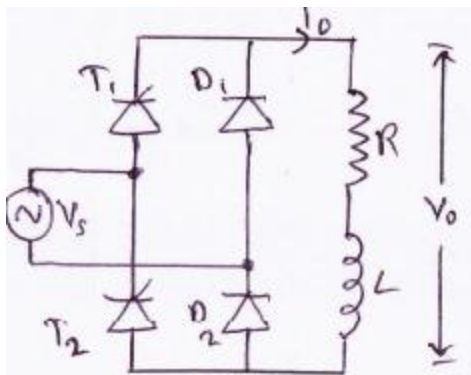


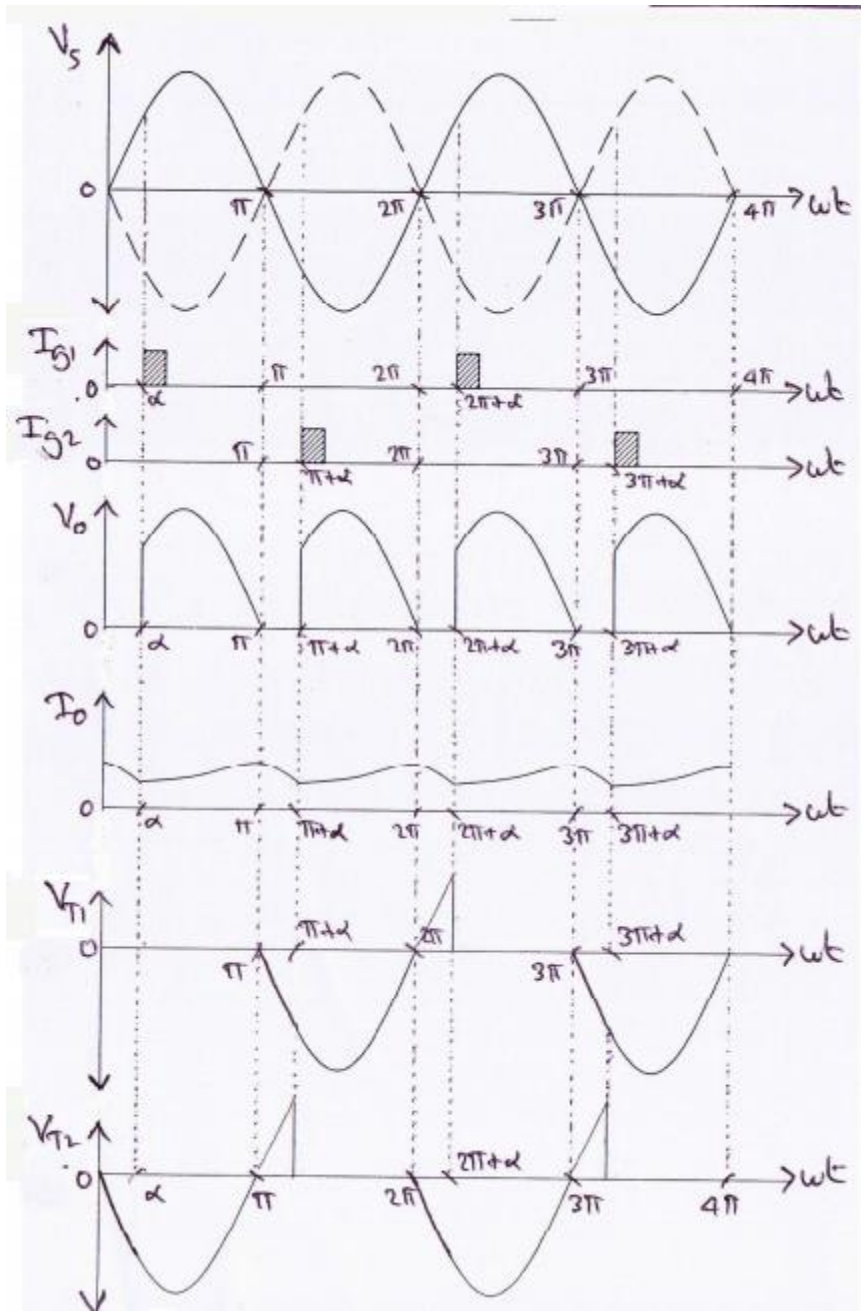
### Single Phase Full Wave Half Controlled Rectifier (Semi Converter)

- 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  $\omega t = \alpha$ , 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.

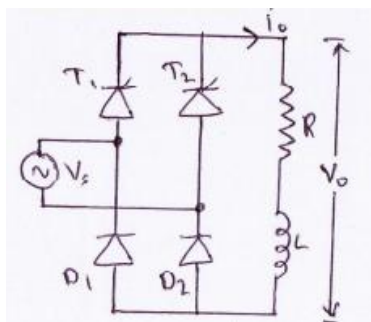
- During the negative half cycle (at  $\omega t = \pi$ ), T2 & D2 is forward biased, the thyristor T1 & D1 gets reverse biased.
- The current shifts its path to D2 and T1 in case of symmetrical converter (D1 & D2 in case of asymmetrical converter) and circulates through the load.
- When a gate pulse is given to the thyristor T2 at  $\omega t = \pi + \alpha$ , 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  $\omega t = 2\pi$ ), 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 asymmetrical 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  $\alpha$ .
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.

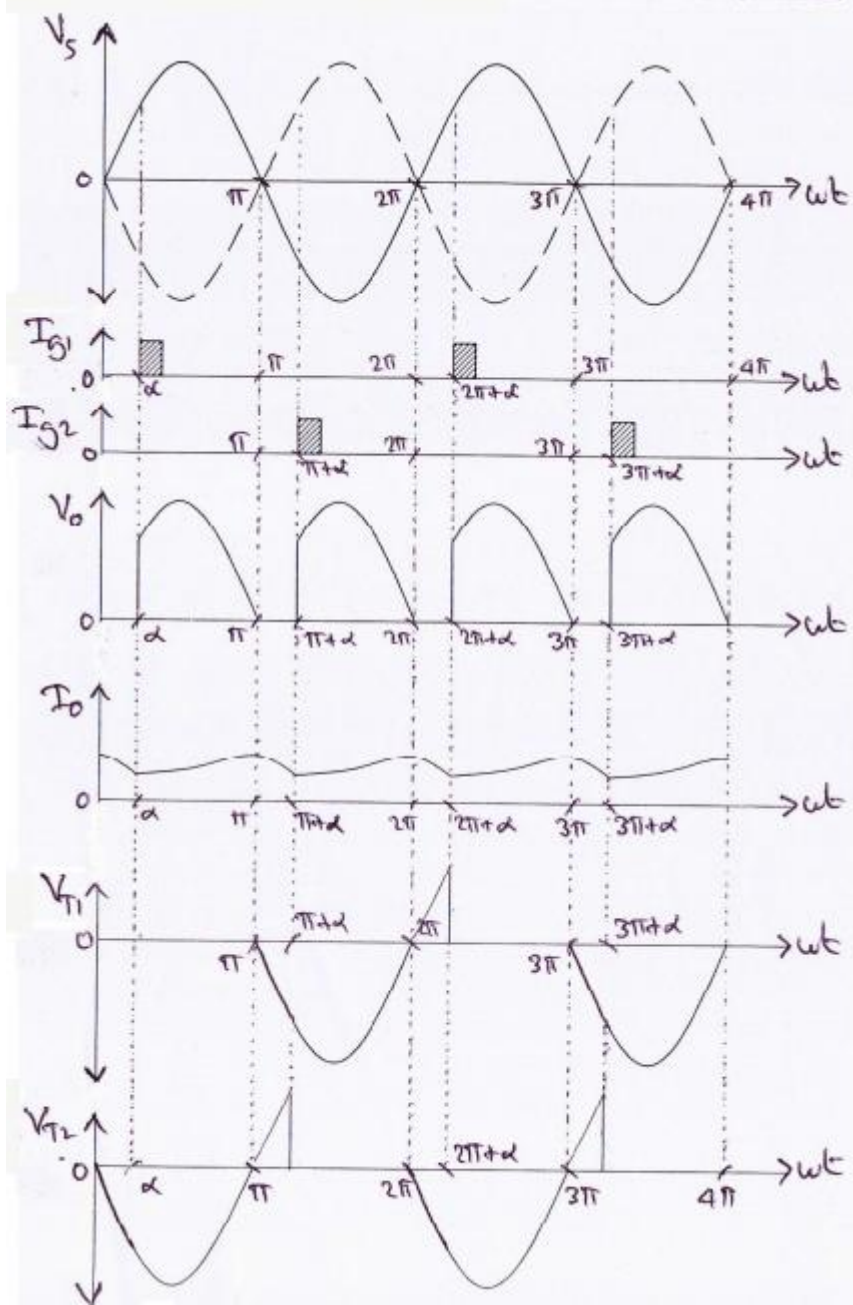
Single Phase Semi Converter (symmetrical semi converter)





Single Phase Semi Converter (asymmetrical semi converter)



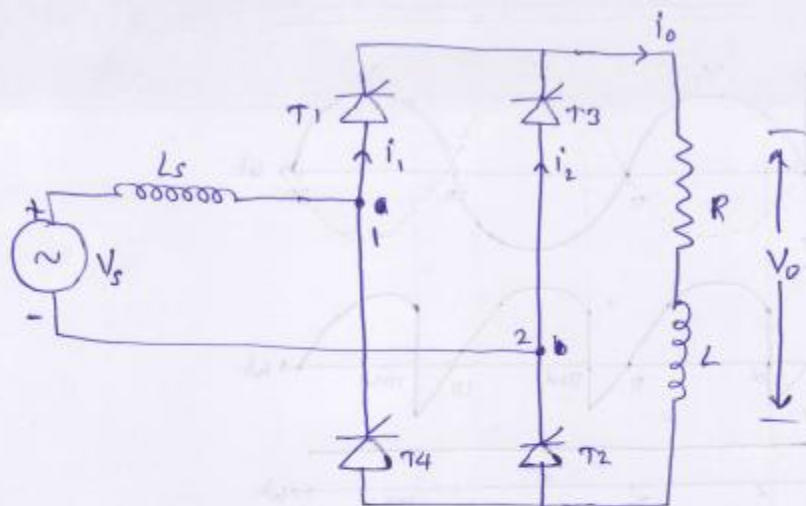




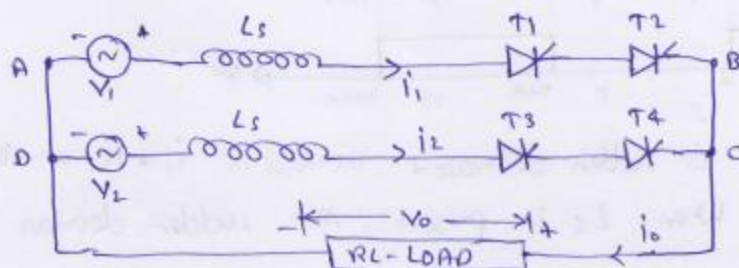
## Effect of source impedance on 1 $\phi$ full converter

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 1 $\phi$  full wave converter with RL load, along with an inductive impedance at source side.

Consider a 1 $\phi$  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



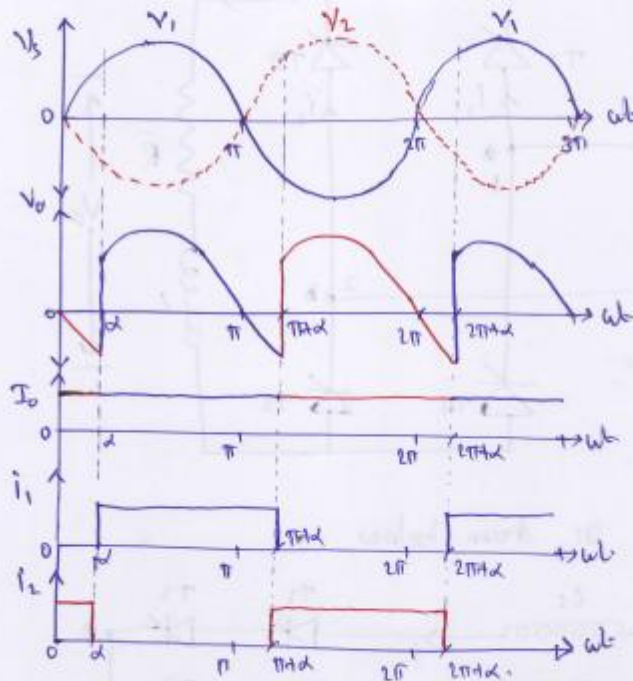
Let us consider the case when  $L_s$  is not present i.e. when the source inductance is zero. Here the source arm is not  $T_1$  &  $T_2$  are fired at  $\alpha$ .

So from  $\alpha$  to  $(\pi + \alpha)$  the o/p current  $i_o$  is same as current through  $T_1 + T_2$  is  $i_1$   
is from  $\alpha$  to  $\pi + \alpha$  ;  $i_o = i_1$



At  $\pi + \alpha$ ,  $T_3 + T_4$  is fired. Now the load current shifts its path from  $T_1 + T_2$  to  $T_3 + T_4$ . At this time,  $i_o$  is same as current through  $T_3 + T_4$  is  $i_2$

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



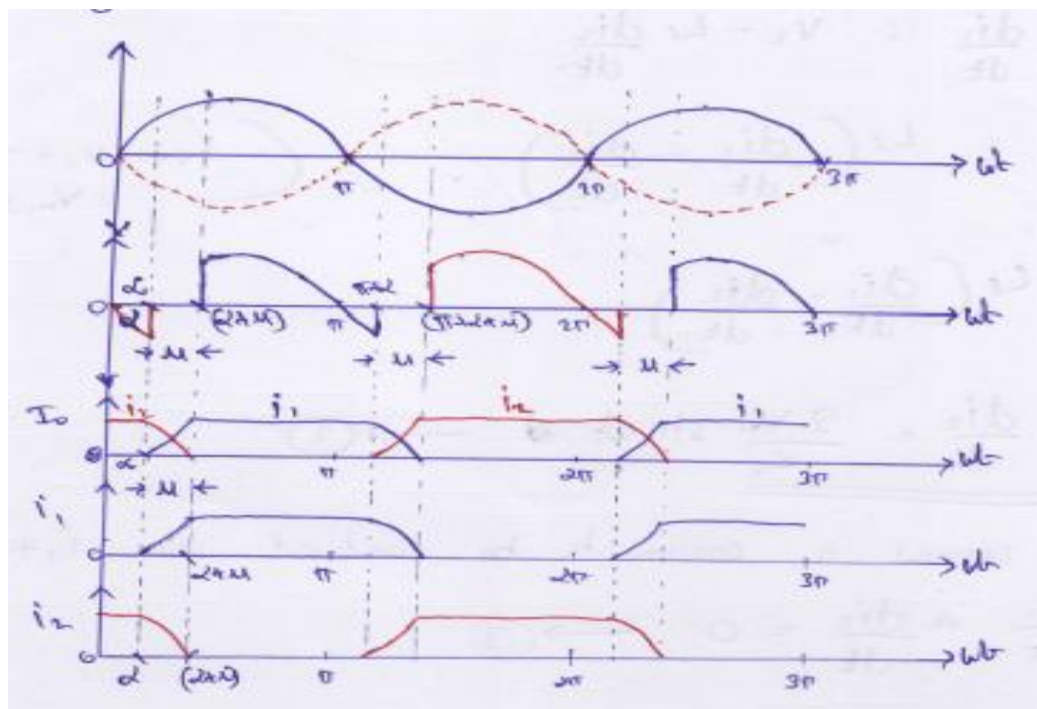
Here we can see a sudden decrease & increase in  $i_1$  &  $i_2$  at  $\alpha$ ,  $\pi + \alpha$ ,  $2\pi + \alpha$  etc. When  $L_s$  is present, this sudden decrease/increase

in load current will not take place, instead a gradual decrease / increase in current takes place. as shown below

In the waveform shown below, the thyristors  $T_1 + T_2$  are triggered at  $(\alpha)$ . So the current  $i_1$  builds up gradually + attains maximum value  $I_o$  at an angle  $(\alpha + \mu)$ .

Next the thyristors  $T_3 + T_4$  are triggered at  $(\pi + \alpha)$ . At this time, the current  $i_1$  (through  $T_1 + T_2$ ) decreases gradually from  $I_o$  to 0 at  $(\pi + \alpha + \mu)$  and current  $i_2$  through  $T_3 + T_4$  increases from 0 to  $I_o$  at  $(\pi + \alpha + \mu)$  and this process repeats at each firing.

Here we can see that during the period ' $\mu$ ', all thyristors  $T_1, T_2, T_3 + T_4$  are conducting. i.e. during the period ' $\mu$ ', the o/p voltage will be 0.



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

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

$$\therefore V_o = \frac{V_m}{\pi} \int_{\alpha + \mu}^{\alpha + \pi} \sin \omega t \, d\omega t$$

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

$$V_o = \frac{V_m}{\pi} \left[ \cos \alpha + \cos (\alpha + \mu) \right] \rightarrow (1)$$

Now load current  $I_o$  ~~increases~~ during turn on of  $T_1 + T_2$  is zero at ' $\alpha$ ' & builds up to  $I_o$  at ' $\alpha + \mu$ '

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

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

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

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

$$\text{ii } \frac{di_1}{dt} - \frac{di_2}{dt} = \frac{2V_m}{L_s} \sin \omega t \rightarrow (2)$$

Since load current is assume to be constant  $\text{ii } i_1 + i_2 = I_o$

$$\frac{di_1}{dt} + \frac{di_2}{dt} = 0 \rightarrow (3)$$

adding ② + ③

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

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

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

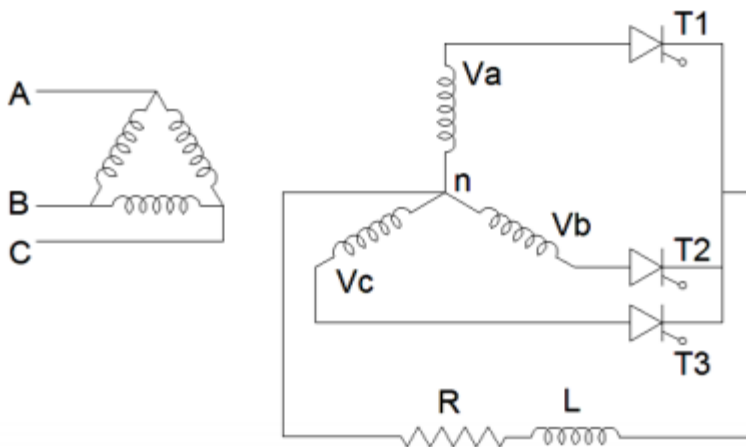
$$\left. \begin{array}{l} \omega t = \alpha \\ \therefore t = \frac{\alpha}{\omega} \end{array} \right\} \text{lower limit}$$

$$\left. \begin{array}{l} \omega t = \alpha + \pi \\ \therefore t = \frac{\alpha + \pi}{\omega} \end{array} \right\} \text{upper limit}$$

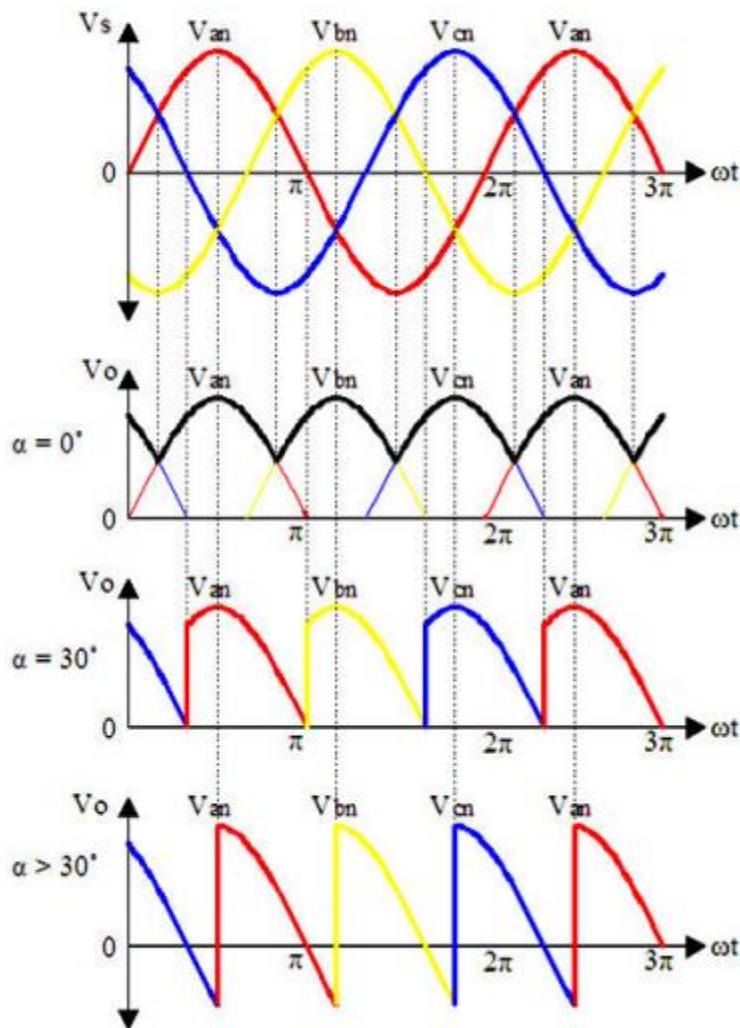
$$\therefore I_o = \frac{V_m}{\omega L_s} \left[ \cos \frac{\alpha}{\omega} - \cos \frac{(\alpha + \pi)}{\omega} \right]$$

$$\therefore I_o = \frac{V_m}{\omega L_s} [\cos \alpha - \cos (\alpha + \pi)]$$

**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

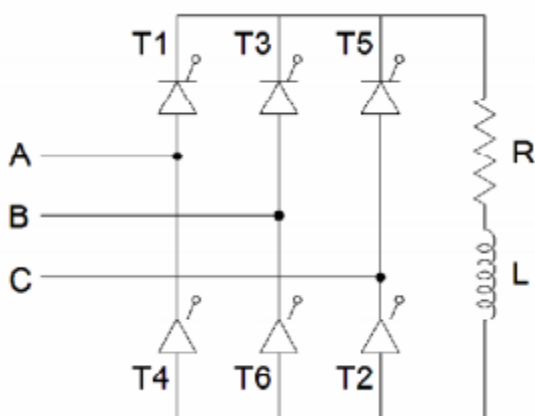
- The circuit consists of a delta star transformer and 3 thyristors T1, T2, T3 which are connected on the secondary star connected winding and a RL load.
- When  $V_a$  is positive, T1 becomes forward biased and conducts. During the negative cycle of  $V_a$ , the current through T1 is not zero due to inductor present in the load.
- So T1 will remain ON during the negative cycle of  $V_a$
- When  $V_b$  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  $V_b$ , the current through T2 is not zero due to inductor present in the load.
- So T2 will remain ON during the negative cycle of  $V_b$
- When T3 is triggered during positive cycle of  $V_c$ , the load current is transferred from T2 to T3. At this instant, T2 turns OFF

- Similarly T3 conducts during the negative cycle of  $V_c$  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,  $V_a$  is denoted as  $V_{an}$ ,  $V_b$  as  $V_{bn}$ ,  $V_c$  as  $V_{cn}$ .

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

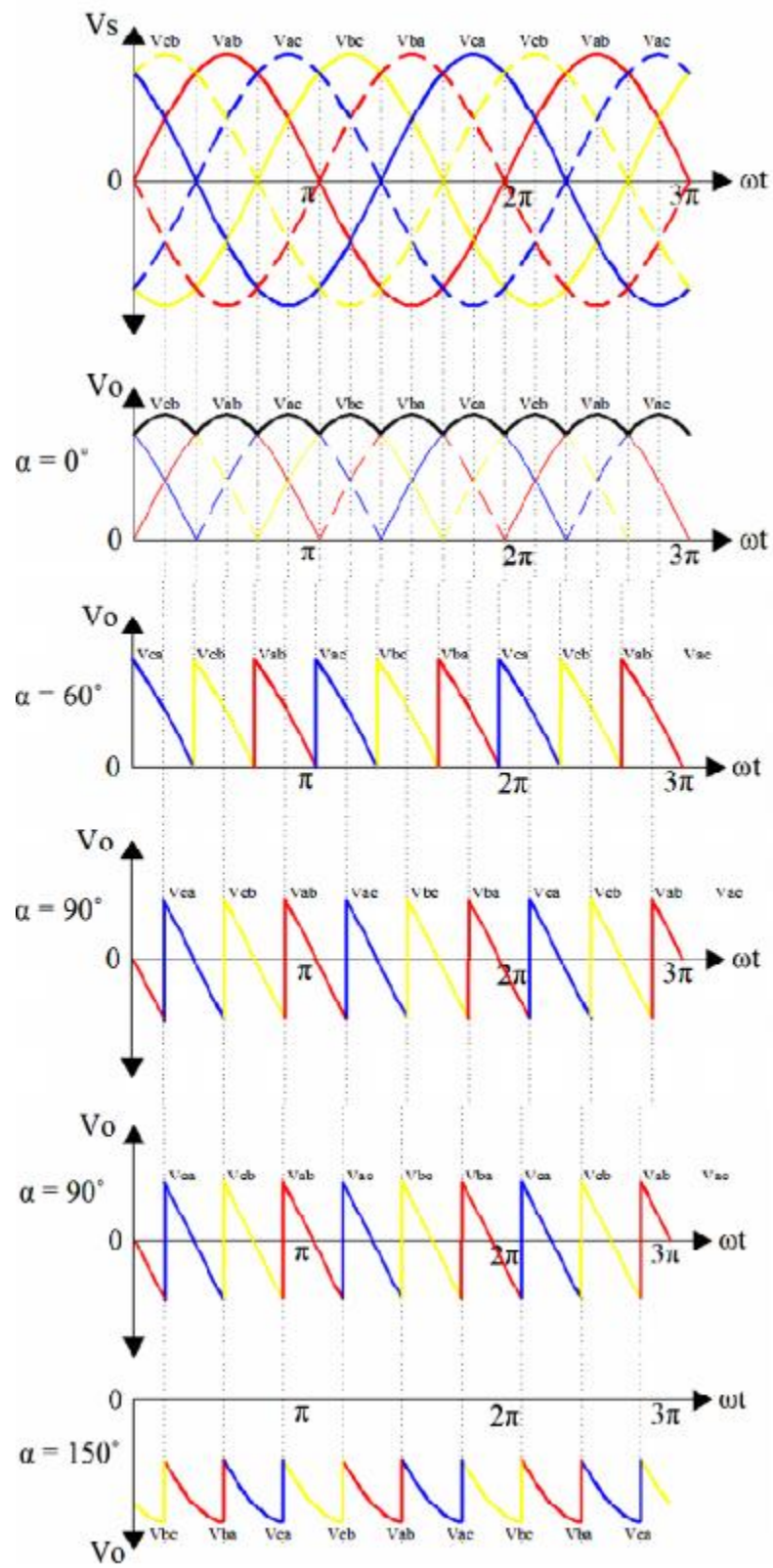
- The circuit consist of a delta star transformer and 3 thyristors T1, T2, T3 which are connected on the secondary star connected winding and a RL load.
- When  $V_a$  is positive, T1 becomes forward biased and conducts. During the negative cycle of  $V_a$ , the current through T1 is not zero due to inductor present in the load.
- So T1 will remain ON during the negative cycle of  $V_a$  • When  $V_b$  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  $V_b$ , the current through T2 is not zero due to inductor present in the load.
- So T2 will remain ON during the negative cycle of  $V_b$
- When T3 is triggered during positive cycle of  $V_c$ , the load current is transferred from T2 to T3. At this instant, T2 turns OFF
- Similarly T3 conducts during the negative cycle of  $V_c$  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,  $V_a$  is denoted as  $V_{an}$ ,  $V_b$  as  $V_{bn}$ ,  $V_c$  as  $V_{cn}$ .

#### 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.

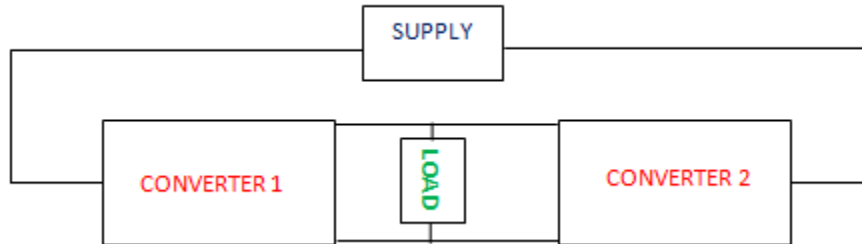
- The thyristors T1, T3, T5 form the positive group.
- The thyristors T4, T6, T2 form the negative group.
- Thyristors T1, T3, T4, T6 produces the full wave rectified output of  $V_{ab}$  across the load.
- Thyristors T3, T5, T6, T2 produces the full wave rectified output of  $V_{bc}$  across the load.
- Thyristors T1, T5, T4, T2 produces the full wave rectified output of  $V_{ca}$  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.





## 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.



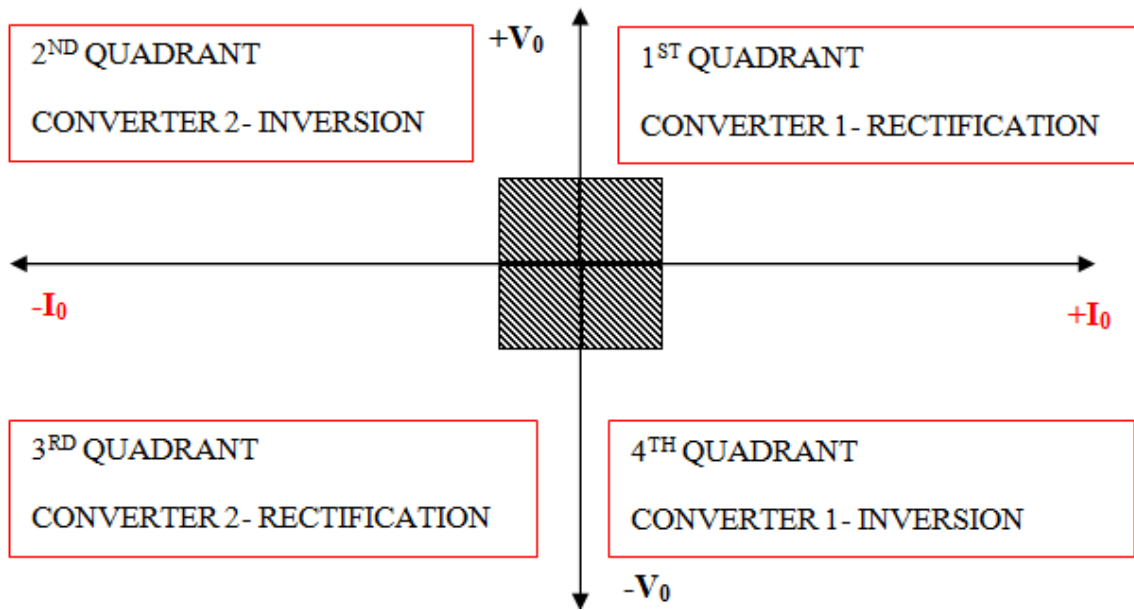
### Modes of Operation of Dual Converter

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

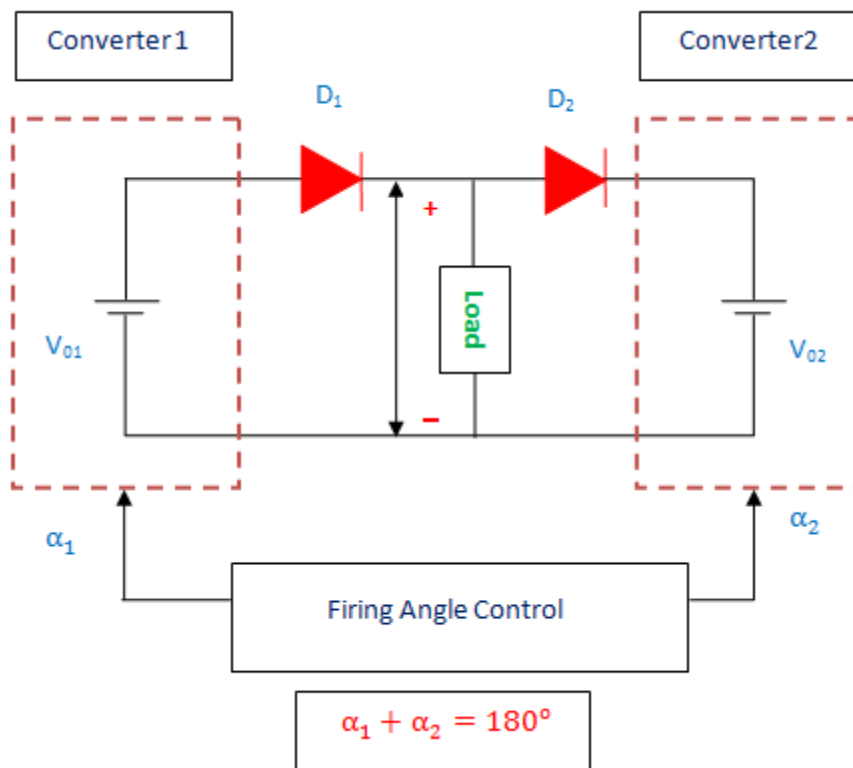
#### Circulating Current Mode

- 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 ( $\alpha_1$ ) + firing angle of converter 2 ( $\alpha_2$ ) =  $180^\circ$ .
- Converter 1 performs as a controlled rectifier when firing angle be  $0 < \alpha_1 < 90^\circ$  and Converter 2 performs as an inverter when the firing angle be  $90^\circ < \alpha_2 < 180^\circ$ . In this condition,  $V_{dc}$  and  $I_{dc}$  are positive.
- Converter 1 performs as an inverter when firing angle be  $90^\circ < \alpha_1 < 180^\circ$  and Converter 2 performs as a controlled rectifier when the firing angle be  $0 < \alpha_2 < 90^\circ$ . In this condition,  $V_{dc}$  and  $I_{dc}$  are negative.
- The four quadrant operation is shown below.



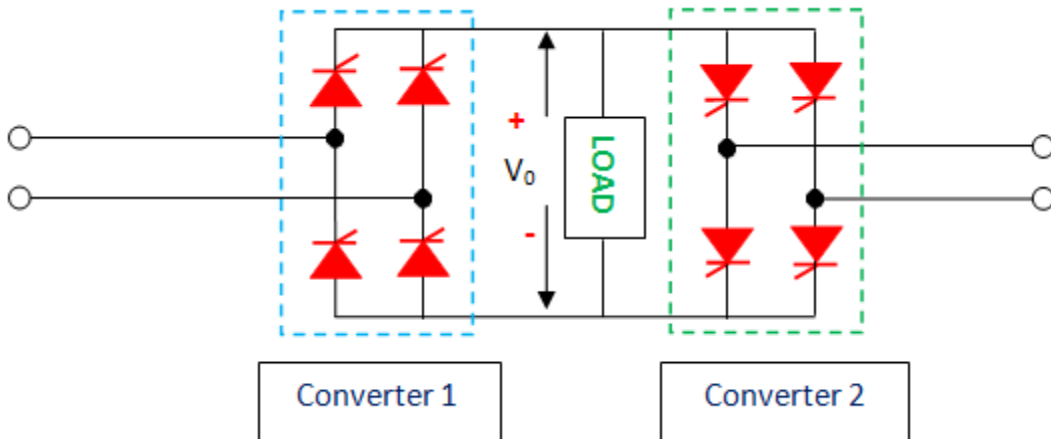
### Ideal Dual Converter

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.



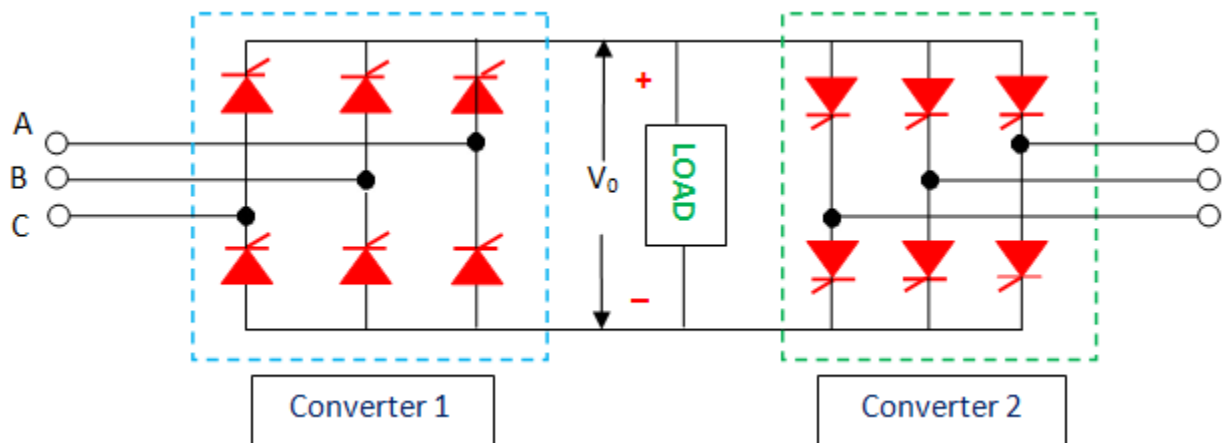
### Single Phase Dual Converter

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

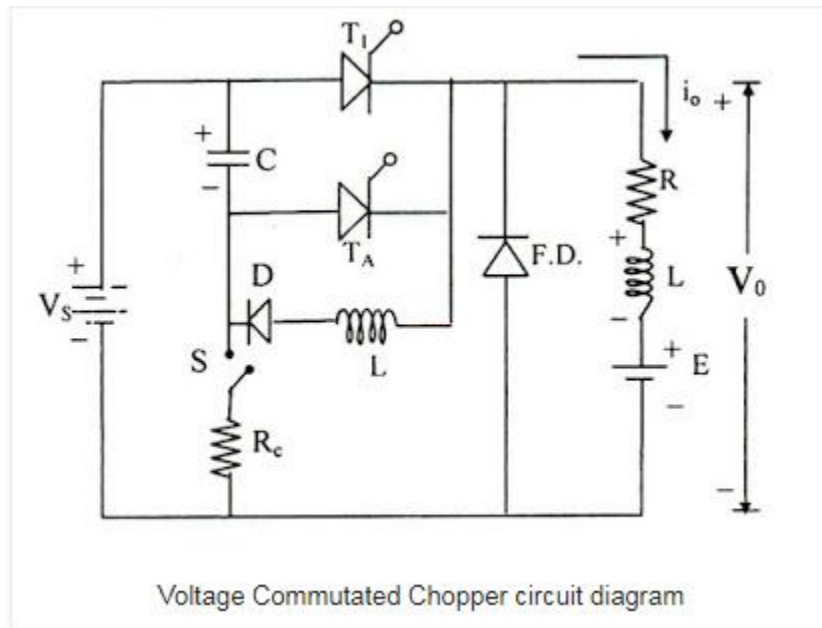
Here, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second converter. It will do the DC to AC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



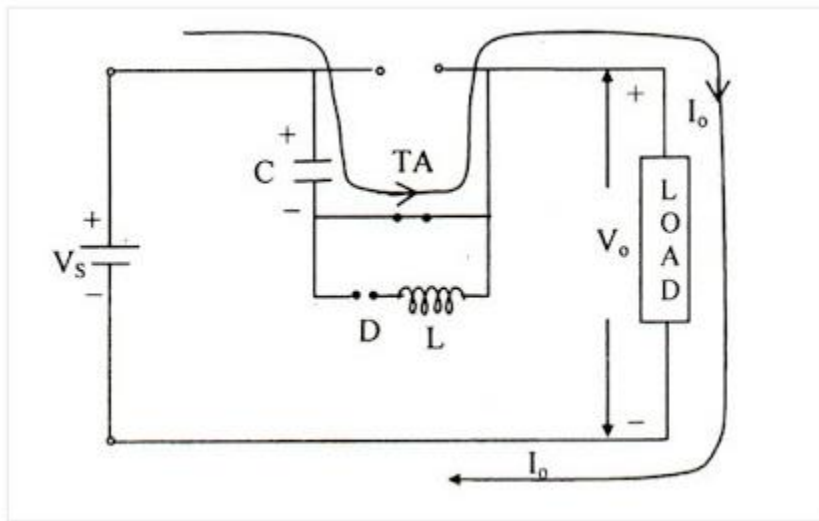
## UNIT -3

### DC TO DC CHOPPER

#### Voltage Commutated Chopper



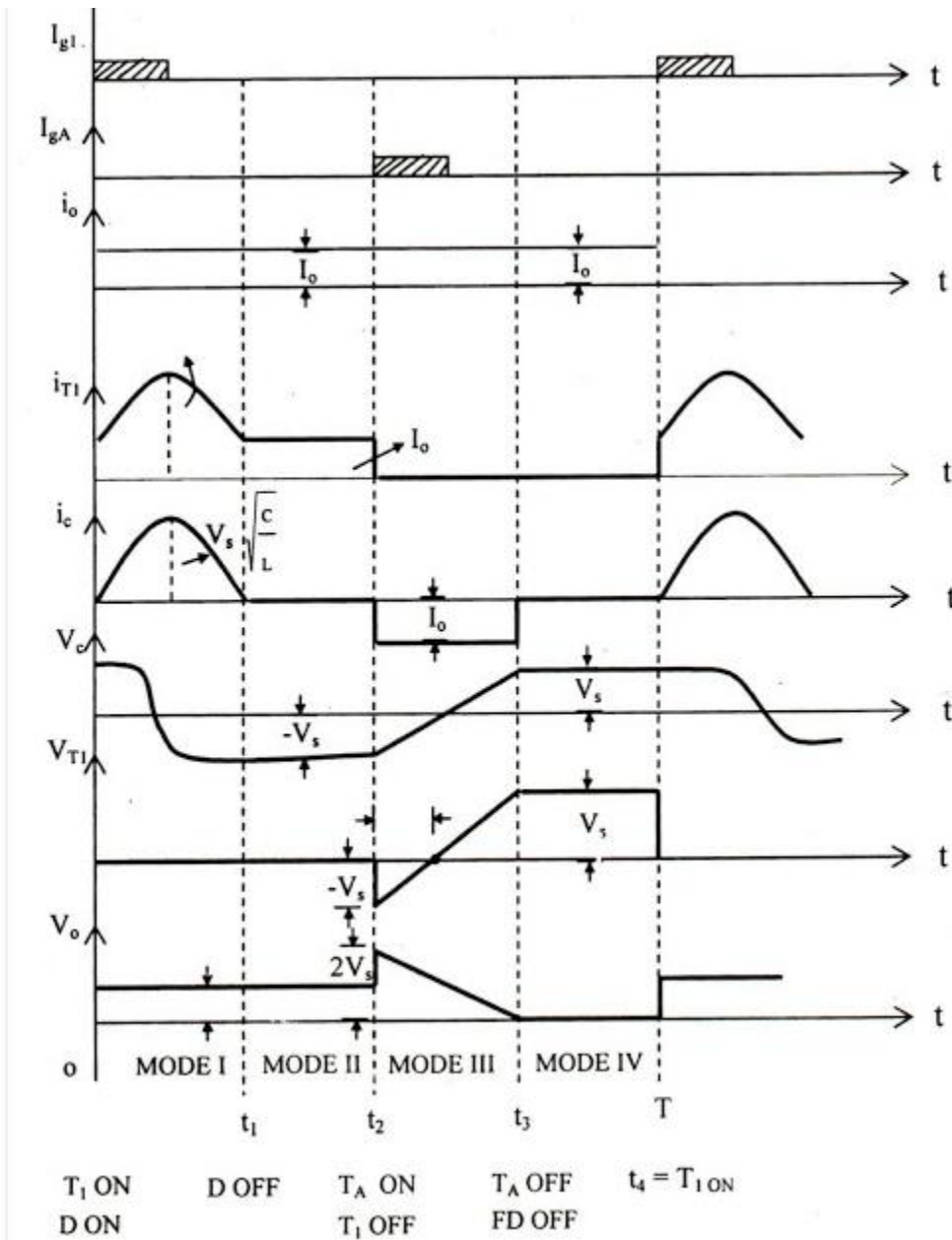
- Similar to step down chopper.
- $T_1$  = Main thyristor,  $T_A$  = Auxiliary thyristor,  $L, C$  = commutating components,  $R_c$  = charging resistor
- Assume output current is constant.
- Close the switch, initially capacitor short circuited, after 4 - 5 time constants,  $V_c = V_s$ .
- At  $t = 0$ ,  $T_1$  is on, load is connected across the supply  $V_o = V_s$ .
- Tank circuit starts conduction ( diode forward bias).
- After conduction polarities across capacitor are changed.
- $D$  is reverse biased polarities across capacitor are changed.
- Upto  $t_2$  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  $V_s$ , C, TA and the load.
- Voltage across the capacitor changes.
- Now make the voltage across capacitor  $> V_s$ .
- 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  $2V_s$  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 from  $-V_s$  to  $V_s$  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.



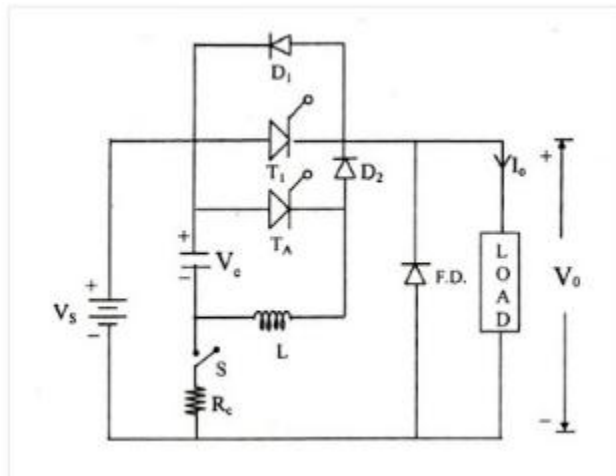
- The values of commutating components C and L can be obtained.
- The values depend upon turn off time of main thyristor T1. during  $t_c$  capacitor voltage changes from  $-V_s$  to zero linearly.
 
$$i_c = C \frac{dV}{dt} \text{ for a constant load current } I_o.$$

$$I_o = C \cdot V_s / t_c$$

$$C = I_o \cdot t_c / V_s$$
- The commutation circuit turn off time  $t_c$  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  $V_s$ , main thyristor  $T_1$  is fired at  $t = 0$ . So that load voltage  $V_o = V_s$ .
- At  $t = t_1$ , auxiliary thyristor is turned on to commutate main thyristor.
- With turning on of  $T_A$ , an oscillatory current  $i_c$  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  $t_2$ ,  $V_c = -V_s$  and  $i_c$  tends to reverse in the auxiliary thyristor  $T_A$ , it gets naturally commutated.
- As  $T_A$  is reverse biased and turned off at  $t_2$ . Oscillatory current  $i_c$  begins to flow through  $C$ ,  $L$ ,  $D_2$  and  $T_1$ .
- At  $t_3$   $i_c$  rises to  $i_o$  so that  $i_{T1} = 0$ . As a result main SCR  $T_1$  is turned off at  $t_3$ . Since oscillating current through  $T_1$  turns it off it is called current commutated chopper.
- After  $t_3$   $i_c$  supplies load current  $i_o$  and the excess current.  $i_{D1} = i_c - i_o$  is conducted through diode  $D_1$ .
- After  $t_4$ , a constant current equal to  $i_o$  flows through  $V_s$ ,  $C$ ,  $L$ ,  $D_2$  and load.
- Capacitor  $c$  is charged linearly to source voltage  $V_s$  at  $t_5$ , so during time  $(t_5 - t_4)$   $i_c = i_o$ .
- 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

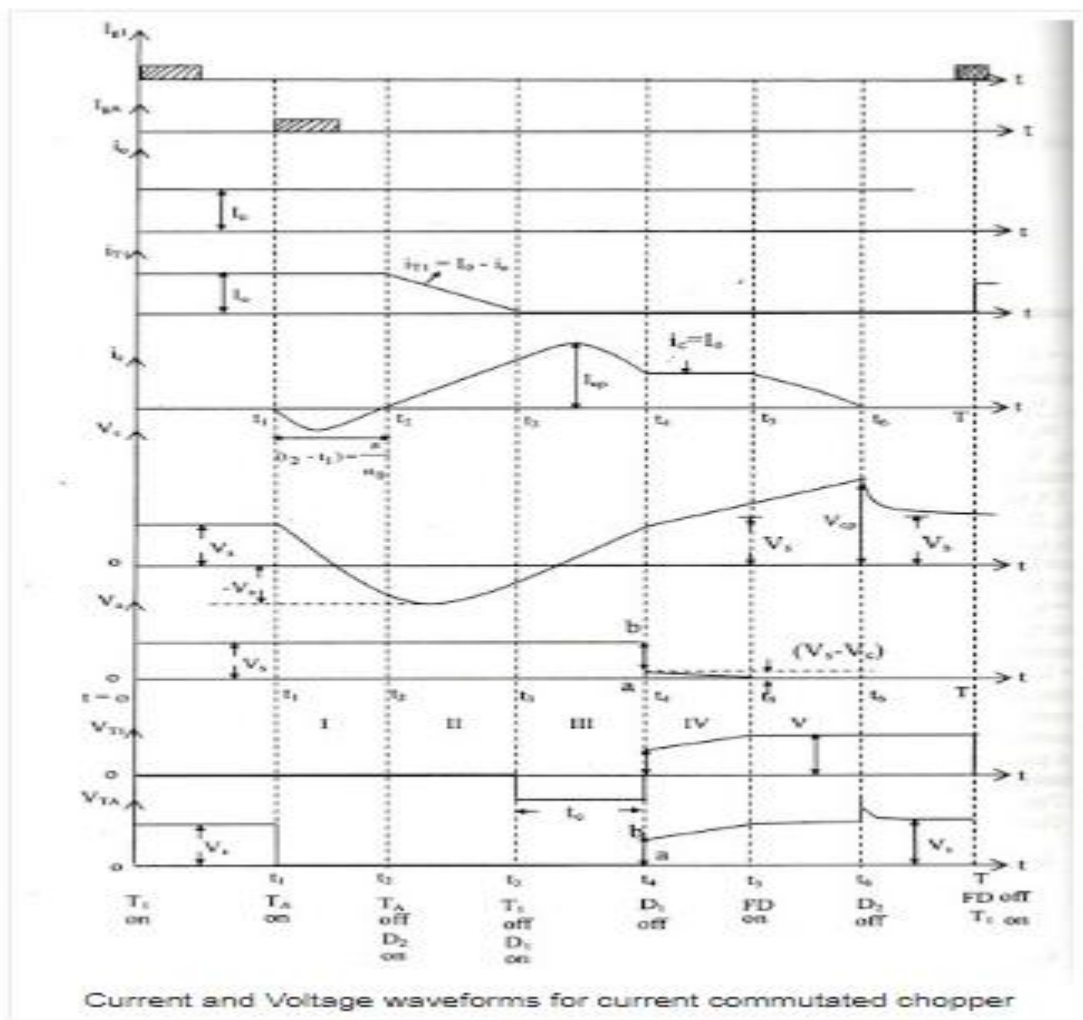
1. Turn off time increases.
2. Turn off power loss increases.

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

$$\text{where } x = \frac{I_{cp}}{I_o}$$

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

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





## UNIT - 3

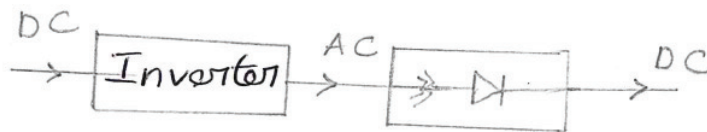
### DC To DC CHOPPER

\* Many Industrial Applns. require power from dc voltage source.

⇒ Subway cars, trolley buses

Two types of dc to dc converters :-

(i) Ac Link Chopper



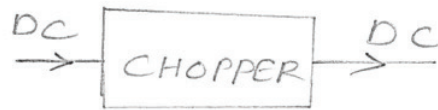
→ dc is first converted to ac by an inverter (dc to ac converter)

→ 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 :-

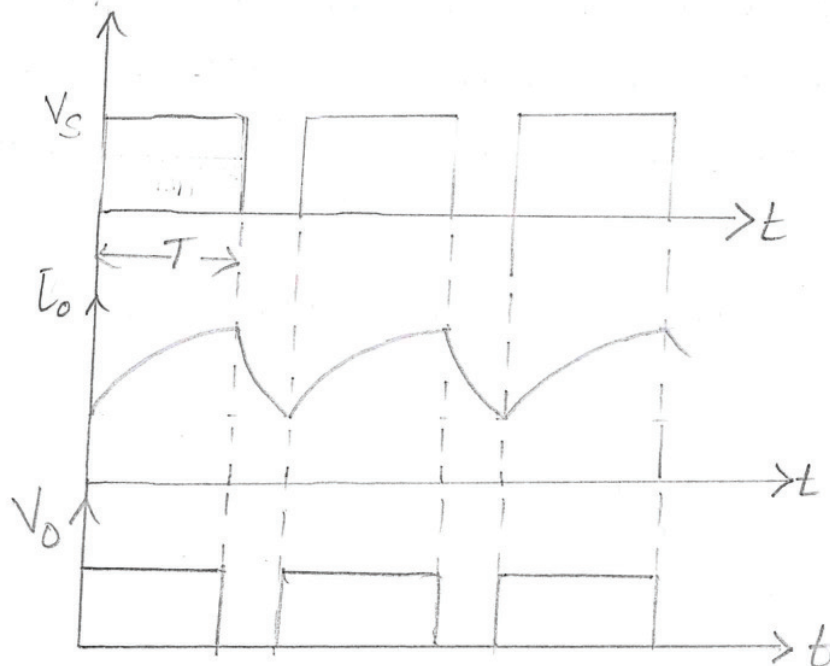
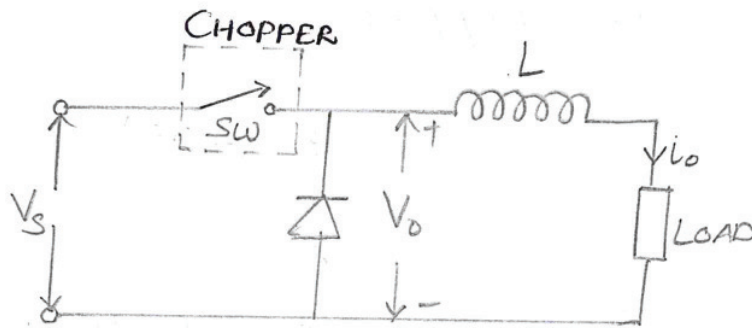


→ Direct conversion (one stage conversion)

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

→ Power BJT, Power MOSFET, GTO or IGBT

### 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  $T_{ON} \rightarrow$  load current rises  
 $T_{OFF} \rightarrow$  load current decays.

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

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

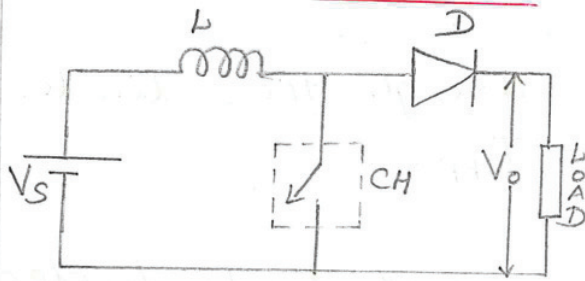
$T_{on} \rightarrow$  on-time

$T_{off} \rightarrow$  Off-time

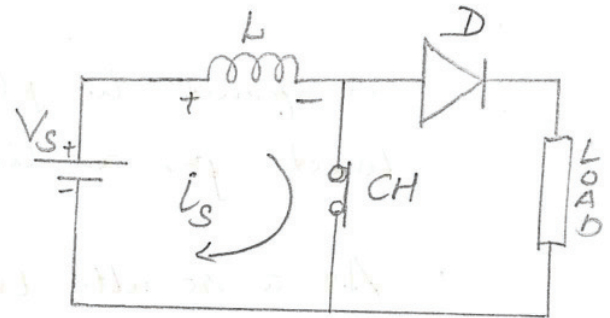
$T = T_{on} + T_{off}$  (Chopping Period)

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

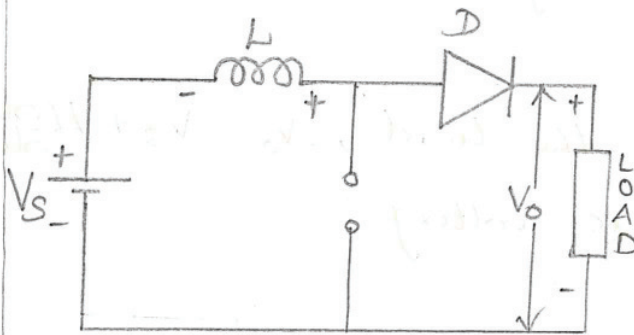
# STEP UP CHOPPERS :-



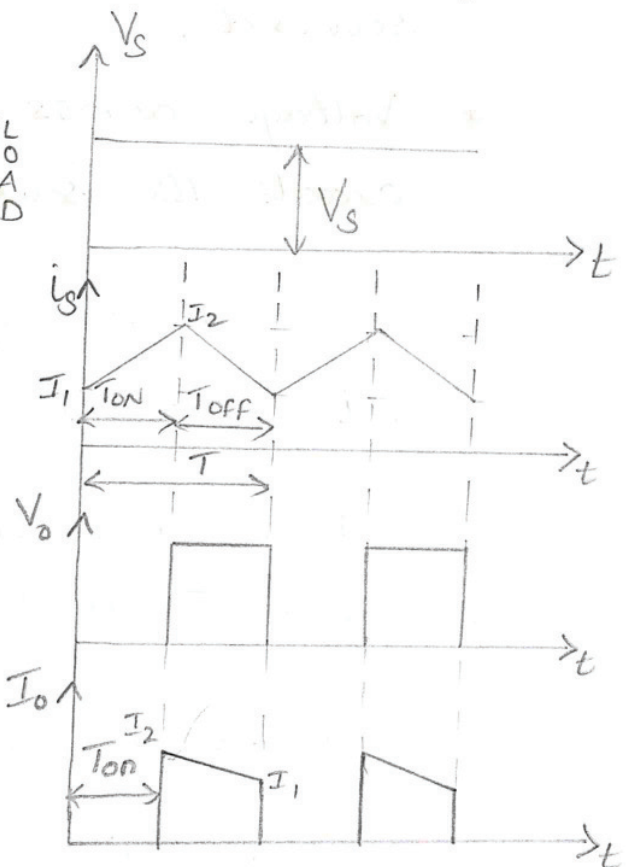
(a) Step-up chopper



(b) L stores charge



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



\* Avg. ofp voltage  $V_o$  greater than the input voltage  $V_s$ .

$$V_o > V_s$$

⇒ Called as step-up chopper.

\* Inductor 'L' is series with source vge  $V_s$ .

\* When CH is on, the inductor stores the energy.

\* During  $T_{on} \rightarrow L$  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.

$\Rightarrow$  When CH is ON, the current thru. the inductance  $L$  would rise from  $I_1$  to  $I_2$ .

$\Rightarrow$  When CH is OFF, current would fall from  $I_2$  to  $I_1$ .

$$\Rightarrow CH \rightarrow ON \rightarrow V_s = V_L$$

$$CH \rightarrow OFF \rightarrow V_L = V_o - V_s$$

$$V_L \rightarrow \text{vge across } L.$$

$$\text{Avg. ofp vge, } V_o = V_s \left( \frac{T}{T_{off}} \right)$$

$$V_o = V_s \left( \frac{1}{1-d} \right)$$

## Types Of CHOPPERS

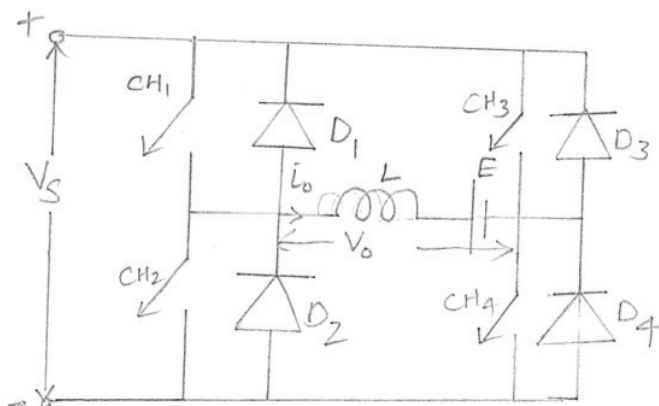
- (i) First quadrant (or) Type-A chopper
- (ii) Second quadrant (or) Type-B chopper
- (iii) Two quadrant type A chopper (or)  
Type C chopper
- (iv) Two-quadrant Type B chopper (or)  
Type D chopper
- (v) Four quadrant chopper (or) Type E chopper.

---

### 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.

\*  $CH_1$  &  $CH_4 \rightarrow ON \rightarrow V_o = V_s$ ; load current begins to flow.

\*  $V_o$  &  $I_o$  are +ve (I quadrant)

$\Rightarrow$  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 source thru. diodes  $D_1$ ,  $D_4$ .

\*  $(E + L \frac{di}{dt})$  is more than source voltage  $V_s$ .



\* Load Voltage  $V_o$  is positive

$I_o$  is negative

⇒ Second quadrant operation of chopper.

\* Power is fed 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  $V_o$ ,  $I_o$  are negative

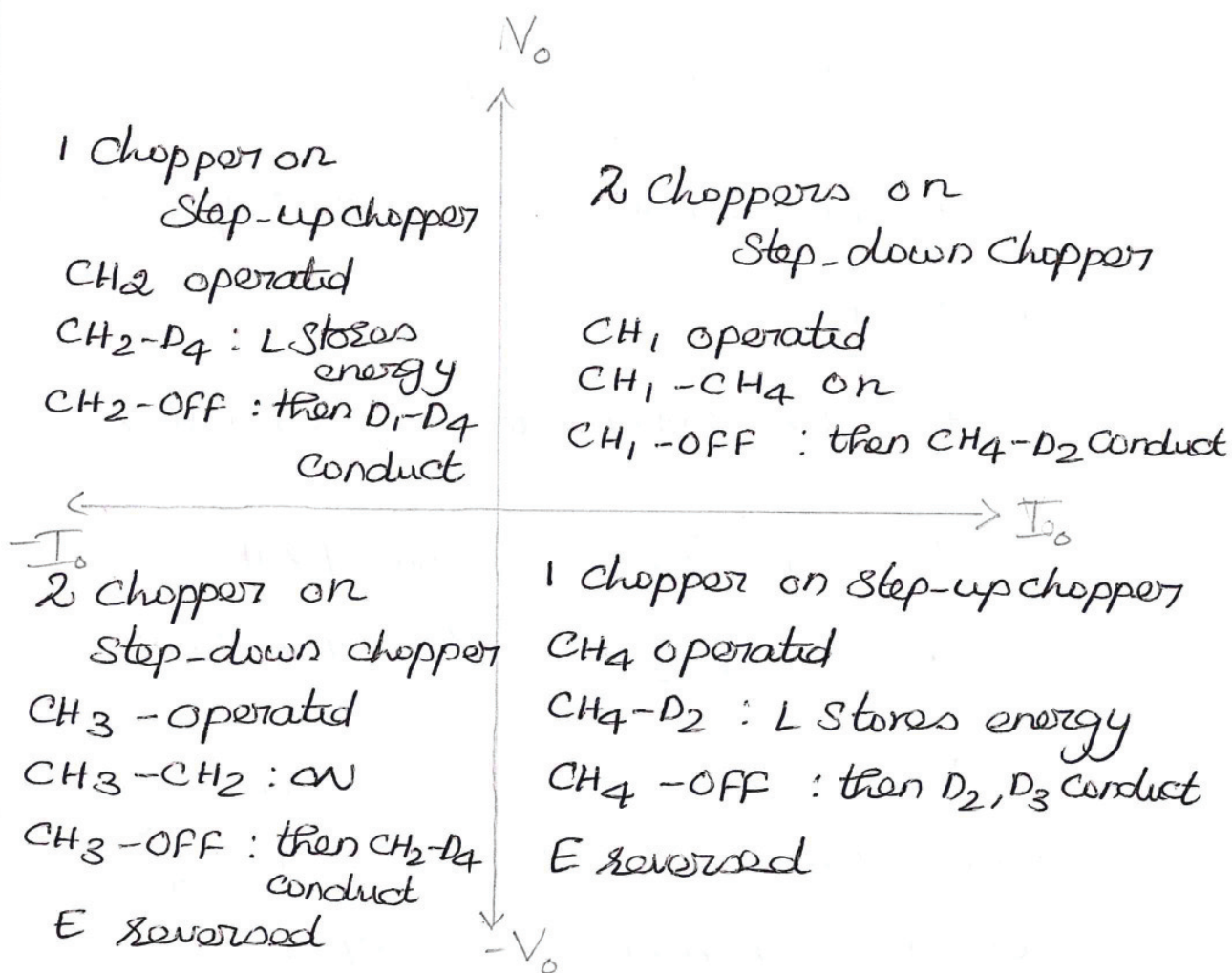
⇒ Third Quadrant operation.

\*  $CH_3 \rightarrow$  turned off, negative current freewheels through  $CH_2$ ,  $D_4$ .

\* Load Voltage  $V_o$  is negative

$I_o$  is negative

"Step-down chopper".

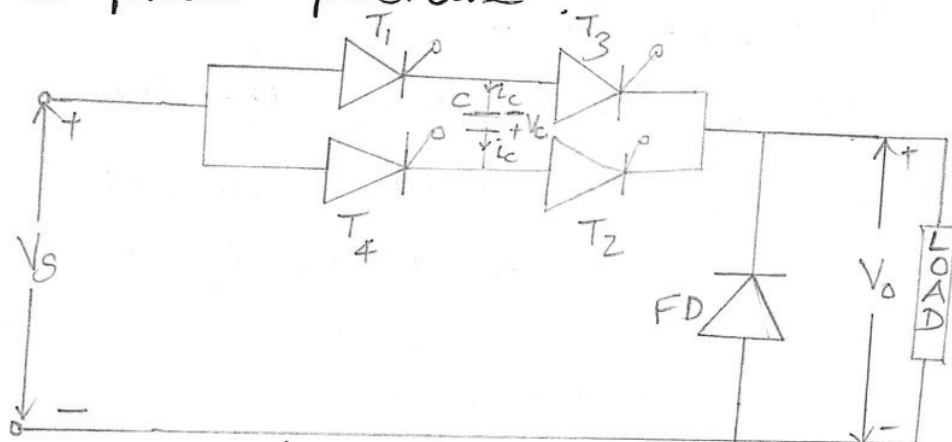


Fourth Quadrant :-

- \*  $CH_4$  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  $CH_4 \rightarrow$  turned OFF, current is fed back to source through diodes  $D_2, D_3$ .
  - \*  $V_o \rightarrow$  negative &  $I_o \rightarrow$  Positive
  - \* Power is fed back from Load to source
- $\Rightarrow$  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  $c$ .
- \*  $T_1, T_2 \Rightarrow$  ONE PAIR
- \*  $T_3, T_4 \Rightarrow$  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  $t=0$ , 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 at once shoots to  $V_o = V_s + V_c = 2V_s$ .

\* Load current now flows from source to load.

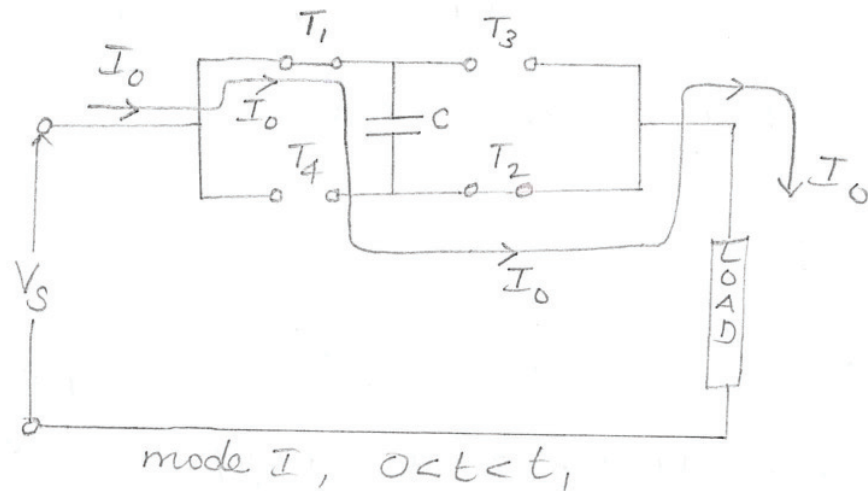
\* The capacitor 'C' is charged linearly by constant load current  $I_o$  from  $V_s$  at  $t=0$  to  $(-V_s)$  at  $t_1$ .

\* When the capacitor voltage becomes  $(-V_s)$ , the load voltage falls from  $2V_s$  to  $V_o = V_s - V_s = 0$

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

i.e) 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 II :-

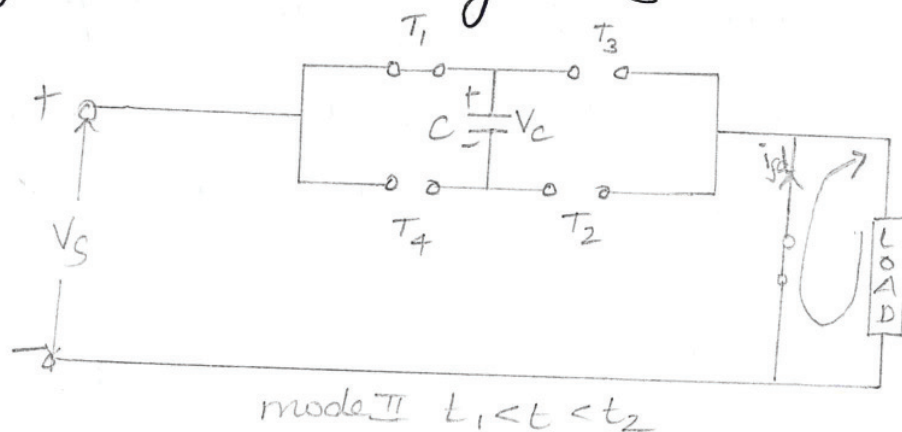
\* At  $t_1$ , capacitor  $C$  is slightly overcharge as a result freewheeling diode gets forward biased & load current is transferred from  $T_1, T_2$  to FD.

\* From  $t_1$  onwards load current freewheels through FD.

\* During  $(t_2 - t_1)$ ,  $V_C = -V_S$ ,  $V_o = 0$ ,  $i_c = 0$ ,

$i_{fd} = I_0$ ,  $i_{T_1} = i_{T_2} = 0$ ;  $V_{T_3} = V_{T_4} = V_S$  &

$V_{T_1} = V_{T_2} = -\Delta V_S$  as capacitor is overcharged by a small voltage  $\Delta V_S$ .



Mode III :-

\* At  $t_2$ ,  $T_3$  &  $T_4$  is triggered load voltage  
 $V_o = V_s + V_c = 2V_s$ .

\*  $T_1$  &  $T_2 \Rightarrow$  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  $t_3$ .

$\Rightarrow$  load voltage falls from  $2V_s$  at  $t_2 = 0$  at  $t_3$ .

\*  $t_3 - t_2 \Rightarrow i_c = -I_o$

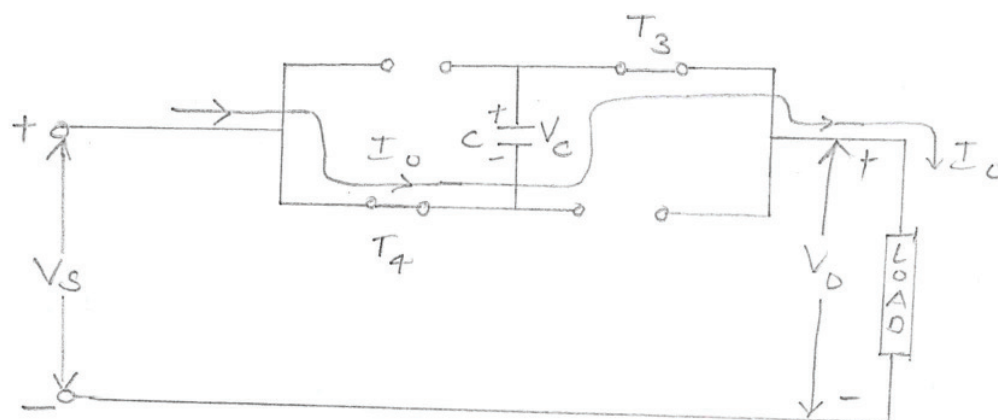
$$i_{T_3} = i_{T_4} = I_o$$

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

$\therefore T_1, T_2$  gets forward biased at  $t_3$ .

\* At  $t_3$  capacitor 'C' is overcharged, FD gets forward biased & therefore after  $t_3$ , load current free wheels through FD & load.

$\Rightarrow$  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) total change in  $v_{ce}$  is  $2V_s$  in time  $T_{on}$ .

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

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

$$\text{OFF Voltage, } V_o = \frac{1}{2}(2V_s)T_{on} \cdot \frac{1}{T}$$

$$V_o = V_s T_{on} f \longrightarrow \textcircled{2}$$



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

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

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

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

∴ Max. chopping freq,

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

$$\text{From eqn (1)} \Rightarrow C = \frac{I_0}{2V_s} \cdot \frac{1}{f_{max}}$$

The circuit turn off time

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

$$t_c = \frac{C V_s}{I_0}$$

$$\text{Total commutation interval, } T_{on} = \frac{2C V_s}{I_0}$$



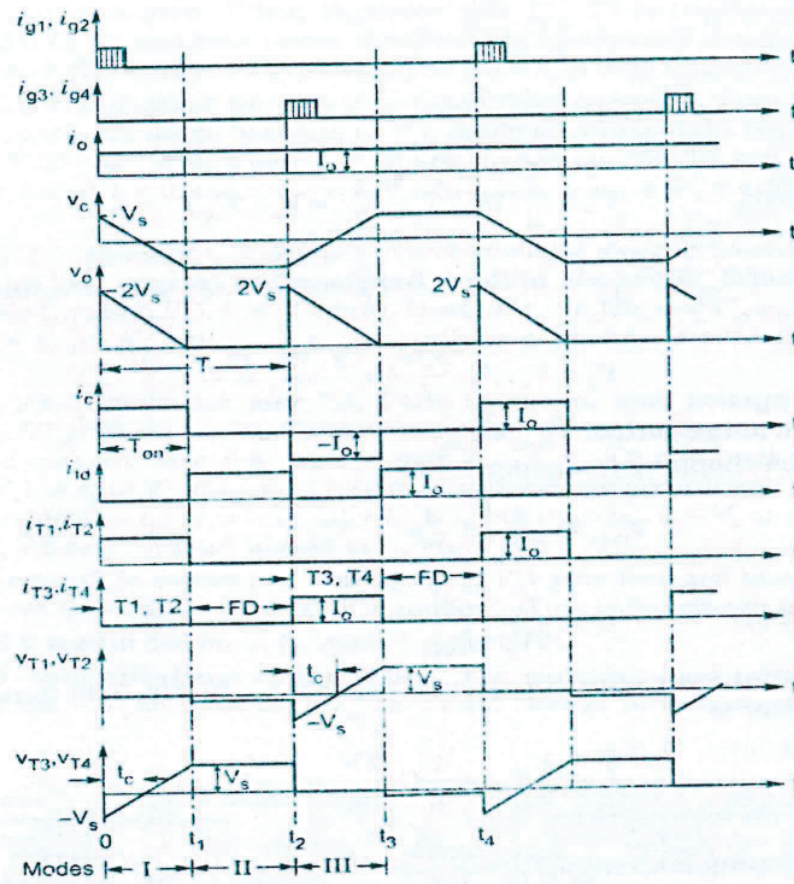


Fig. 7.33. Voltage and current waveforms for a load-commutated chopper.

### 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 to twice the supply voltage. This can be rectified by filtering.
- (ii) For high power applications, efficiency may become low because of higher switching losses at high operating frequency.
- (iii) Freewheeling diode is subjected to twice the supply voltage.
- (iv) Commutating capacitor has to carry full load current at a frequency of half the chopping frequency.
- (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 = 230V, load resistance =  $10\Omega$ . Take a voltage drop of 2V across chopper when it is on. For a duty cycle of 0.4. Calculate

- Average & rms values of o/p vge
- 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.

$$\therefore \text{Avg. o/p vge} = \frac{(V_s - 2)T_{on}}{T} = \alpha(V_s - 2)$$
$$= 0.4(230 - 2) = 91.2V$$

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,

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

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

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

$$P_i = 2097.6 \text{ W}$$

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

$$= 99.13\%$$


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## UNIT - 4

### INVERTERS

A device that converts dc power into ac power at desired  $V_{ge}$  & freq. is called as an INVERTER.

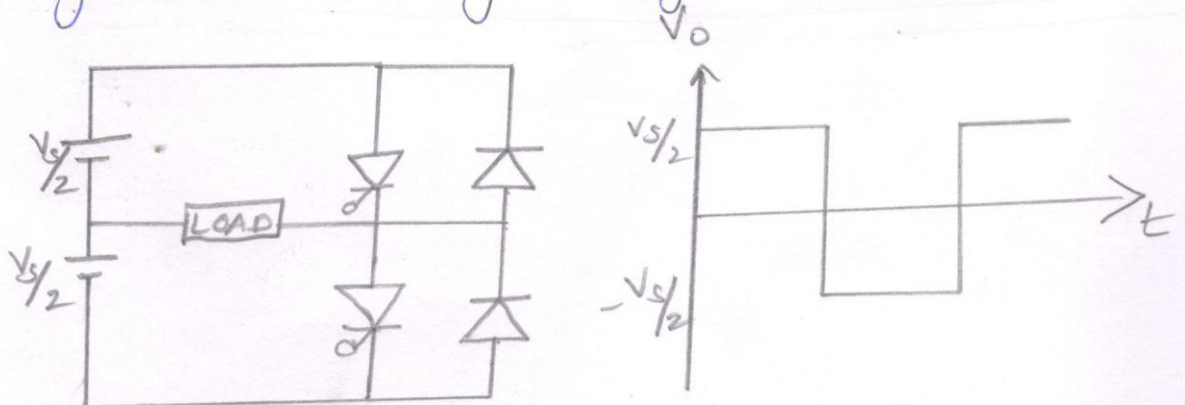
#### Classification

- (1) Bridge Inverter
- (2) Series Inverter
- (3) Parallel Inverter.

#### 1, (i) Single-Phase $V_{ge}$ Source Inverters:-

- \* 1 $\phi$  Half-bridge inverter
- \* 1 $\phi$  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 d.c supply.

$$V_o = V_s/2 \quad 0 < t < T/2$$

$$-V_s/2 \quad T/2 < t < T$$



## 2, Voltage Control In Single Phase Inverters :-

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

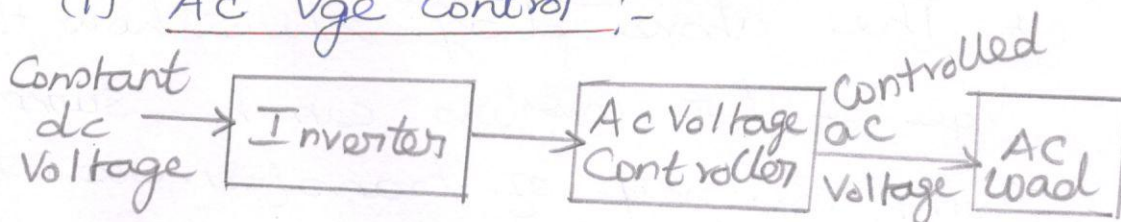
Various Methods :-

- (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.

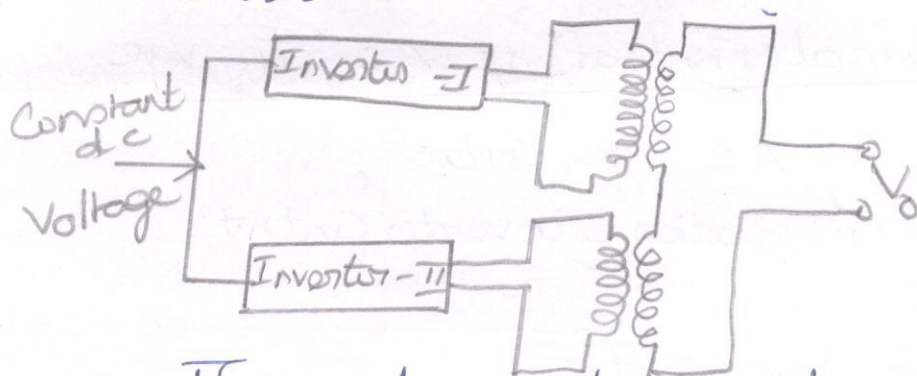


\* This method gives rise to higher harmonic content in the stp vge; particularly when stp vge from the ac vge controller is at low level.

→ rarely employed except for low power appls.

## (ii) Series-inverter Control :-

\* Involves the use of two or more inverters in series



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

⇒ Inverter stp is fed to 2 transformers whose secondaries are connected in series.

\* Phasor sum of the two fundamental vge  $V_{o1}$ ,  $V_{o2}$  gives the resultant fundamental vge  $V_o$ .

$$V_o = [V_{o1}^2 + V_{o2}^2 + 2 V_{o1} V_{o2} \cos \theta]^{1/2}$$



## Advantages :-

- (i) OFP vge w/f & its harmonic content are not affected appreciably as the inverter OFP 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 OFP vge varies from two or three. More power handling stages result in more losses & reduced  $\eta$  of the entire scheme.
- (ii) Filter circuit is required in all types of schemes, which rises the cost, weight & size & at the same time reduces the  $\eta$  & makes the transient response sluggish.
- (iii) As the dc i/p is used, the commutating capacitor vge also uses. This has the effect of reducing the ckt turn-off time ( $t = C \frac{V}{I}$ ) for the SCR for a constant load current.
- \* Control of dc i/p vge is not conducive for a large variation of OFP vge for a constant load current.

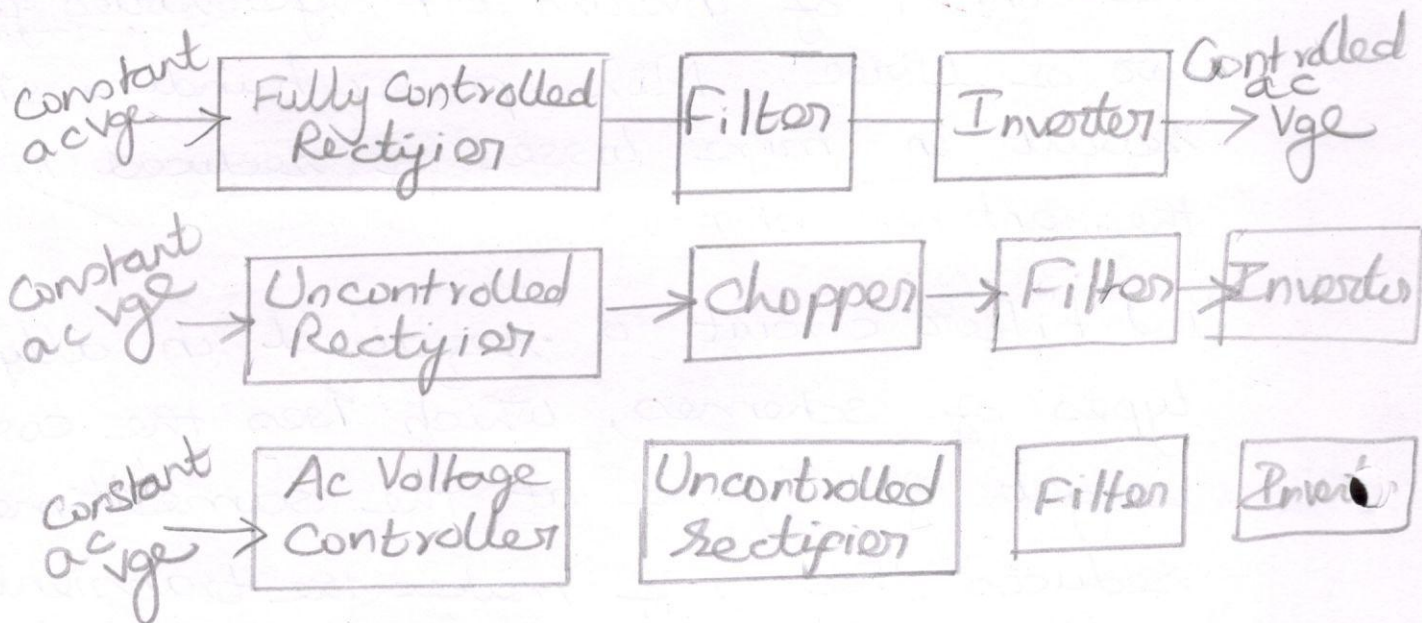


\* Freq. of o/p vges  $V_{o1}$ ,  $V_{o2}$  from the two inverters is the same.

$\Rightarrow$  When  $\theta = 0$  ;  $V_o = V_{o1} + V_{o2}$  &  
 $\theta = \pi$   $V_o = 0$  in case  $V_{o1} = V_{o2}$

\* Angle  $\theta$  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 modn. control used within an inverter.

#### Pulse Width modn. Control

→ In this method, a fixed dc i/p  $V_{ge}$  is given to the inverter & a controlled ac o/p  $V_{ge}$  is obtained by adjusting the on & off periods of the inverter components.

\* Most popular method of controlling the o/p  $V_{ge}$  & 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  $V_{ge}$  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  $\rightarrow$  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.
- $\Rightarrow$  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.

Appls :-

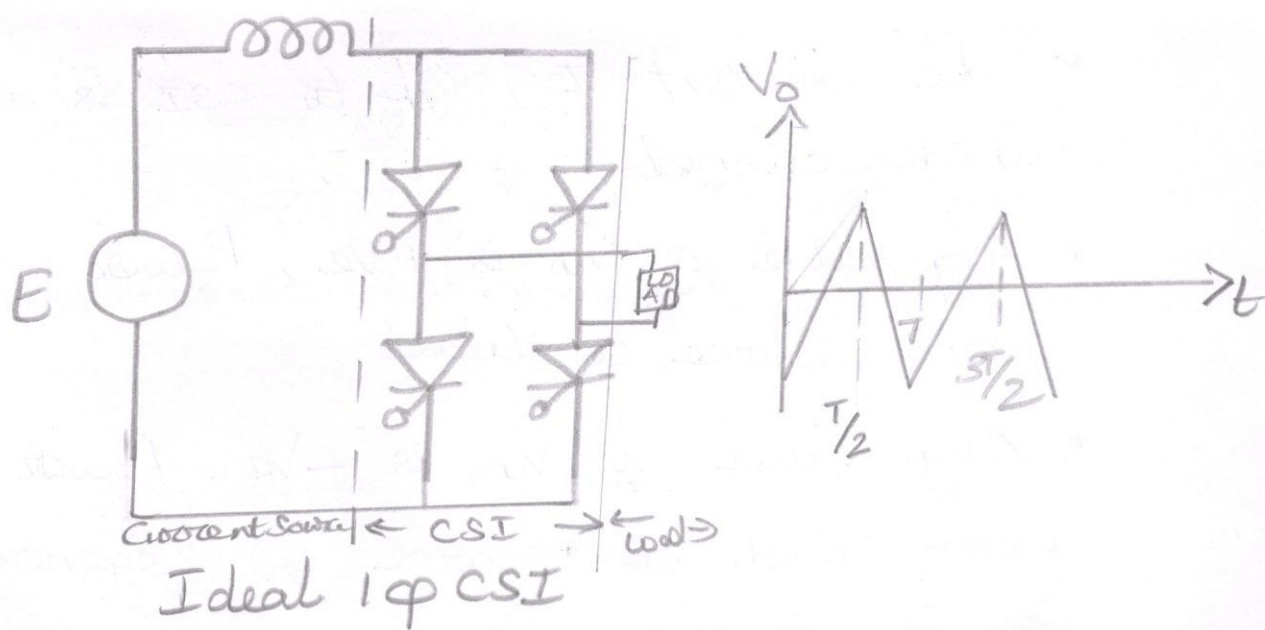
- (i) Speed Control of ac motors
- (ii) Induction heating
- (iii) Lagging Var Compensation
- (iv) Synchronous motor starting

## Single-phase CSI with Ideal Switches: -

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

\* Source consists 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.



\*  $T_1 T_2 \rightarrow ON$ ,  $i_o$  is  $+V_e$   $i_o = I$ .

$T_3 T_4 \rightarrow ON$ ,  $i_o$  is  $-V_e$  &  $i_o = -I$ .



\* 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.

$\Rightarrow$  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 (20 kHz to 100 kHz).

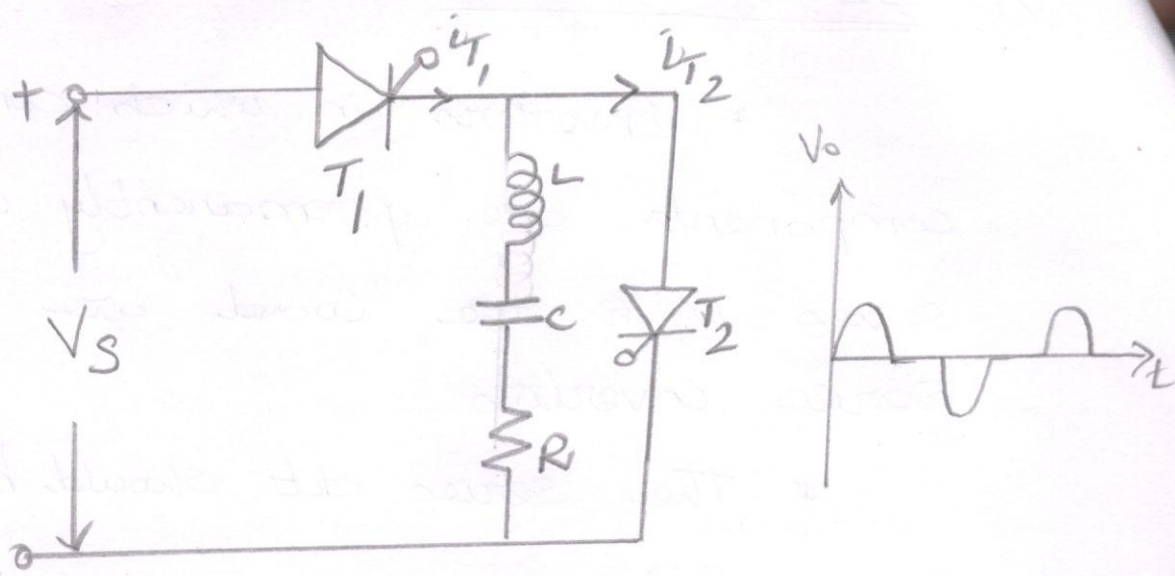
#### Basic Series Inverter :-

\* Consists of Load resistance  $R$  in series with components in) 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 building 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  $t_{qmin}$  must elapse for  $T_1$  to regain its f/d blocking capability.

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

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

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

⑦

\* time interval b/w  $T_2$  turned ~~off~~ <sup>ON</sup> &  $T_1$  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.

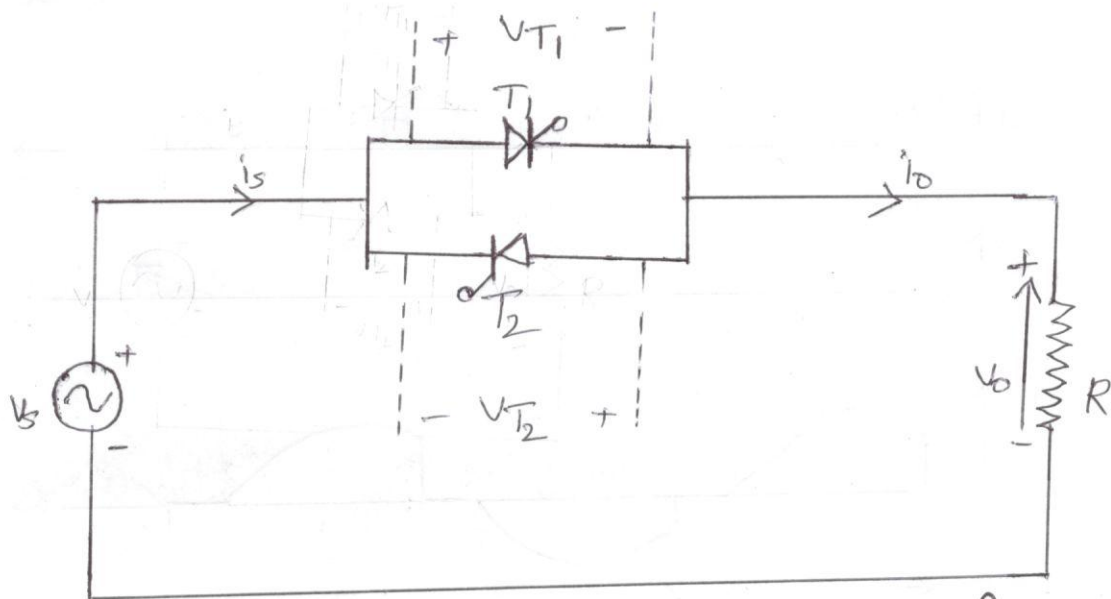
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## UNIT - V

### Single Phase full wave Ac voltage controller with R-Load.

⇒ In a Single Phase full wave Ac. Voltage controller, two thyristors are connected in anti parallel.



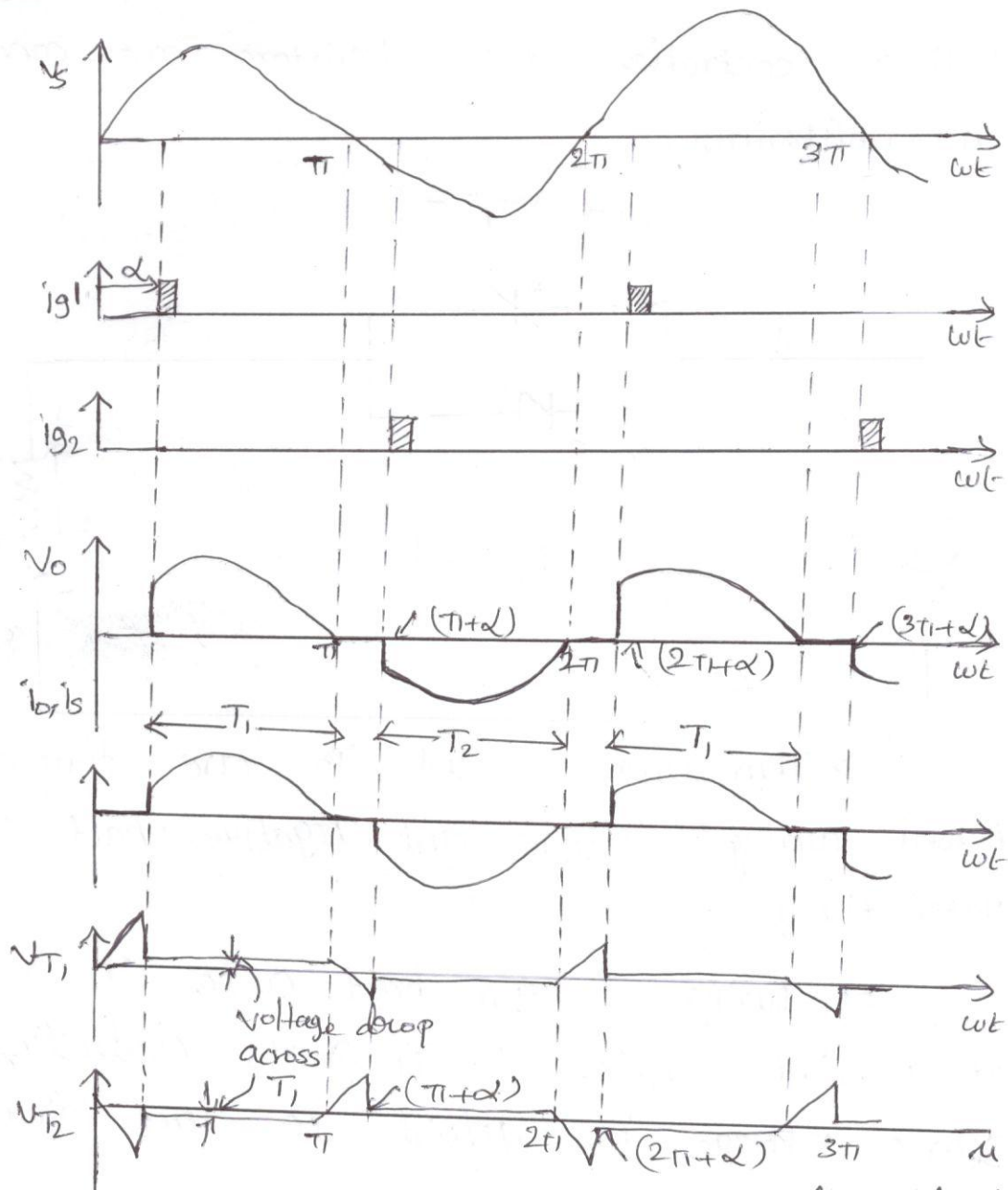
⇒ Thyristors  $T_1$  and  $T_2$  are forward-biased during positive and negative half cycles respectively.

⇒ During positive half cycle,  $T_1$  is triggered at a firing angle  $\alpha$ .  $T_1$  starts conducting and source voltage is applied to load from  $\alpha$  to  $\pi$ .

⇒ At  $\pi$ , both  $V_o$ ,  $i_o$  falls to zero. Just after  $\pi$ ,  $T_1$  is subjected to reverse bias, it is therefore turned off.



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



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

⇒ From  $\pi + \alpha$  to  $2\pi$ ,  $T_2$  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,

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

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

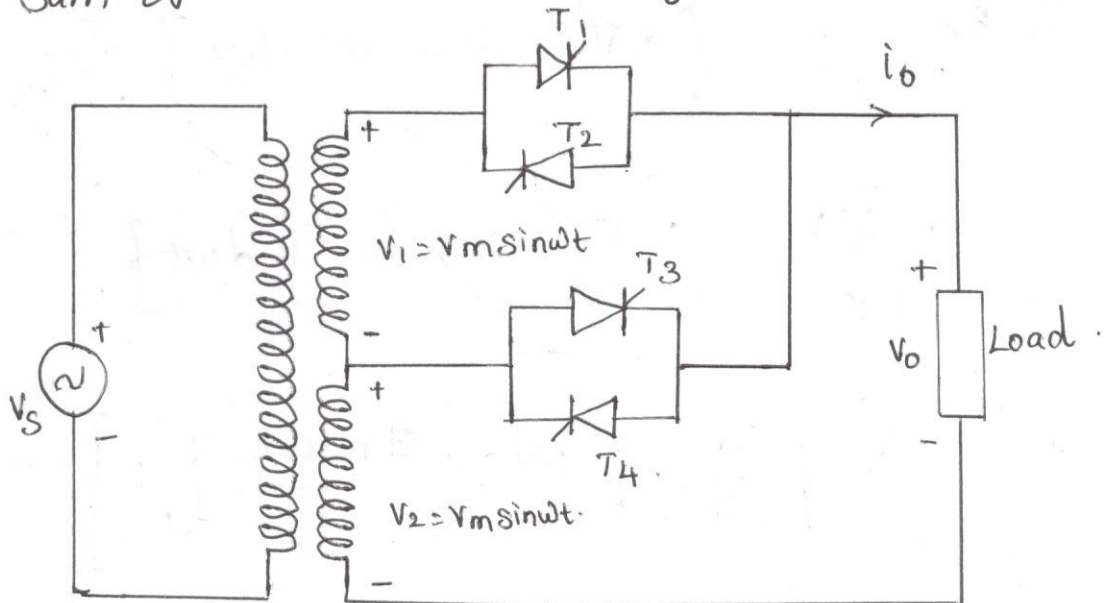
$$= V_s \left[ \frac{1}{\pi} \left[ \omega t - \frac{\sin 2\omega t}{2} \right]_{\alpha}^{\pi} \right]^{1/2}.$$

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

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

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

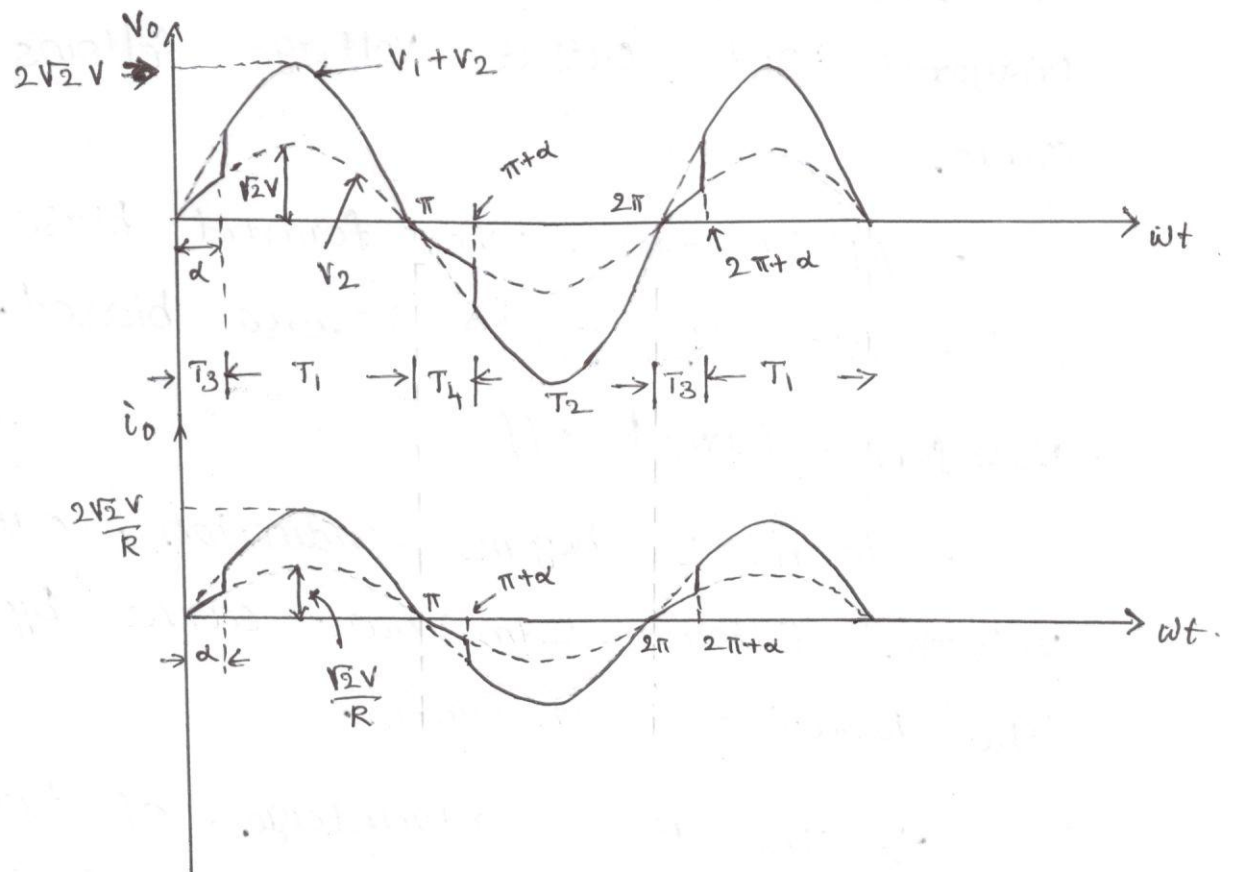
⇒ A two stage sequence control of ac voltage controller employs two stages in parallel as shown in fig. The turns ratio from primary to each secondary is taken as unity. This means that for source voltage  $V_s = V_m \sin \omega t$ ,  $V_1 = V_2 = V_m \sin \omega t$  and sum of two secondary voltage 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,  $\alpha$  is  $180^\circ$  for  $T_3, T_4$  and for  $V$ ,  $\alpha$  is zero.

$\Rightarrow$  For output voltage control from  $V$  to  $2V$ ,  
 $\alpha$  for thyristor pair  $T_3, T_4$  is always zero and  
 for thyristor pair  $T_1, T_2$ ;  $\alpha$  is varied from  
 zero to  $180^\circ$ .



$\Rightarrow$  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  $180^\circ$  to zero for obtaining output voltage from  $V$  to  $2V$ .

$\Rightarrow$  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.

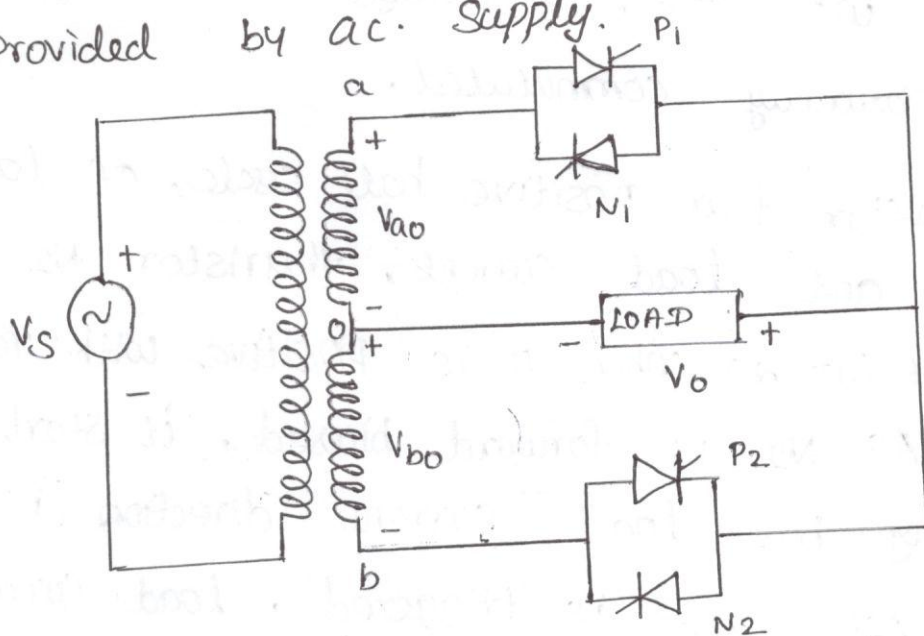
⇒ When  $T_2$  begins conduction, output voltage follows  $2V_m \sin \omega t$  curve by the negative half cycle.

⇒ 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  $\alpha$  is positive with respect to 0, forward biased SCR  $P_1$  is triggered at  $\omega t = \alpha$ . With this, load current  $i_o$  starts building up in the positive direction A to O.

⇒ Load current  $i_o$  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  $\pi$ .

⇒ After half cycle,  $b$  is positive with respect to  $o$ . 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 reverse

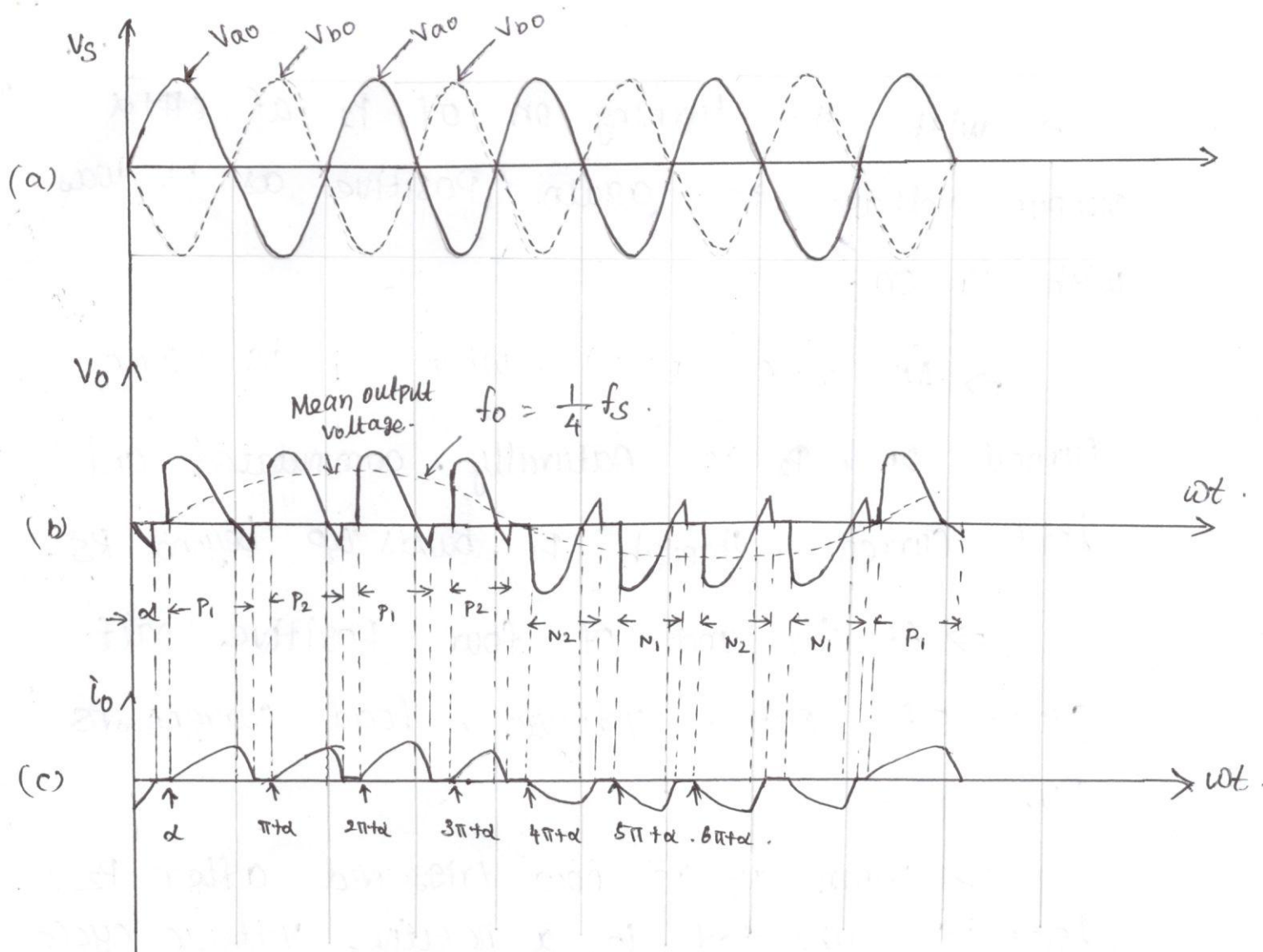
⇒ After  $N_2$  is triggered, load current builds up in the negative direction.

⇒ 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.

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



**continuous load current:**

$\Rightarrow$  when  $\alpha$  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.

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

$\Rightarrow$  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.



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

$\Rightarrow$  At  $\omega t \leq 2\pi + \alpha$ , when  $P_1$  is again turned on,  $P_2$  is naturally commutated and load current through  $P_1$  builds up beyond  $R_u$ .

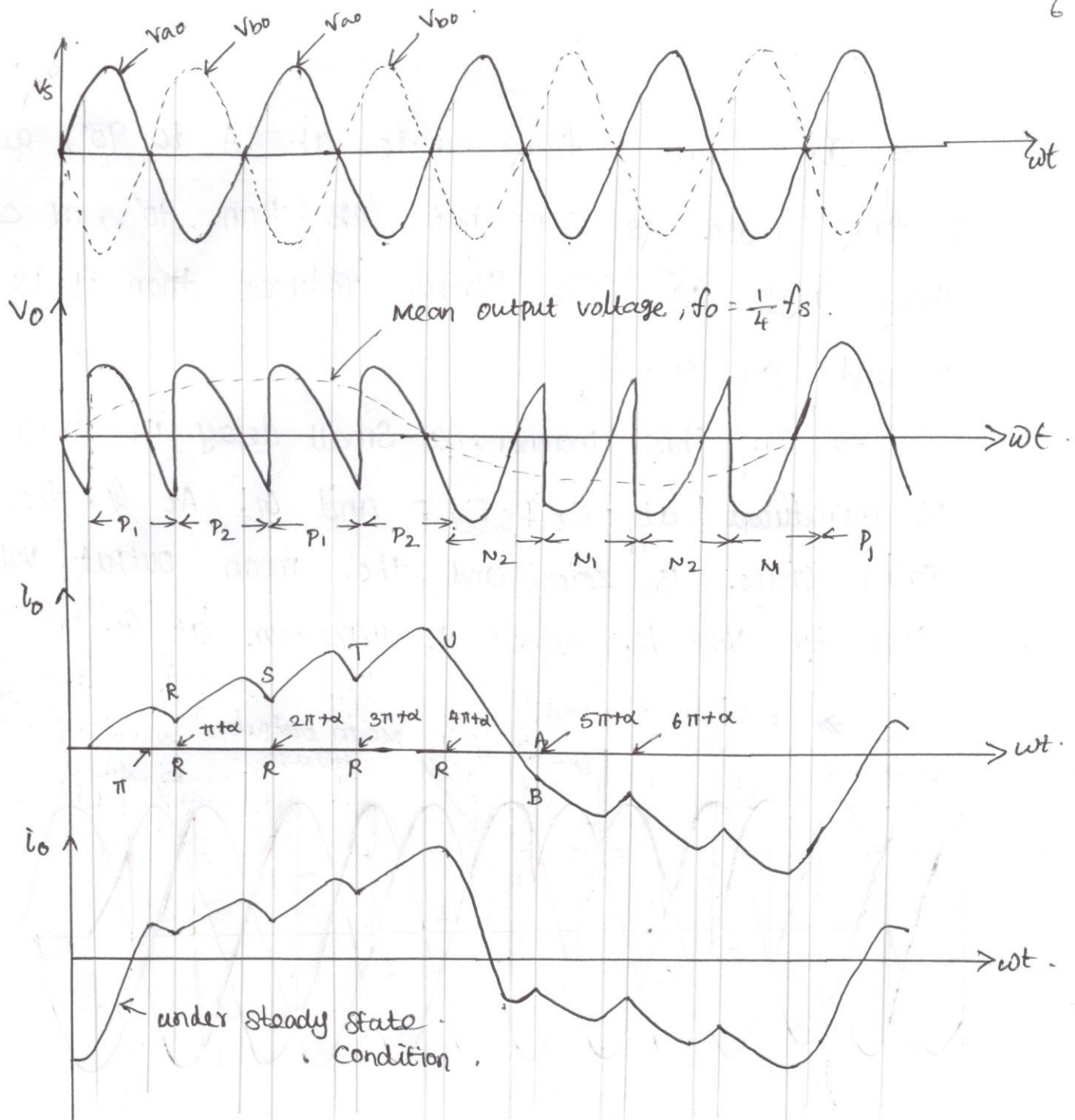
$\Rightarrow$  At the end of four positive half-cycles of output voltage, load current is  $R_u$ .

$\Rightarrow$  When  $N_2$  is now triggered after  $P_2$  load is subjected to a negative voltage cycle and load current decreases from positive  $R_u$  to negative  $AB$ .

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

$\Rightarrow$  The positive group of voltage group and current wave consists of four pulses and same is true for negative group.

$\Rightarrow$  The supply voltage has, however, gone through four cycles. The output frequency is, therefore  $f_o = \frac{1}{4} f_s$ .



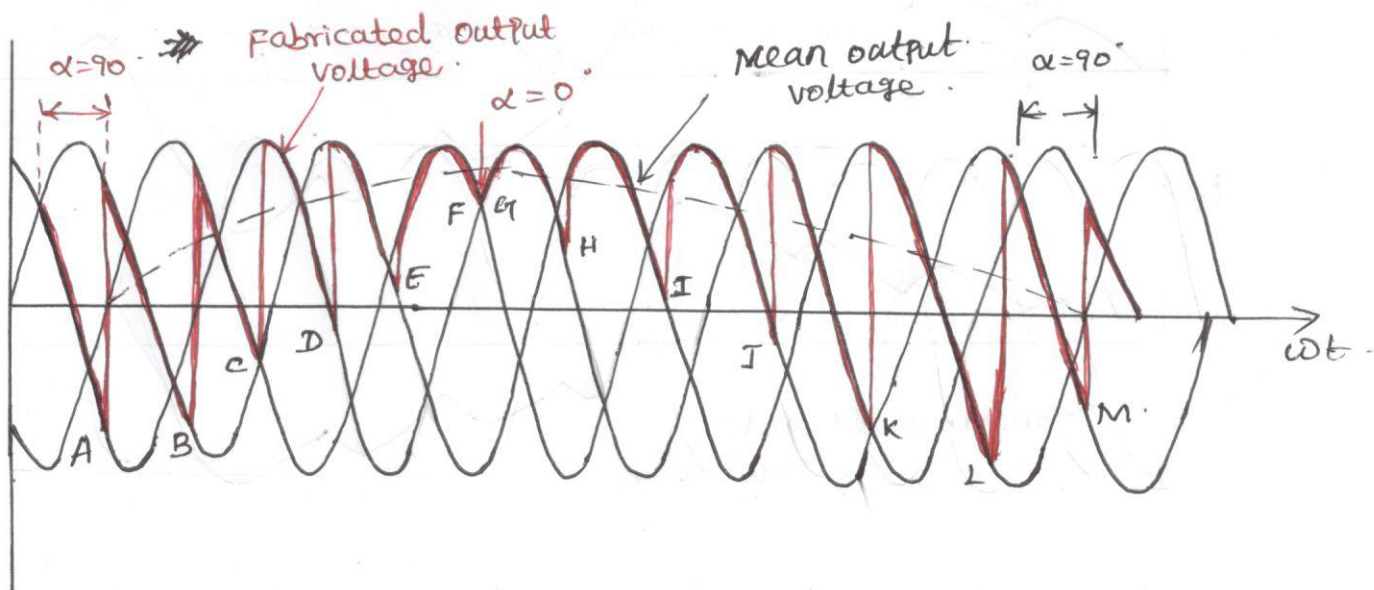
### Three Phase to Single Phase Cycloconverter:

⇒ 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  $90^\circ$ , at B firing angle is somewhat less than  $90^\circ$ , 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  $V_o = V_{do} \cos \alpha$  is maximum at G.



⇒ At A, the mean output voltage is zero as  $\alpha = 90^\circ$ . 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  $90^\circ$  and the value of mean output voltage is zero.

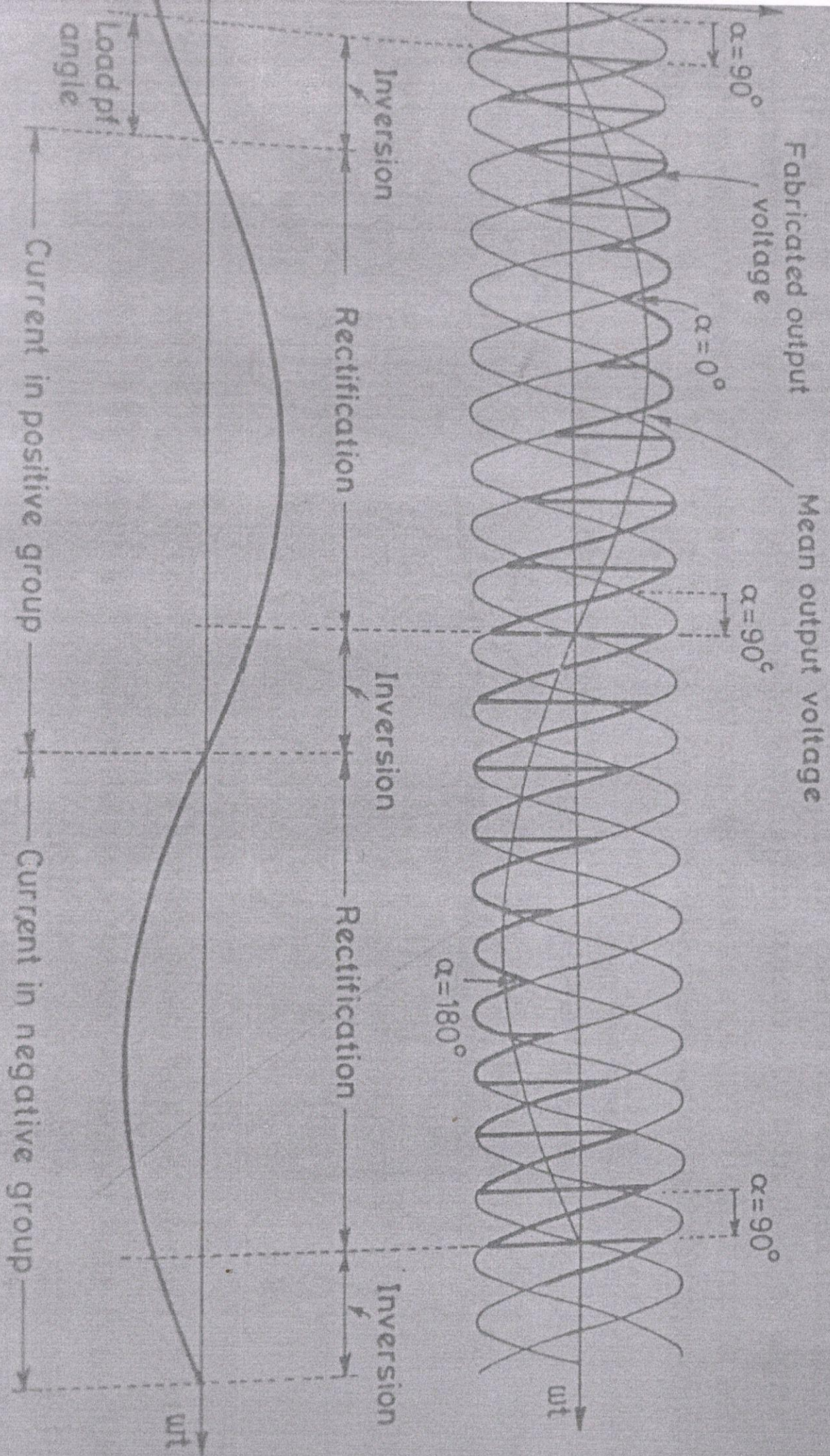
⇒ The Single Phase Output voltage fabricated from 3-phase input voltage is shown by thick curve.

⇒ 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  $f_s$  is the supply frequency.

⇒ For obtaining one cycle of low frequency output voltage, the firing angle should be varied from  $90^\circ$  to zero degree to  $90^\circ$  for positive half cycle and from  $90^\circ$  to  $180^\circ$  and back to  $90^\circ$  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, ~~the~~ two three phase half-wave converters connected in anti parallel.



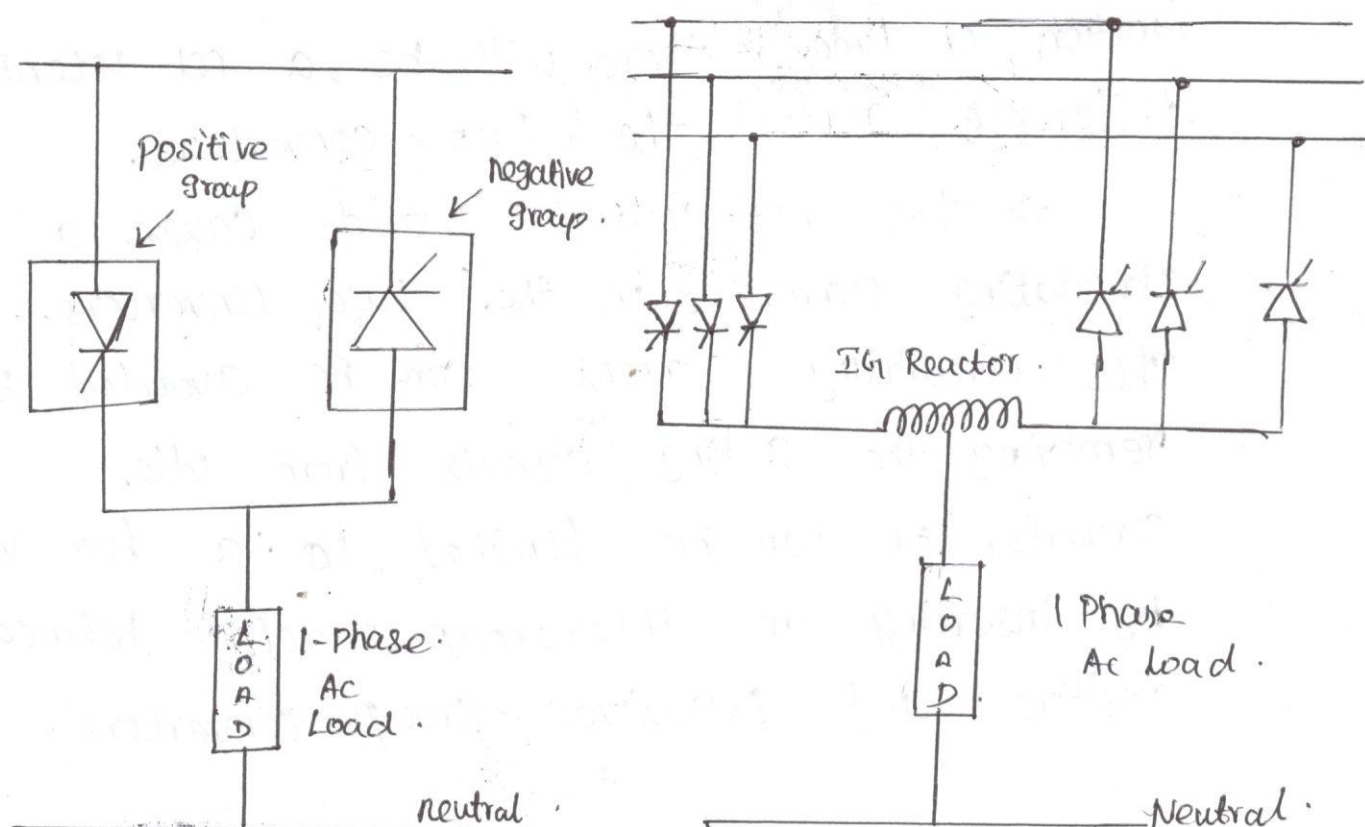




⇒ The converter circuits that permits the flow of current during ~~one~~ positive half cycle of low frequency output current is called Positive converter Group.

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

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.

- The control range of firing angle.
- The maximum value (or) rms load current.
- The maximum power and power factor.
- The maximum values of average and rms thyristor currents.

Given.

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

Solution:

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

$$\phi = \tan^{-1} \left( \frac{4}{3} \right) = 53.13^\circ$$

The maximum value of firing angle is  $180^\circ$ .

$\therefore$  The firing angle control Range is

$$53.13^\circ \leq \alpha \leq 180^\circ$$

(b)

The maximum value of rms load current is

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

$$I_0 = 46 \text{ A}$$

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

$$= 46^2 \times 3$$

$$P_0 = 6348 \text{ W}$$

$$\text{Power factor, } P_f = \frac{I_0^2 R}{V_s I_0}$$

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

$$P_f = 0.6$$

Maximum value of .

(d) Average thyristor current ,

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

$$I_{TAV} = 20.707 \text{ A.}$$

Maximum value of RMS thyristor current is,

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

$$I_{TM} = 32.527 \text{ A.}$$

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