Unit-1

Power Semiconductor Devices

Power:-

The power stages are Generation, Transmission, Distribution.

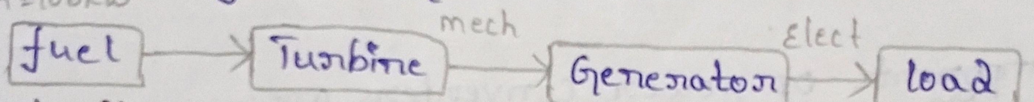
Electronics:-

Solid state devices, Signal processing.

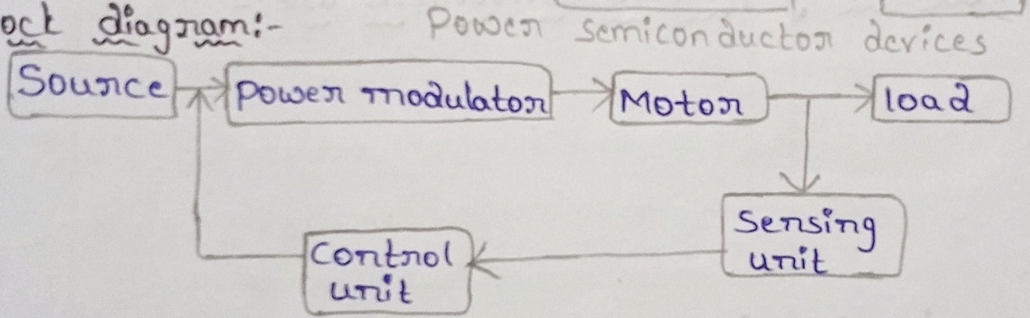
Control:-

(i) Steady state characteristics

Power Gen=100kw (ii) Dynamic characteristics.



Block diagram:-



Source:- It may be Ac or Dc.

power modulator:- It is also known as power Converter which is used for Converting the source voltage to the required voltage of the motor i.e, Ac to Dc (or) Dc to Ac.

Motor:- The motor may be DC motor, induction motor, Synchronous motor, Ac series motor etc...

Sensing unit:- It senses the output of motor i.e, Speed, torque etc...

Control unit:- The control unit receives the feedback from the Sensing and gives signals to the power modulator using the feedback obtained.

load:- The load may be resistive and capacitive load.

Types of power convertors:-

(1) Ac to Dc convertor - Rectifier.

(2) Dc to Ac convertor - Inverter.

(3) Dc to Dc convertor - chopper.

(4) Ac to Ac convertor - Cyclo converter.

(5) Ac regulator - [fixed frequency].

The main components of power converters are:-

(i) SCR

(ii) MOSFET

(iii) IGBT

* MOSFET:-

It is a three terminal device which is used in high power applications the 3 terminals are * Drain
* Source
* Gate

These are mainly classified into 2 types.

a.) Enhancement type mosFET

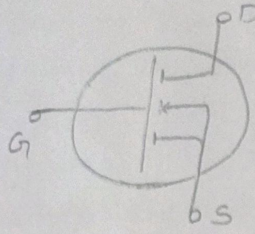
b.) Depletion type MOSFET.

These MOSFET are again classified into

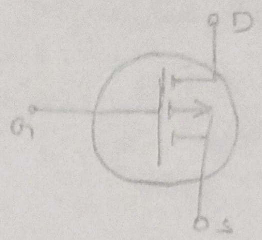
* N-channel MosFET

* P-channel MosFET.

Symbol of MosFET:-



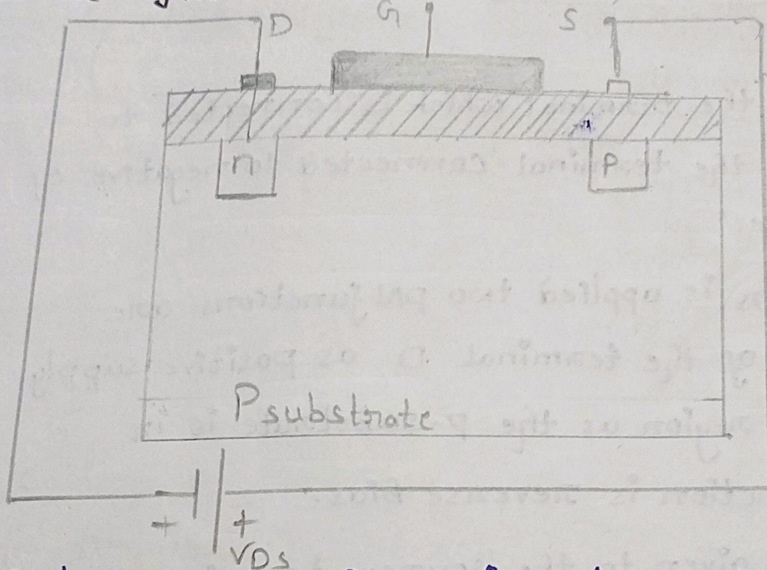
n-channel



P-channel.

* Metal oxide silicon field effect transistor (MosFET)

Structure of MosFET:- (construction)



(1) A p-type semi conductor is taken and this behaves as base for the mosfet and it is called as a substrate.

(2) Two regions on the same side of the substrate are heavily doped with a n-type impuritie as shown.

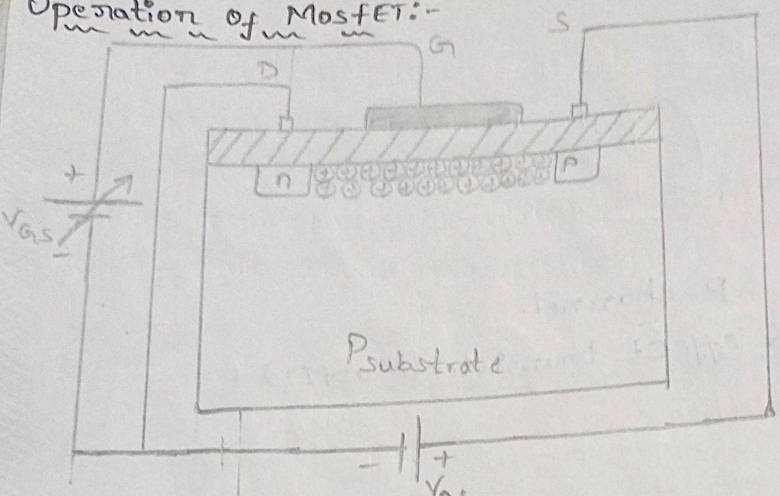
(3) The Drain and source terminals are taken from this impurity.

(4) Now, the entire top layer of the substrate is coated with silicon dioxide (SiO_2) as shown. and this behaves as an insulation between the gate and subtract.

(5). On this layer a metallic plate is placed and the gate termin is taken from this metallic plate.

(6) Hence, the gate is insulated from the substrate and sou and drain are directly connected as shown.

Operation of MosfET:-



(1) The voltage V_{DS} is applied the terminal which is connected to Positive is called drain and the terminal connected to negative of V_{DS} is called as a source.

(2) As soon as the voltage V_{DS} is applied two pn junctions are formed in the substrate of the terminal D as positive supply is given to the N-type region as the P-substrate is in high polaritie here, the junction is reverse bias.

(3) As the negative supply is given to the source terminal to the n-type region here the junction is forward bias.

(4) Hence, there is no significant Current flows from drain to source.

(5) Only the minimum leakage current flows due to the minority charge Carriers.

(6) Now, the voltage is applied to the gate terminal i.e V_{GS} as the minority carriers attracted to the gate terminal and forms as a channel as shown in figure

(7) This channel is known as n-channel and the MosfET is Called the N-channel MosfET.

(8) As the gate voltage is increase number of free electrons accumulated nearer the plate gets increased. Hence,

the conductivity of the MosFET depends upon the gate voltage.

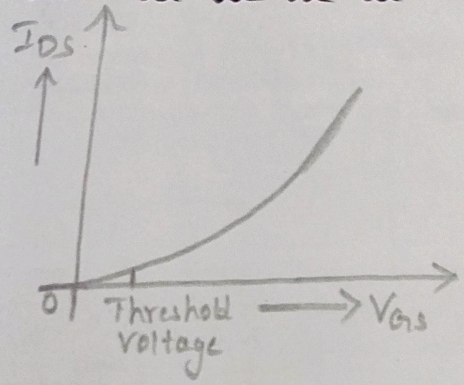
9) Due to the Electrostatic attraction the conduction takes place because between Drain and Source.

(10) If the gate voltage is greater than the threshold voltage value the MosFET Comes to ON state.

(11) When the gate voltage is less than the threshold voltage value the MosFET is in off state. Hence, these device is called voltage controlled device.

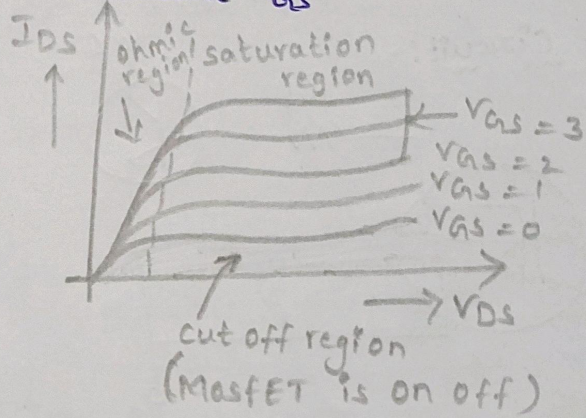
Characteristics of MosFET:-

(i) Transfer characteristics:-



(ii) Output characteristics:-

drawn between V_{DS} & I_{DS} at constant V_{GS}



Applications of MosFET:-

(1) High frequency Inverters.

(2) In SMPs, Motor control applications

(3) Industrial process Control.

IGBT:-

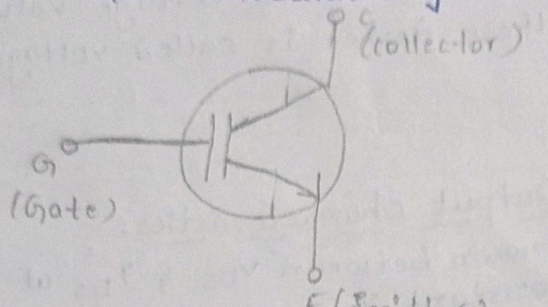
Insulatoted gate bi-polar Transistor

MOIGT - Metal oxide Insulated gate transistor

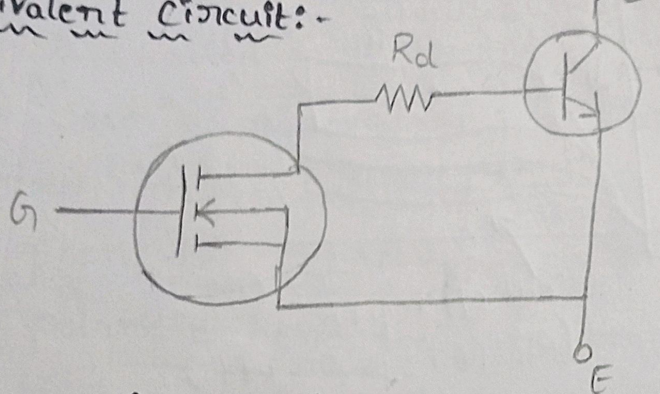
IGT - Insulated gate Transistor

COMFET - Conductivity Modulated field effect transistor

GEMFET - Gain modulated field effect transistor.

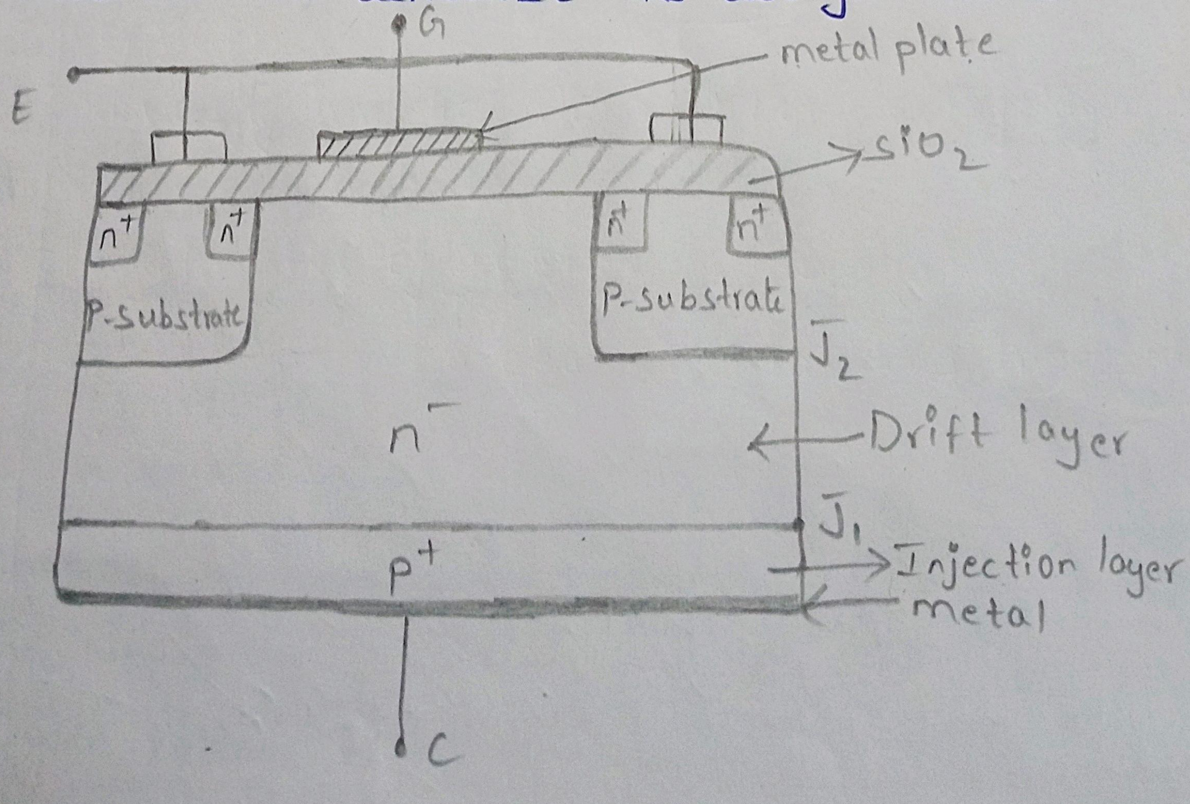


Equivalent circuit:-



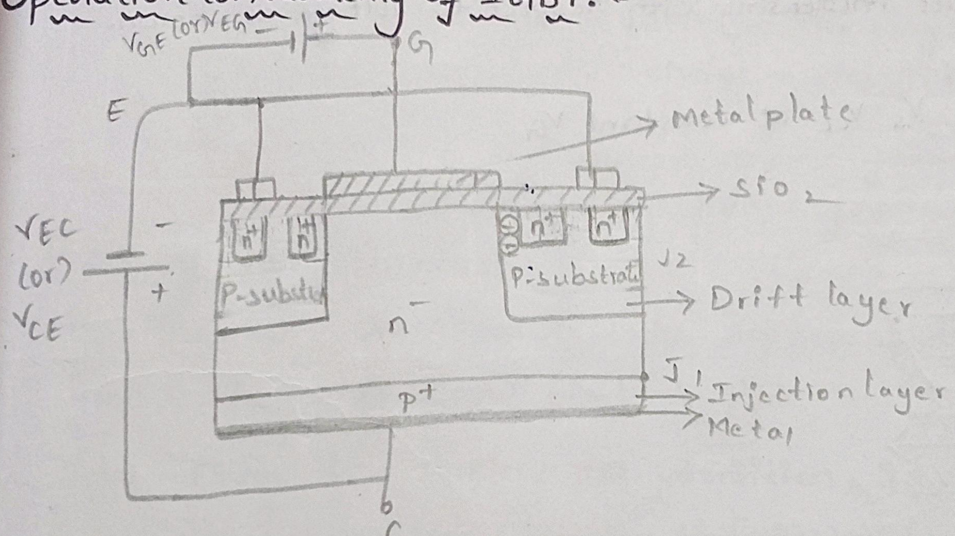
Structure (or) Construction of IGBT:

(1) It is a combination of MosFET and BJT and it is a four layer three terminal device. It has two junctions.



2) The first layer is p-layer is also known as injection layer as a Carriers are injected from this layer.
(3) The Second layer is drift layer it determines the break down voltage in this layer.
4) Next layer is similar to MosFET where the p-substrate and N-type material is dopped as shown in figure.
(5) The silicon dioxide is Coated on the top layer and a metal plate is placed from this metal plate the gate terminal(G) is taken.
(6) Collector terminal is taken from first layer i.e p layer and Emitter terminal is taken from the third layer which is like a MosFET.

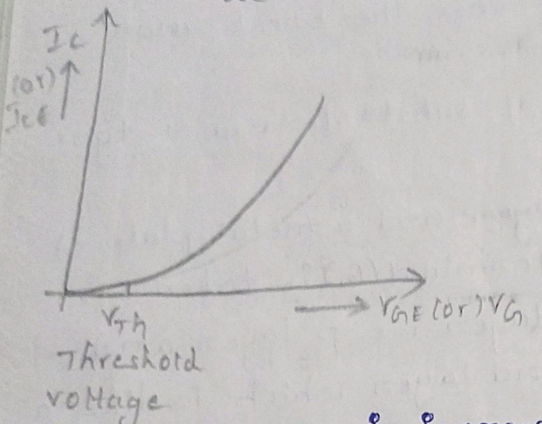
Operation (or) Working of IGBT:-



(1) The supply voltage V_{cc} is applied between emitter and collector and gate voltage is "0" volts. At this Condition junction J_1 is forward bias and junction J_2 is reverse bias. Hence only a leakage current due to minority Charge Carries it flow through the IGBT.
(2) when the voltage V_G is applied along with V_{cc} then a Capacitance effect is forward at the gate terminal. hence all the minority charge Carriers gets attracted towards the gate as shown.
(3) Hence the conduction part is created from collector to emitter as shown. Hence the IGBT comes to ON state. So, the current I_c flow in the circuit.

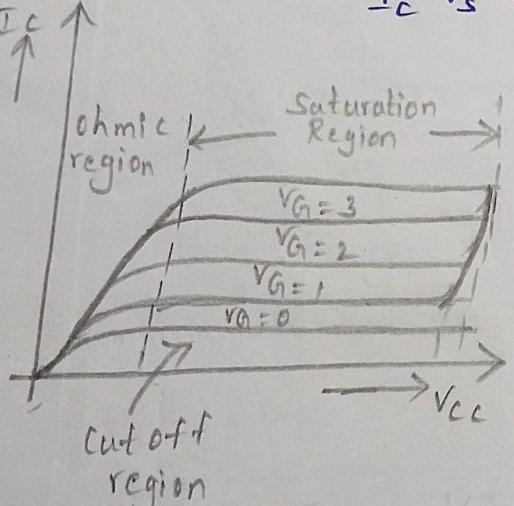
Characteristics of IGBT:-

Transfer characteristics



As, the gate voltage is increased from zero After the threshold value the current I_C starts increasing with respect to voltage as shown.

Output characteristics:- I_C Vs V_{CC} at constant V_G

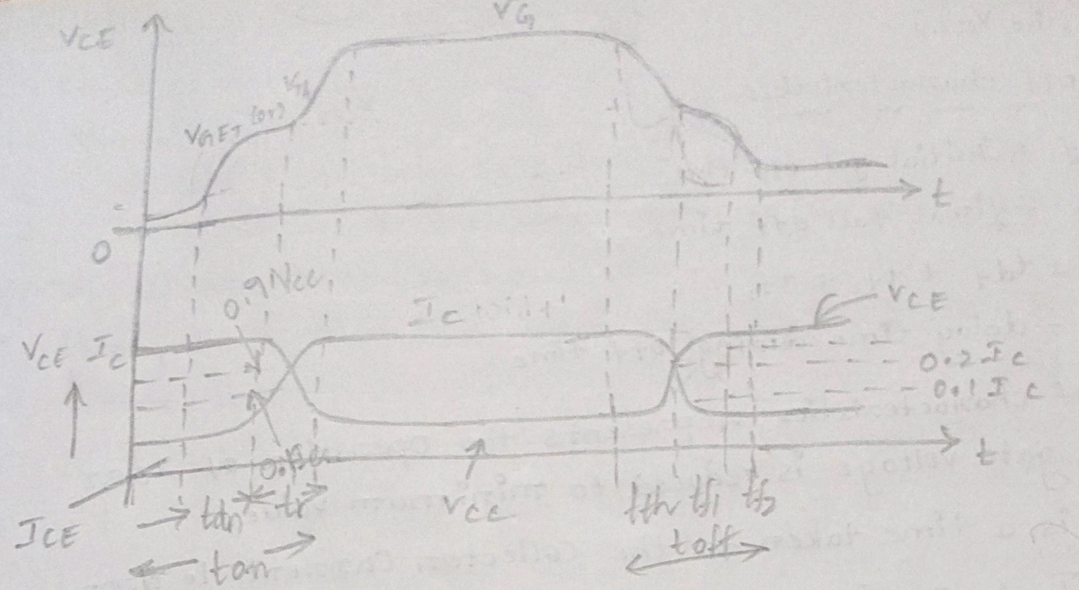


Applications of IGBT:-

Switching devices of inverters, Air conditioners, Refridgerators and Industrial motor application.

Switching characteristics of IGBT:-

* It is contains turn "on" characteristics and turn "off" characteristics



Generally during turn ON - current moves from 0 to ∞
voltage moves from ∞ to 0.

During Turn off - Current moves from ∞ to 0
voltage moves from 0 to ∞

Turn ON characteristics:-

* The turn ON characteristics represents operation of IGBT from forward blocking state to conduction state.
* t_{dN} - Delay time during ON Condition, It is defined as when the gate voltage reaches the threshold value from minimum value it is also defined as the time taken for the collector voltage (V_{CE}) drops from V_{CE} to $0.9\,V_{CE}$
* It is also defined as the time taken for the collector current to raise from I_{CE} to $0.1\,I_C$
* raise time t_r it is defined as time taken for the collector voltage fall from $0.9\,V_{CE}$ to $0.1\,V_{CE}$.
* And it is also defined as the rise of collector current from $0.1\,I_{CE}$ to I_C (maximum value)

Turn off characteristics:-

$t_{off} = t_{df} + t_{f_1} + t_{f_2}$

$t_{df} =$

* finally the voltage drops to very small value called as conductio

drop, i.e V_{CES}.

* Turn off characteristics:-

t_{f1} = Initial fall off time

t_{f2} = final fall off time

$t_{off} = t_{df} + t_{f1} + t_{f2}$

t_{df} = delay time during off time

Turn off characteristics represents the operation of IGBT when the gate voltage is reduced to minimum value.

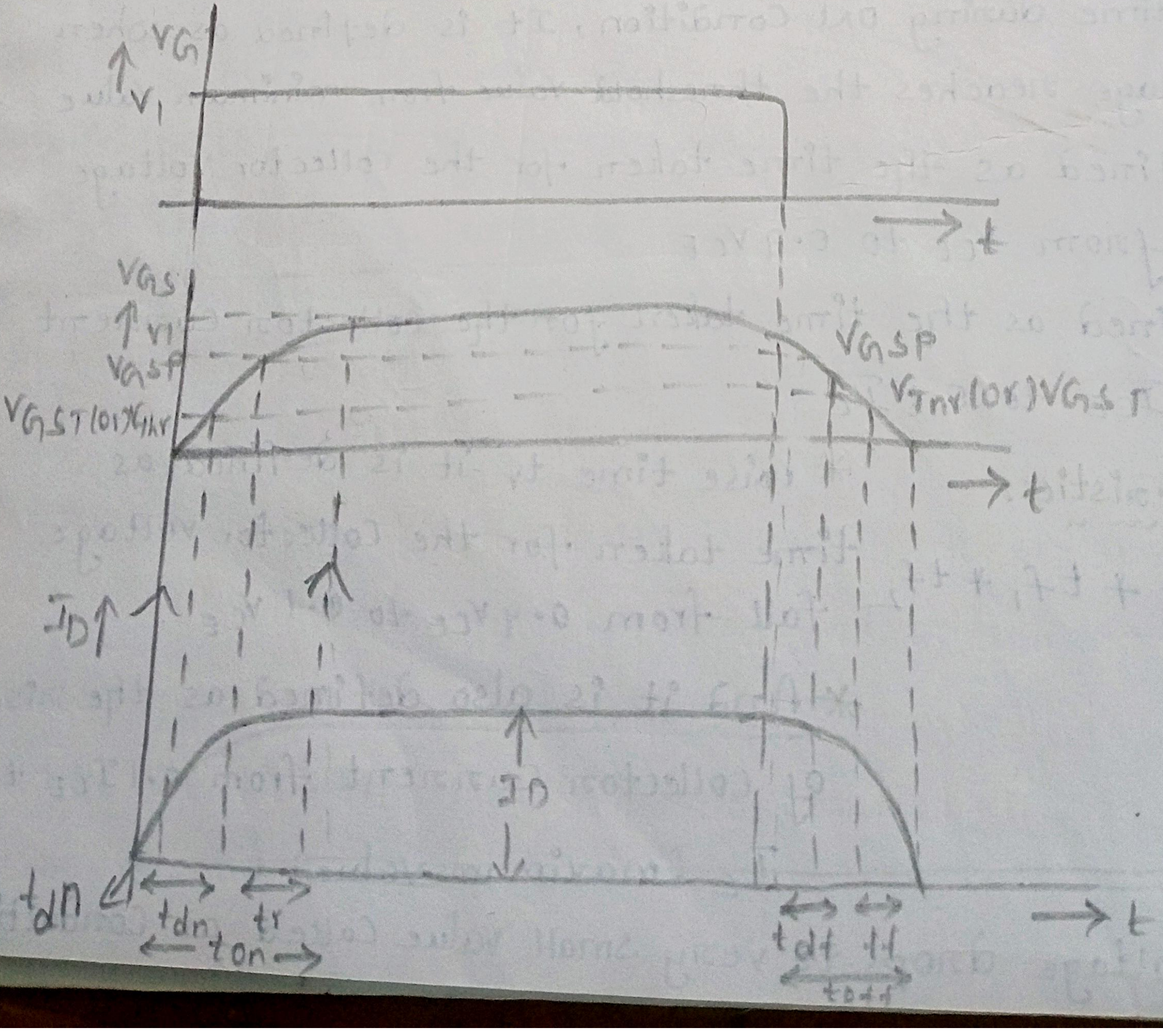
t_{df} - It is a time taken for the collector current to drop from I_C to $0.9\,I_C$

t_{f1} - It is the time taken to drop off collector current from $0.9\,I_C$ to $0.2\,I_C$

t_{f2} - It is the time taken for the collector current to reach $0.1\,I_C$ from $0.2\,I_C$.

Here, the voltage raises to V_{CE} value.

* Switching characteristics of MOSFET:-



Turn on characteristics:-

$t_{on} = t_{dn} + t_r$

Where,

t_{dn} is the delay time during ON state.

* It is defined as the time taken for the rise of voltage from 0 to threshold voltage

* During this period no current flows in the MOSFET it is represented as t_{dN}

* t_r is the time taken for the voltage to reach its maximum value i.e V_{GSP}. (full gate source voltage)

* It is also defined as time taken to raise current from 0 to Maximum value I_D.

Turn off characteristics:-

$t_{off} = t_{df} + t_f$.

* t_{df} - Delay time during off state

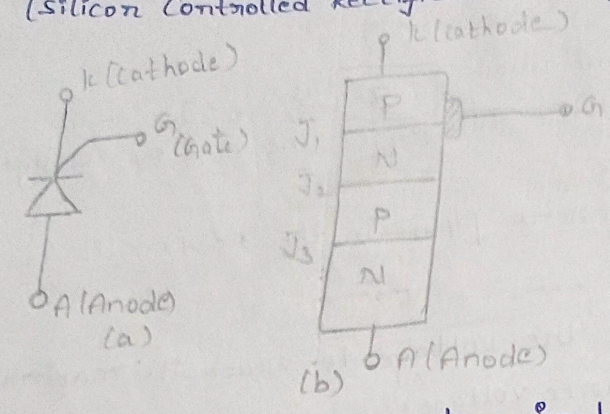
* It is the time taken for the gate voltage to start decreasing when the gate pulse is removed.

* t_f is the fall time

It is the time taken for the voltage to reduce from V_{GSP} to V_{thr}

Hence, the current also starts reducing to 0 i.e $I_D = 0$.

* **SCR:-**
(silicon Controlled Rectifier)' (or) Thyristor



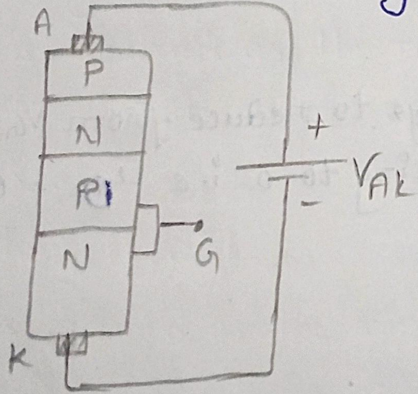
* It is a four layer three terminal 3 junction device.

It operates in 3 modes they are.

* forward blocking mode
* forward Conduction mode
* Reverse blocking mode.

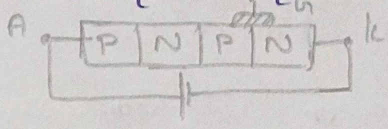
forward blocking mode:

In this mode anode is given positive supply and Cathode is connected to Negative Supply as shown

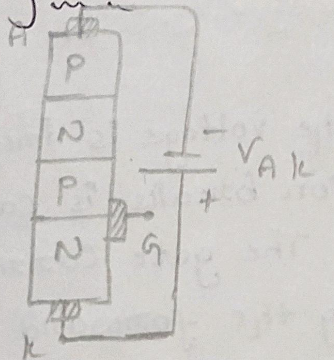


In this mode junction J_1, J_3 are forward bias and the junction J_2 is reverse bias. Because of formation of depletion layer at the junction J_2 it does not allows the flow of electrons through the device only a small leakage current flows through the circuit. This is current is not sufficient the device to conduct. Hence this mode is called forward blocking mode *forward Conduction mode:* voltage

As, the Anode to Cathode Current increases the width of the depletion layer gets reduced. If the voltage is continously increased a stage comes where the depletion layer varnishes at junction J_2. Hence the reverse bias Junction J_2 breakes down at this stage and this is known as Avalenche break down and this mode is known as forward conduction and hence the device starts Conducting



Reverse blocking mode:-



In this mode the anode is connected to negative supply and Cathode is connected to positive supply. Hence, the junction J_2 is only forward bias and the junctions J_1 & J_3 are reverse bias. Because of this only a small amount of leakage current flows through the circuit. Hence, the device will not ~~conduct~~. conduct. Hence, this mode is called reverse blocking mode.

Characteristics of SCR:-

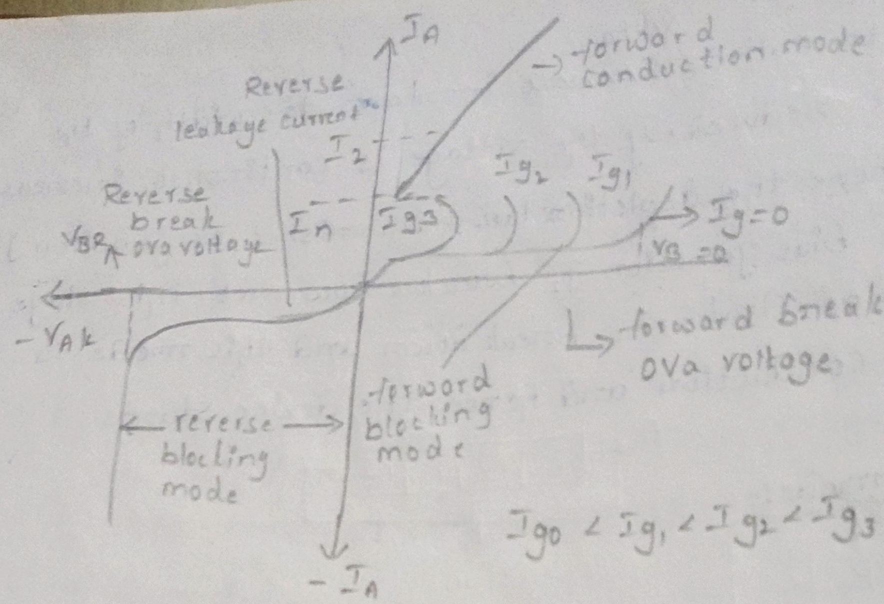
There are two types of characteristics

They are

* static characteristics
* Dynamic characteristics

Static characteristics (or) VI :-

In reverse blocking mode. if the reverse voltage is increased continously the point where the junction breaks is called reverse break over voltage V_{BR}. And the current starts flowing in the reverse direction as shown



In forward blocking mode if the voltage is increased continously the point where junction breaks is called forward break over voltage V_{BO}. The gate current is applied as shown in figure during the forward conduction mode. Hence the current starts flowing in forward direction as shown.

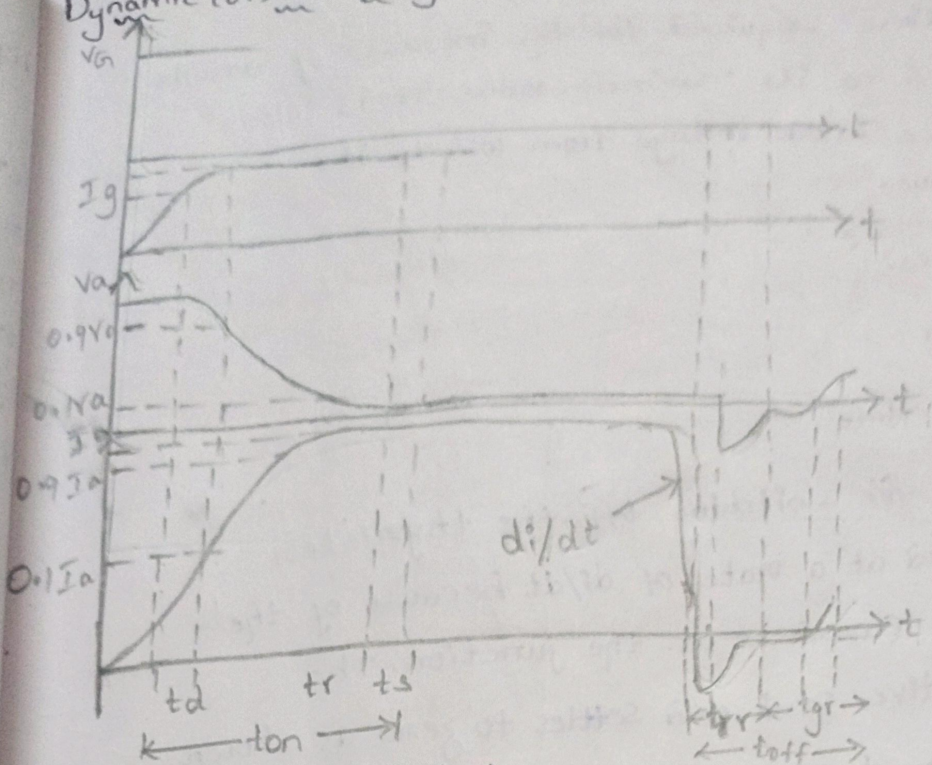
I_H - Holding Current

It is defined as the minimum value of the current flowing through the anode below which the thyristor can not be turned ON.

I_L - latching Current.

It is defined as the minimum current at which the thyristor is maintained at ON state even if the gate pulse is removed.

Dynamic (or) switching characteristics of SCR:-



* Turn ON characteristics:-

$$t_{ON} = t_d + t_r + t_s$$

td → delay time ts → settling time.

tr → rise time

delay time:-
It is the time taken by the gate current to reach its maximum value from 90% as shown in figure.

* It is also defined as the time taken by the anode current to reach 10% as shown

* It is also defined as the anode voltage to decrease 90%. from its maximum value

* Rise time tr

It is defined as the time required for the anode voltage to reduce to 10% of Va as shown

It is also defined as time taken for the increased of anode current from 10% to 90% of its value.

t_s (spread or settling time):-

* It is the time required for the increase of anode current from 90% to its maximum value. It is also defined as to reduce anode voltage from 10% to its minimum leakage value.

Turn off characteristics:-

$$T_{off} = t_{rr} + t_{gr}$$

t_{rr} = Reverse Recovery time.

During this time for switching off the thyristor the current is reduced at a rate of di/dt because of the presence of the charge carriers at the junction. The current go to its negative peak and settles to zero as shown.

t_{rr} is the time taken to remove the charge carriers at junction J_1 & J_3. At this period the voltage spike is also occurs in negative direction as shown in figure.

t_{gr} = Gate recovery time.

It is the time taken to remove the charge carriers at the junction J_2. Hence the thyristor comes to complete off state.

t_c - circuit turn off time.

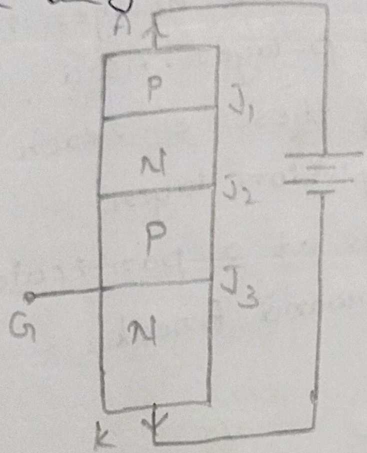
It is the total time of t_{rr} and t_{gr}

* SCR trigerring Methods:-

Turn on (or) firing

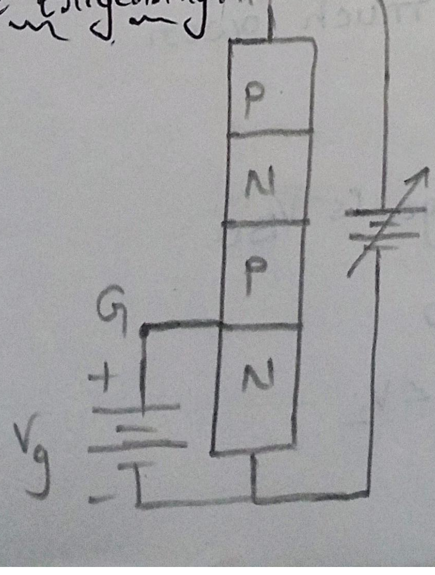
(1) forward voltage trigerring
(2) Gate trigerring
(3) dv/dt trigerring
(4) Temperature trigerring
(5) Light trigerring.

* forward voltage trigerring:-

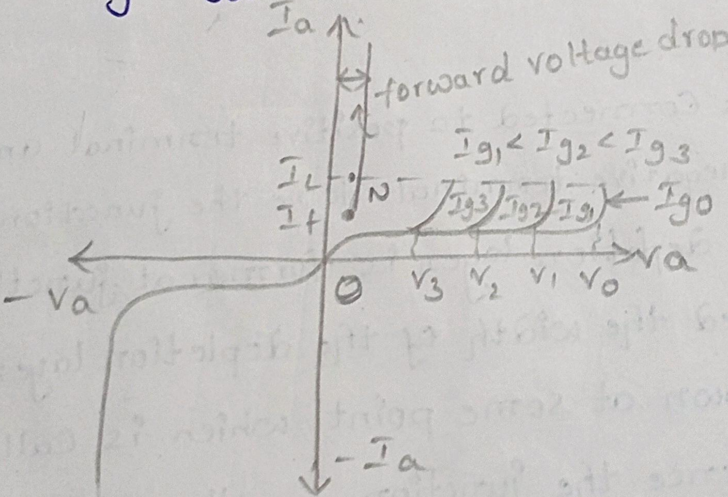


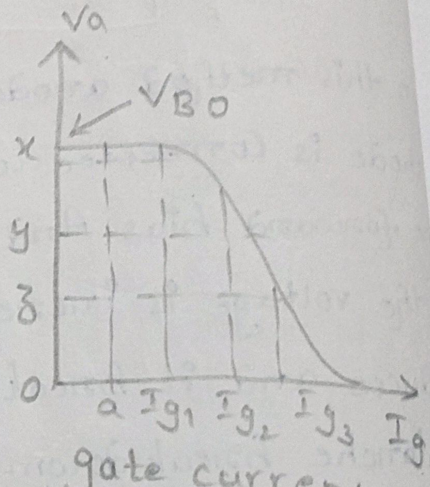
In this method anode is connected to positive terminal and Cathode is connected to negative terminal. Here the junction J_1 & J_3 are forward bias. And a depletion layer is formed at junction J_2. As the voltage is increased the width of the depletion layer reduces and it break down at some point which is called as Avalanche break down. Hence the junction J_2 allows the movement of electrons along the function. Hence the SCR comes to ON state.

Gate trigerring:-



Turning on of SCR by gate triggering is simple, reliable and efficient. Thyristor with a V_{BO} (800 V) higher the normal working voltages (400 V) is choosen. This means SCR remains in off-state with normal working voltages with ($R_g = 0$). When ever +ve gate voltage applied w.r.to cathode, the p-layer is flooded with e^- from the cathode. This is because cathode n-layer is heavily dopped as compared to gate p-layer. As a thyristor is forward biased, some of these e^- reach junction J_2, as a result width of depletion layer decreases and break down is occurs at a particular voltage which is lesser than the forward break over voltage (V_{BO})





$OX = V_1$, $Oy = V_2$, $Oz = V_3$

If the magnitude of gate current increases then the SCR get turned on much lower forward voltage.

At $I_g = 0$ forward breakover voltage is V_{BO}

If at I_{g1} turn on voltage is V_1 & $V_1 < V_{BO}$

at $I_{g2} \rightarrow V_2$ & $V_2 < V_1$ at $I_{g3} \Rightarrow V_3$ & $V_3 < V_2$

(Typical values of I_g (20-200) mA.

$\therefore I_{g3} > I_{g2} > I_{g1} > I_{g0}$ then $V_3 < V_2 < V_1 < V_{BO}$.

This is also shown in fig.

* $\frac{dv}{dt}$ triggering:-

With forward voltage across A-k of SCR, the two layers J_1, J_3 are forward biased & J_3 is reverse biased. This reverse biased junction J_2 has the characteristics of a capacitor due to space charge region (Depletion layer) at junction J2.

If the forward voltage is suddenly applied, a changining current through junction capacitance. Cj may turn on SCR. Almost the entire voltage suddenly applied at A-k appears at junction J_2 the charging current is ic given by

$$i_c = \frac{dq}{dt} = \frac{d(C_j V_a)}{dt}$$

$$= C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt} \approx 0$$

$$\therefore i_c = C_j \frac{dV_a}{dt}$$

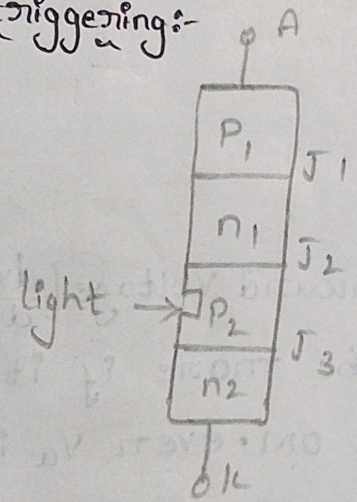
Therefore it rate of rise of forward voltage $\left(\frac{dV_a}{dt}\right)$ is high, the charging current (i_c) would be more if it is greater than I_L then SCR is turned ON. even V_a is small it is the rate of change of V_a. that plays the role of turning-ON the SCR.

* Temperature triggering (Thermal triggering)

During forward blocking, most of the applied voltage appears across reverse biased junction J_2. This voltage across J_2, associated with leakage current would rise temperature of this junction for semi conductor materials. If temperature then resistance at junction J_2 is decreases. This leads allowing of more current through J_2. It is cumlative process. The depletion layer will be vanished and device gets turned-ON.

The semi conductor materials having -ve temperature Co-efficient. i.e If temperature increases then resistance will be decreases.

* light triggering:-



for light triggering SCR P_2-layer having a provision for light. when light is radiated on P_2 layer then collosions takes place at gate terminal the free charge Carriers generated just to like a gate signal.

This flow of charge Carriers reduce the junction J_2 then SCR is ON.

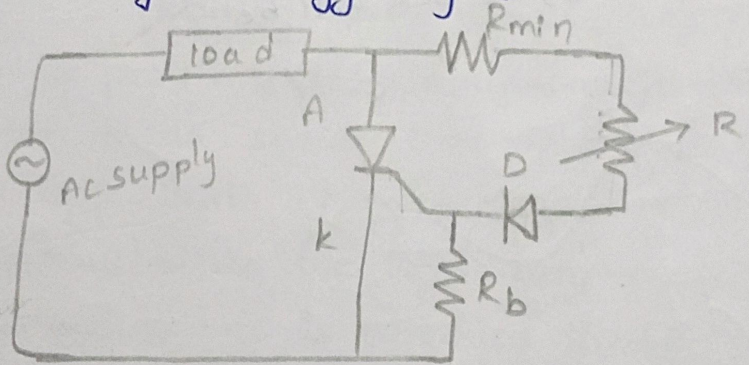
LASCR may be triggered with a light source or with a gate signal. Some times a combination of both lights and gate signal LASCR's have now used in HVDC-transmission system.

* SCR firing circuits

As we have seen in above that out of various triggering methods to turn the SCR, gate triggering is the most effective and reliable method. Most of the control applications use this type of triggering because the desired instant of SCR turning is possible with gate triggering method.

R triggering of SCR:-

(1) R triggering of SCR is one of the methods to turn ON SCR through resistive elements. fig 1 shows the circuit diagram of R triggering of SCR.



Circuit diagram for R triggering of SCR

(2) The resistance Rmin is used to limit the gate current to its maximum value. The value of Rmin is decided by formula

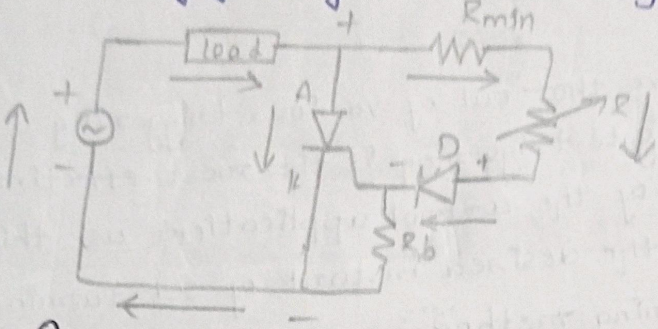
$$R_{min} \geq \frac{V_m}{I_{g\,max}}$$

(3) The resistance Rb is the stabilizing resistance. The resistanc ensures that minimum gate voltage is applied to SCR.

(4) The Variable Resistor R is used to trigger the thyristor T_1. when the value of R is zero.

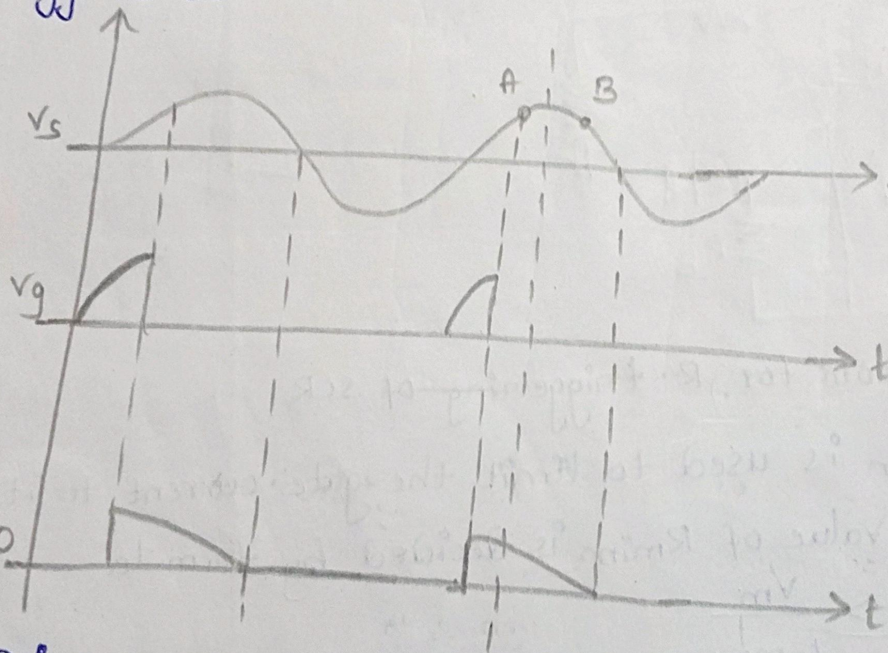
the firing angle is minimum. The firing angle increases as the value of R increases.

(5) figure 2 shows the operation of the circuit with the direction of flow of current during positive half cycle



Operation of the circuit having during positive half cycle

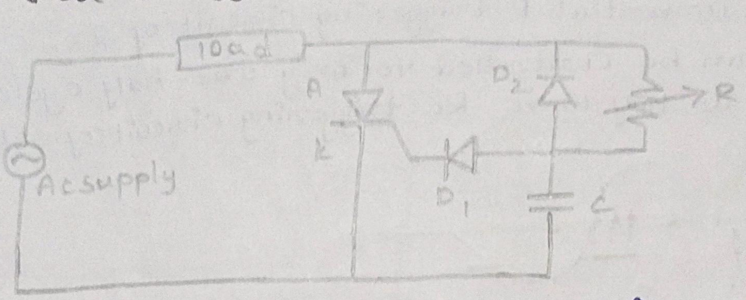
(6) In the above wave forms it can be observed at points A and B the supply voltage is the same. Therefore, if it is desired to trigger SCR at point B, the SCR will be triggered at



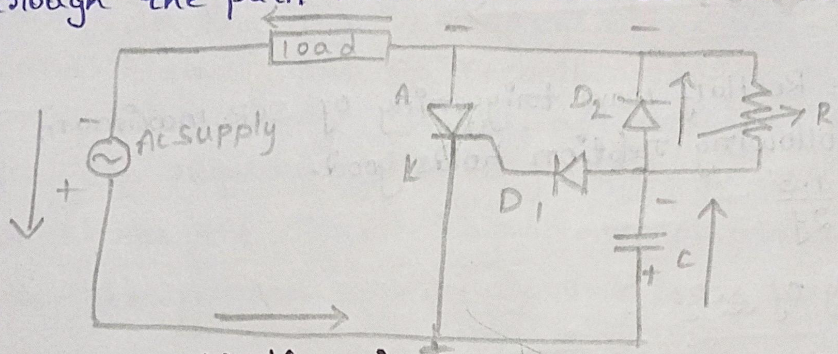
point A. In other words, triggering of SCR can be controlled only for 90°

(7) Hence maximum triggering angle that can be derived is 90°. This is one of the major drawbacks for this circuit.

* RC Half wave Triggering of SCR:-



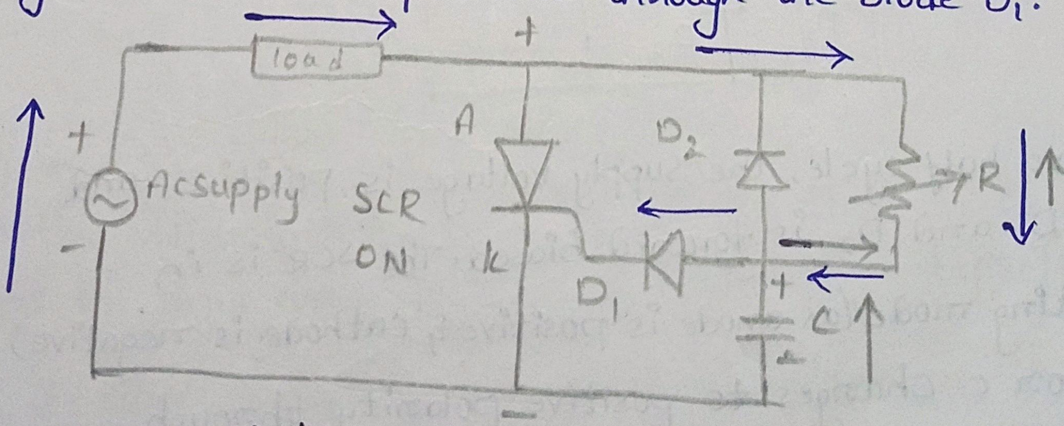
(1) During the negative half cycle the capacitor charges to negative polarity through the diode D_2 as shown. The flow of current is through the path indicated with the red arrow head.



(2)

Working during negative half cycle.

(2) During positive half cycle, the capacitor discharges through the resistor R as shown. Once the energy is discharged, the capacitor starts charging to positive voltage (through the green arrow head). Once the capacitor charges to the gate voltage the gate current is provided through the Diode D_1.

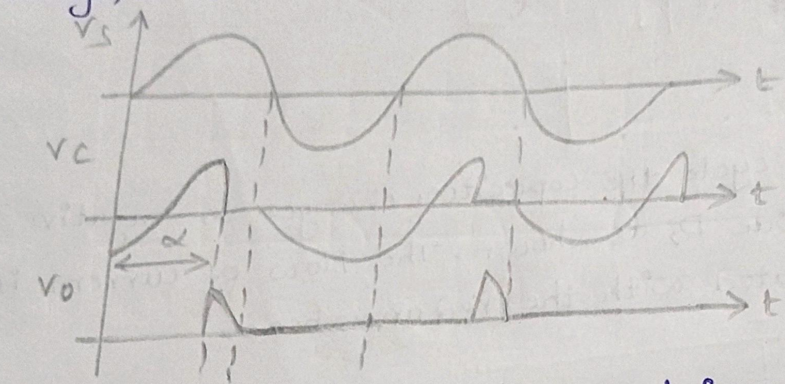


Working during positive half cycle.

) Diode D_1 also prevents negative capacitor voltage to appear across the gate terminal of SCR. the wave form of the RC triggering circu of SCR. It can be observed that the SCR can be triggered for

for 180-degree range. Hence it is having much better control over the convential R triggering circuit of SCR.

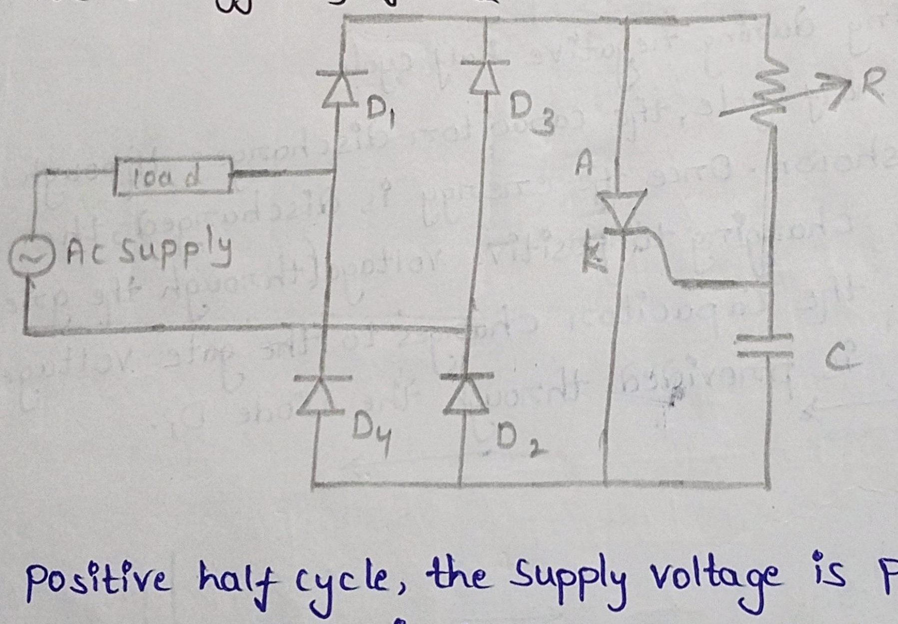
(4) Since the SCR can be controlled for only one-half cycle range, it is called as Half wave Rc triggering circuit of SCR.



(5) for zero Output (i.e Rc Half wave triggering of SCR maximum firing angle), the following relation holds good.

$$RC \geq \frac{1.3}{2f}$$

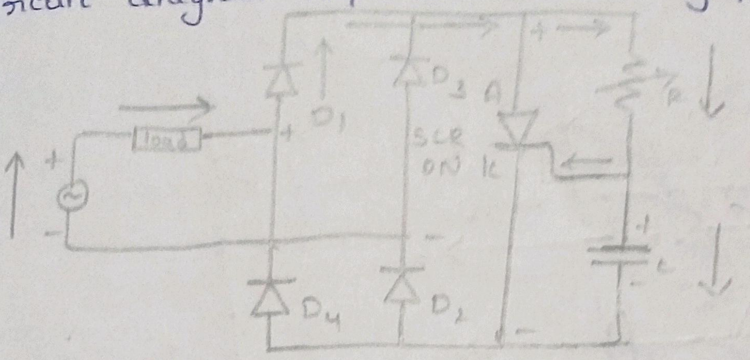
*** Rc full wave triggering of SCR:-**



(1) During positive half cycle, the supply voltage is positive and consequently D_1 and D_2 is forward biased. The SCR is in forward blocking mode (as anode is positive & cathode is negative)

(2) The capacitor c charges to positive polarity through the resistor. Once the capacitor charges to find defind the gate voltage, the capacitor supplies the required gate voltage. The SCR now moves from forward blocking

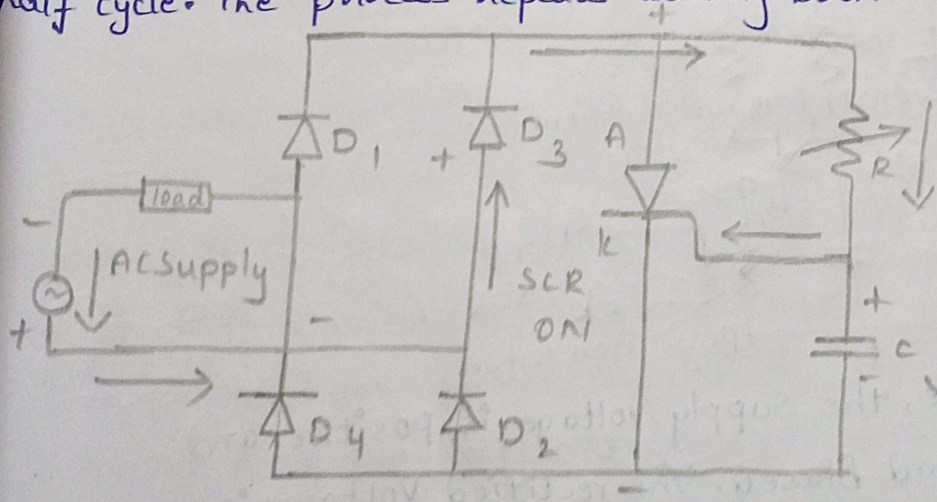
mode to forward conduction mode and turns ON. fig 2 shows the circuit diagram representation during positive half cycle.



During positive half cycle.

3) similarly, during negative half cycle the diode D3 and D4 are forward biased and the capacitor charges to positive voltage. Once the capacitor charges to the defined gate voltage, the capacitor supplies the required gate voltage and the SCR is turned ON.

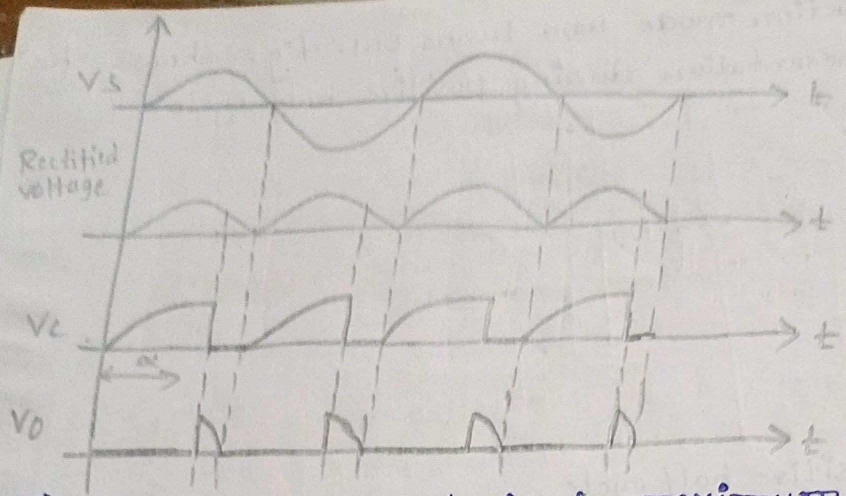
(4) fig 3. shows the circuit diagram representation during negative half cycle. The process repeats during both the half cycles.



During negative half cycle

(5) from the wave form it can be observed that the capacitor char to positive voltages in both the half cycle. The capacitor voltage clamps to zero once the SCR is turned ON.

(6) One of the major advantages with this current circuit is SC can be turned ON with a firing angle between 0 to 180°. In addition, it is possible to control the SCR in both the half Hence the name RC full wave ∫ triggering of SCR.

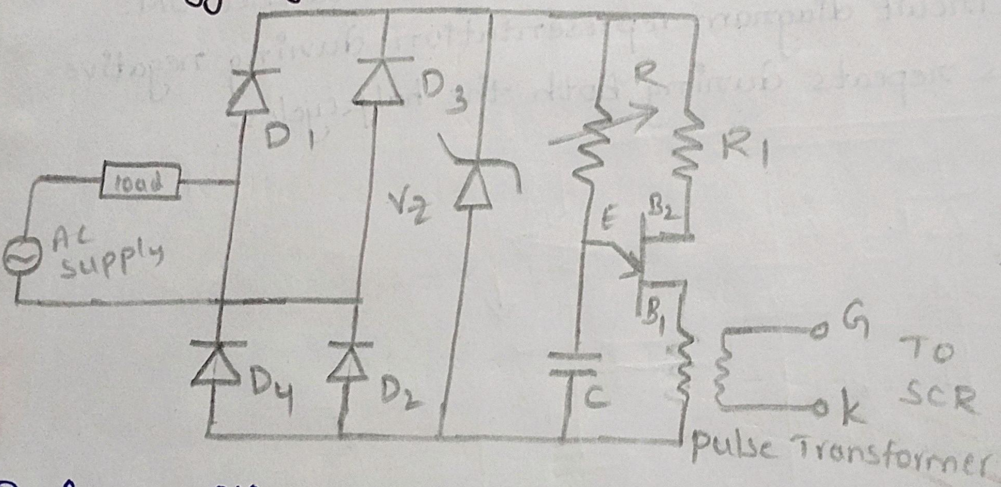


The following relation holds for maximum firing angle,

$$Rc \geq \frac{0.157}{2\pi f}$$

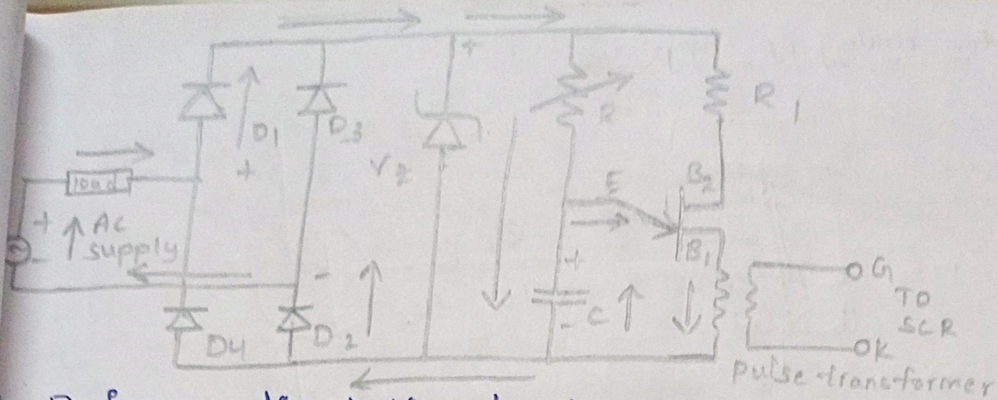
f is the supply frequency in above eqn.

*** UJT triggering Circuit for SCR:-**



(1) During positive half cycle, the supply voltage is positive and diodes D_1 and D_2 are forward biased. The rectified voltage is clamped to zener voltage V_Z through the zener diode. The Capacitor starts charging to positive voltage through the resistor R as shown in fig 2.

(2) Once the Capacitor charges to a peak voltage say V_K it triggers the UJT and starts discharging. The UJT is turned ON and it supplies excitation to the pulse transformer. The pulse transformer provides the pulse to the gate to Cathode terminal to the SCR.

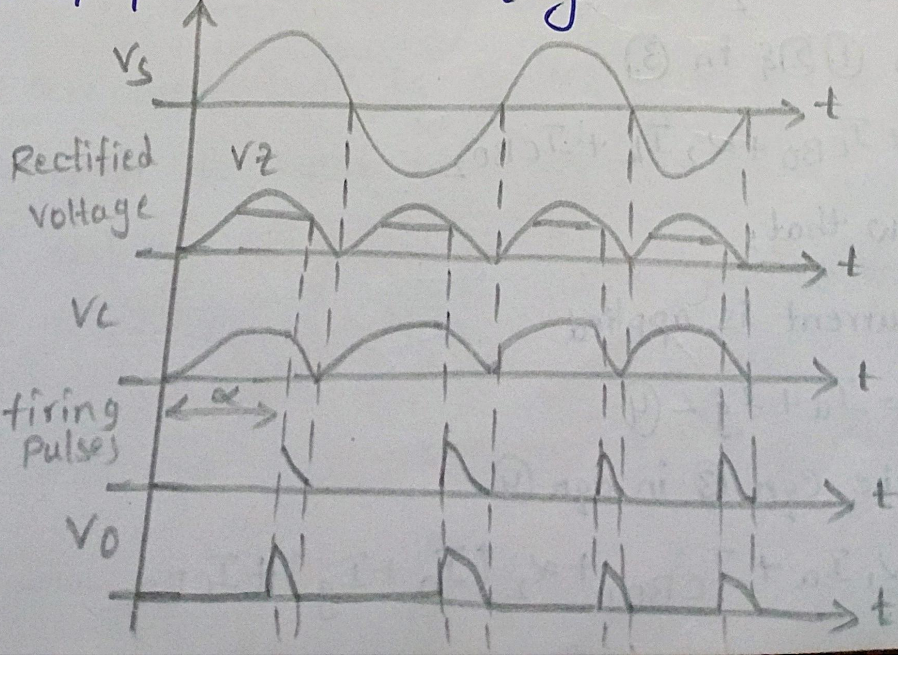


(3) During negative half cycle, the supply voltage is negative and diodes D_3 and D_4 are forward biased. The rectified voltage is clamped to zener voltage V_z through the zener diode. The capacitor starts charging to positive voltage through the resistor R.

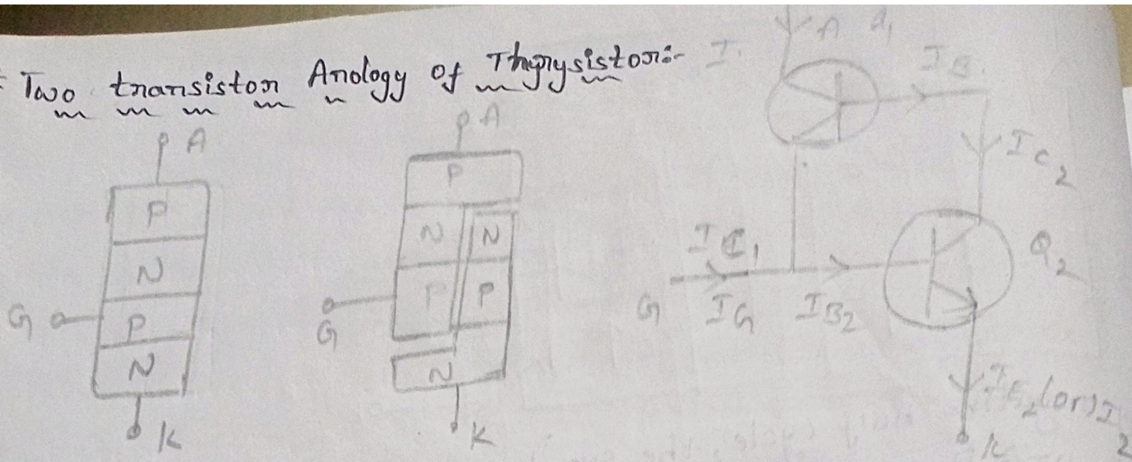
(4) Once the capacitor charges to a peak voltage say, V_K it triggers the UJT and starts discharging. The UJT is turned ON and it supplies excitation to the pulse transformer. The pulse transformer provides the pulse to the gate to cathode terminal of SCR.

(5) This mode of working of UJT is called as relaxation oscillator. The wave-forms of UJT triggering circuit for SCR. The firing angle can be controlled by designing suitable values of R & C elements.

(6) The UJT triggering circuit has the firing angle range from 0 to 180° one of the major advantages of this circuit is that the pulse transformer provides electrical isolation with the source and the load terminals. This adds up as an additional layer of protection for the gate terminal.



* Two transistor Anology of Thyrysistor:-



from the circuit,

$$I_a = I_{E_1}$$
$$I_{B_1} = I_{C_2}$$
$$I_{E_2} = I_k$$

We know that,

$$\text{Current Gain of transistor} = \alpha = \frac{I_C}{I_E}$$

$$I_C = \alpha I_E + I_{CBO}$$

I_{CBO} is the Collector base leakage Current

$$\therefore I_{C1} = \alpha_1 I_{E_1} + I_{CBO_1}$$
$$I_{C_1} = \alpha_1 I_a + I_{CBO_1} \quad \text{-- (1)}$$
$$I_{C_2} = \alpha_2 I_{E_2} + I_{CBO_2}$$
$$I_{C_2} = \alpha_2 I_k + I_{CBO_2} \quad \text{-- (2)}$$
$$I_A = I_{C_1} + I_{C_2} \quad \text{-- (3)}$$

Sub (1) (2) & in (3)

$$I_A = \alpha_1 I_A + I_{CBO} + \alpha_2 I_k + I_{CBO_2}$$

We know that,

when Gate current is applied

$$I_k = I_a + I_g \quad \text{-- (4)}$$

Substitute eqn (3) in eqn (4)

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO_2}$$

$$I_a = \alpha_1 I_a + I_{CBO_1} + \alpha_2 I_a + \alpha_2 I_g + I_{CBO_2}$$

$$I_a - \alpha_1 I_a - \alpha_2 I_a = I_{CBO_1} + \alpha_2 I_g + I_{CBO_2}$$

$$I_a(1-\alpha_1-\alpha_2) = I_{CBO_1} + \alpha_2 I_g + I_{CBO_2}$$

$$I_a = \frac{\alpha_2 I_g + I_{CBO_1} + I_{CBO_2}}{1-(\alpha_1 - \alpha_2)}$$

Commutation - Turning off SCR:-

(1) To turn on a thyristor, a low voltage, short duration pulse is applied to the gate

(2) Once the thyristor is turned-on, the gate loses control and the thyristor will only turn off when the load current falls virtually to zero, or the thyristor is reverse biased

(3) The thyristor will turn off naturally with A.C. supplies as the voltage reverses

(4) No such reversal occurs with D.C supplies and it is necessary to force a voltage reversal if turn-off is to occur. The process is called forced commutation.

Commutation:-

(1) The process of turning off SCR is defined as "Commutation".

(2) In all commutation techniques, a reverse voltage is applied across the thyristor during the turn off process.

(3 The conditions to be satisfied in order to turn off an SCR are:

* $I_A < I_H$ (Anode current must be less than holding current)
* A reverse voltage is applied to SCR for sufficient time enabling it to recover its blocking state

* Natural commutation
* forced Commutation.

* Natural commutation:-

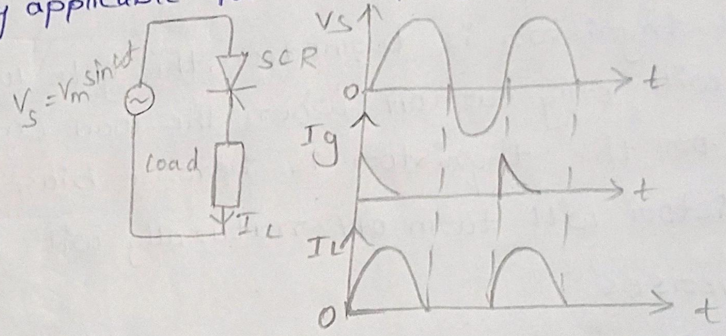
In Ac circuit, the current always passes through zero for every half cycle.

As the Current passes through natural zero, a reverse voltage will simultaneously appear across the device.

This will turn off the device immediately

This process is called as natural Commutation, since no external circuit is required for this purpose

This method is only applicable for Ac supply



* forced commutation:-

To turn off a thyristor the forward anode Current should be brought to zero for sufficient time to allow the removal of charged carriers

In case of Dc circuits, the forward current should be forced to zero by means of some external circuits.

This process is called as forced commutation

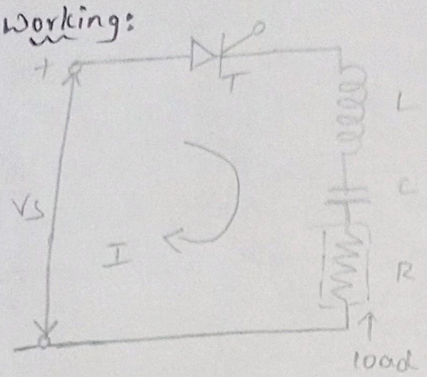
with D.c supply, we use external circuit and active/passive components to reduce passing Current's value below holding current.

The Circuit involved in this procedure is called commutation circuit.

The Components used are called commutating components.

* class-A commutation:-

working:



Class A commutation is also called as self-commutation or resonant commutation or load commutation

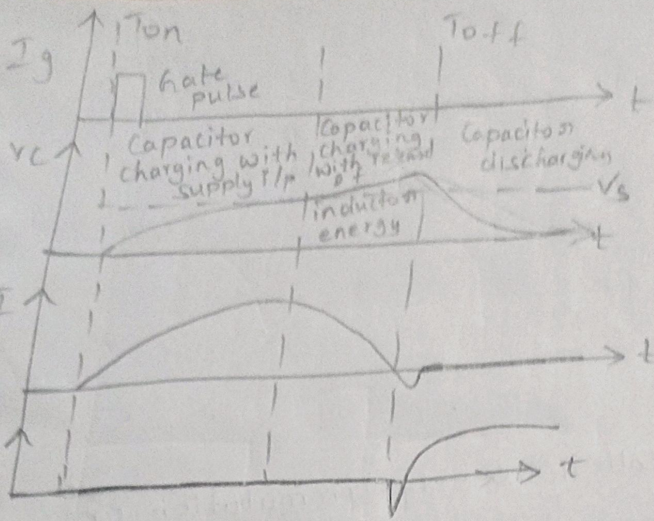
On applying an external dc i/p signal, the current starts flowing through the circuit. In order to turn on the SCR in the circuit, a gate trigger pulse is required. so, simultaneously gate signal is applied that will put the thyristor in forward conduction mode

Hence, after the SCR gets on, the forward current that flows through the SCR begins to charge the capacitor. At the same time, the inductor connected in the circuit stores energy.

We know that it is the property of the inductor, that it opposes, the change in current. so, once the capacitor gets charged up to the peak of the supply input, the polarity of the inductor connected in the circuit will get rereversed and now the inductor will oppose any further flow of current through it

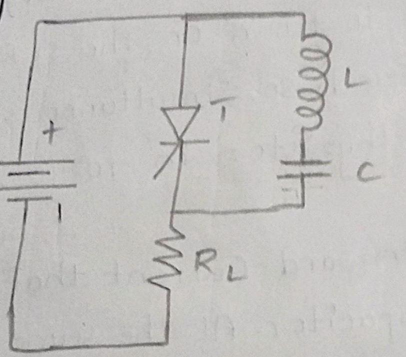
As, the inductor does not further allow the flow of current, the output current starts to decrease and reaches zero.

This means here the commutating components make the current through the load zero and this commutate the thyristor



* Class - B Commutation:-

Working:-



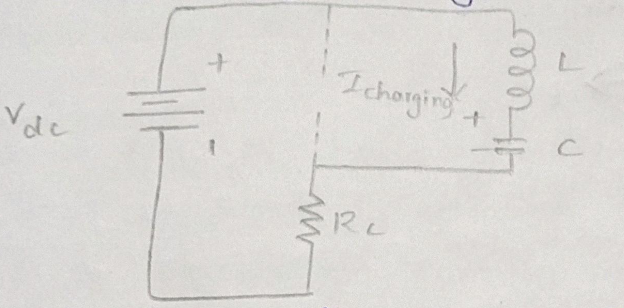
Class B commutation is also called as Resonant-pulse Commutation.

At the initial level when external i/p supply V_{dc} is provided to the circuit then this causes the capacitor to get charged. As no gate excitation is provided to the SCR thus the externally supplied i/p signal will not bring the thyristor into forward conduction mode. But due to supply i/p, the current in the circuit flows through commutating components L & C & the load.

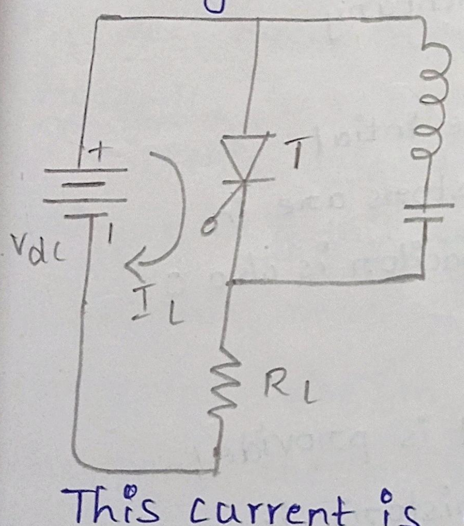
This causes charging of the capacitor with the same polarity as that of the supply i/p. The capacitor gets charged up to the peak of supply i/p voltage

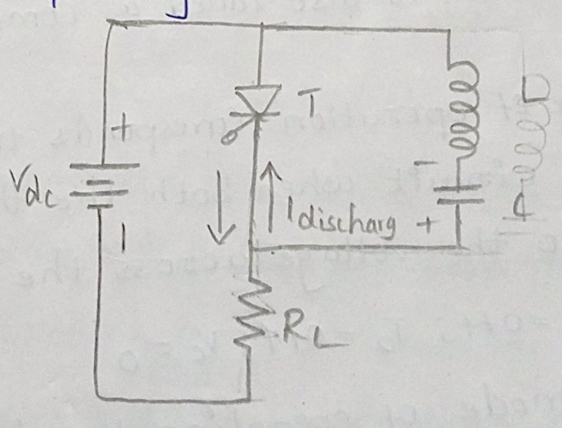
As, the Capacitor does not have a path to discharge thus it will hold the charge +Vdc

More, over at this time, if the thyristor is triggered, then the device comes in forward conduction mode. And so in this condition, SCR starts conduction and current begins to flow from the thyristor & load part of the circuit. The direction in which current flow through the thyristor takes place is shown.

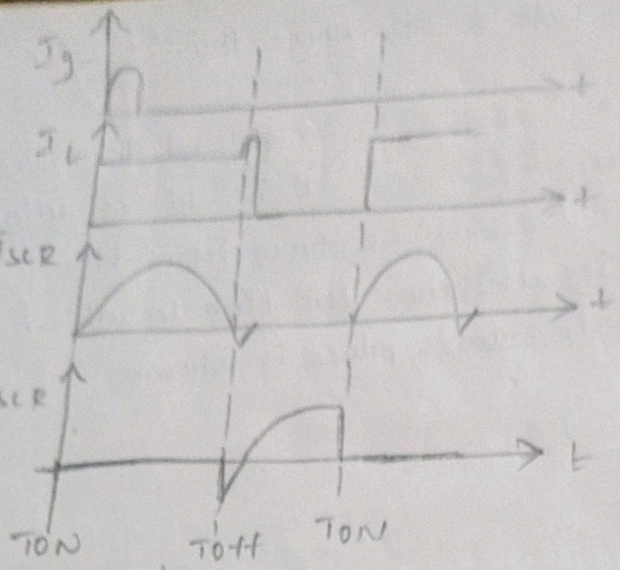


Now, once the Capacitor gets completely discharged then due to the direction of flow of discharging current, reverse polarity will exist at the Capacitor. More simply, in the presence of supply i/p and gate triggering pulse, the thyristor will be in on state & at the same time after getting discharged once, the Capacitor begans to charge with opposite polarity



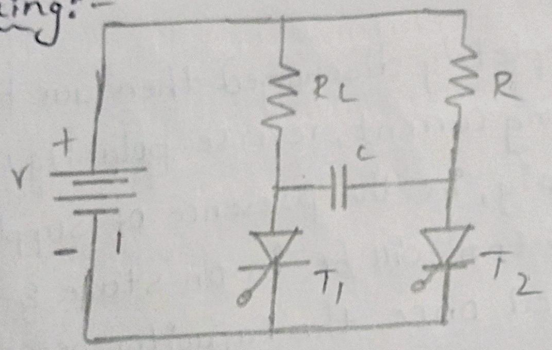


This current is known as Commutating Current and is denoted by I_C & this I_C opposes the flow of I_L in given circuit. As soon as the value of I_C exceeds I_L then this makes the current flowing through the thyristor fall below the value holding current resultantly turning the thyristor off.



* Class - C Commutation:-

Working:-

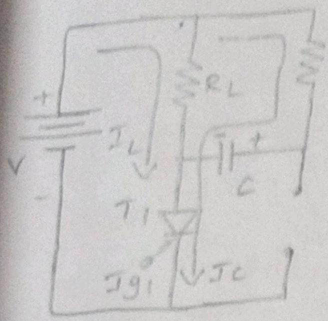


Class C commutation is also called as complementary commutation

Mode 0: This mode of operation corresponds to the intial state of the circuit when both the thyristors are in off state and so the voltage across the capacitor is also 0.

This means, $T_1 = \text{off}$; $T_2 = \text{off}$; $V_C = 0$

Mode 1:- In this mode of operation, the circuit is provided with dc supply i/p & along with that thyristor T_1 is triggered with a gate signal. Due to this T_1 will come in conducting state. This leads to two currents one will be the load current while the other will be charging current of capacitor to flow through the whole circuit



The load current & capacitor current are given as $I_L = \frac{V}{R_L}$

while the charging current will be

$$I_C = \frac{V}{R}$$

Hence, the overall current that flows through SCR, T_1 will be the sum of load current & charging current. This is given as

$$I = \frac{V}{\ } + \frac{V}{\ }$$

Mode-I

Due to flow of the charging current, the capacitor gets charged up to peak of supply i/p accordingly to the polarity as shown

However, the charging current reduce to 0, once the capacitor gets fully charged up to the supply i/p, & thus the only current that continues to flow through T_1 is the load current. Even when the moment C is holding the charge, T_1 continues to remain in conducting state. Hence,

$T_1 = on; T_2 = off; V_C = V$

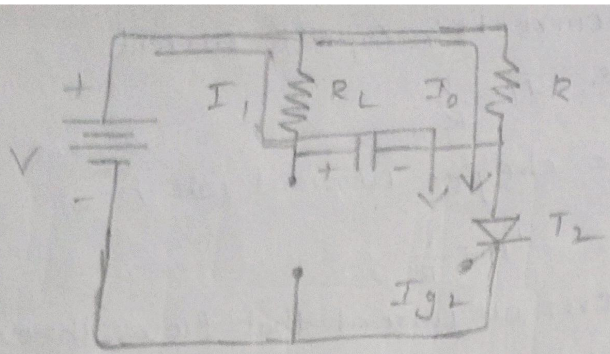
Now, our attempt should be to commutate T_1 & this is explained in next mode of operation

Mode-II

In this state of operation, T_2 is provided the gate pulse that triggers it & this leads to turning off T_1. Now, the

So, this mode of operation is such that by providing a triggering pulse to T_2 the path becomes short-circuted. Once this happens, the polarity of charge stored by the capacitor reverse biases the thyristor T_1.

This reverse biased condition leads to turning off of the thyristor T_1. So, when T_2 is conducting state



The current flowing through $R-T_2$ will be given as

$$I_0 = \frac{V}{R}$$

Mode-II

However, the flow of current through the capacitor again charges the Capacitor but this time with reverse polarity i.e opposite to the case discussed previously

Hence, mode II operataion provides,

$T_1 = off;\ T_2 = on;\ V_{C_1} = -V$

sed previously

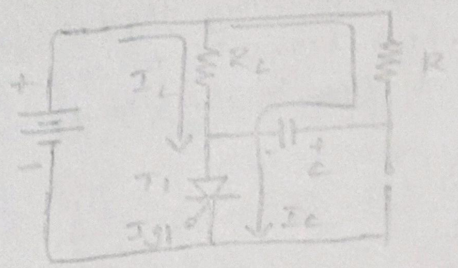
Mode-III

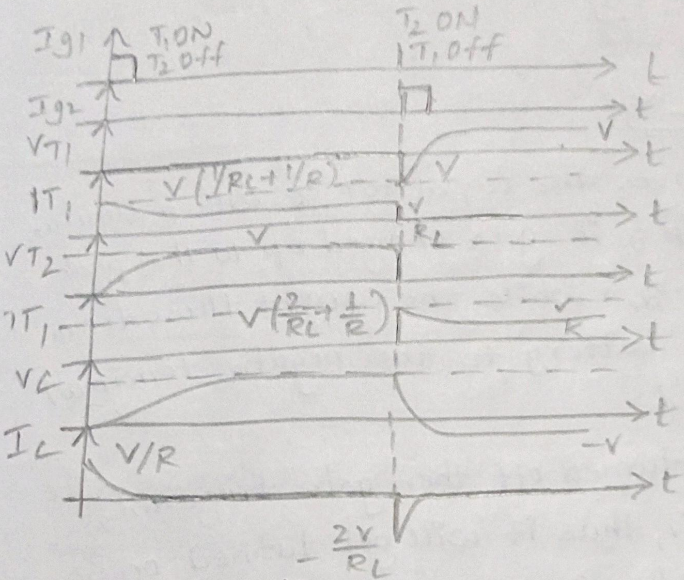
In order to turn off T_2, T_1 is triggered using gate pulse. Once T_1 starts conduction then the polarity existing across C reverse biases T_2 due to which T_2 stops conduction & the current flows through T_1 like we have discussed in

Hence, the mode III operation will lead cause

$T_1 = on;\ T_2 = off;\ V_C = V$

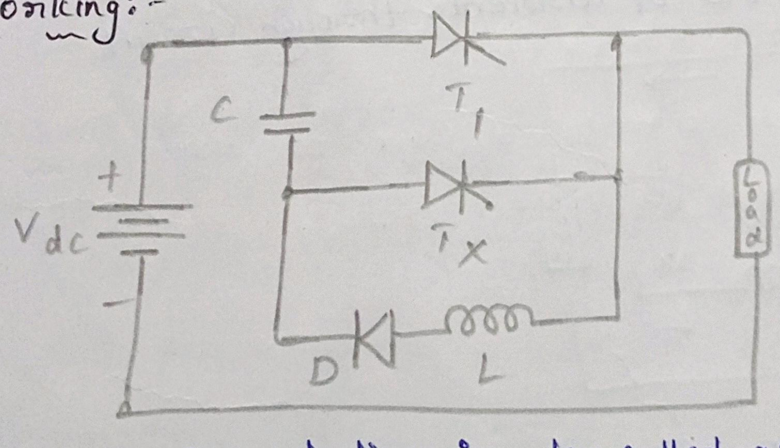
Mode-III





*Class - D Commutation:-

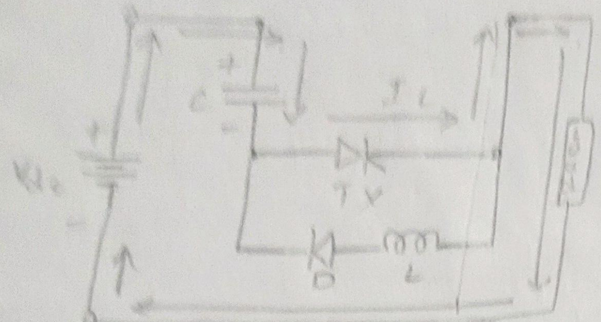
Working:-



Class D commutation is also called as Impulse commutation or Voltage Commutation.

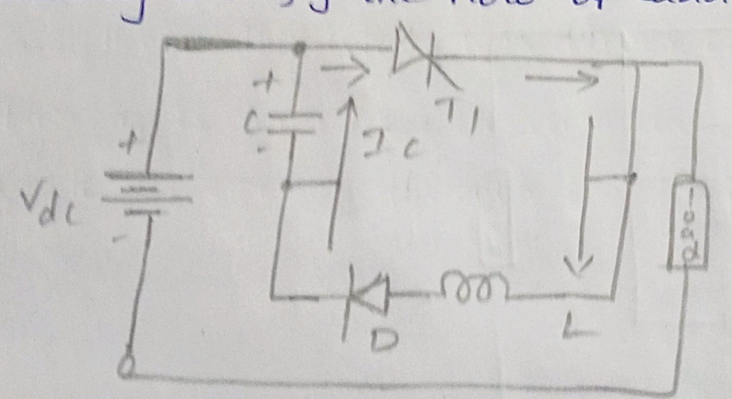
Intially on applying voltage V across the circuit but in the absence of gate triggering pulse both the thyristors are in the off state. Due to the supply i/p, the diode fig is reverse biased condition thus, no flow of current takes place through the circuit hence the voltage across the capacitor will be 0.

Further, out of two thyristors, the auxiliary thyristor is provided gate triggering pulse which brings it to conducting state, thus, the current starts to flow in the circuit.



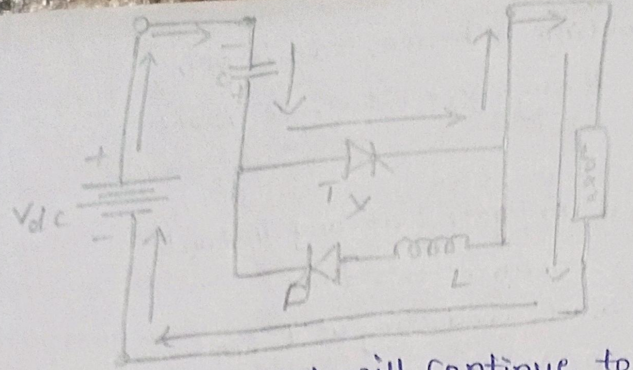
This flow of current charges the capacitor C with a similar polarity as that of supply i/p & it gets charged up to the peak of the pea supply value i.e. V_{dc}. while the current flows from the positive terminal of the battery to the negative terminal, by passing through the load.

Moreover, once T_X gets turned off then gate triggering pulse is given to thyristor T_1, thus it will get turned on under presence of supply i/p. As T_1 comes into the conducting state, & the flow of currents through circuit

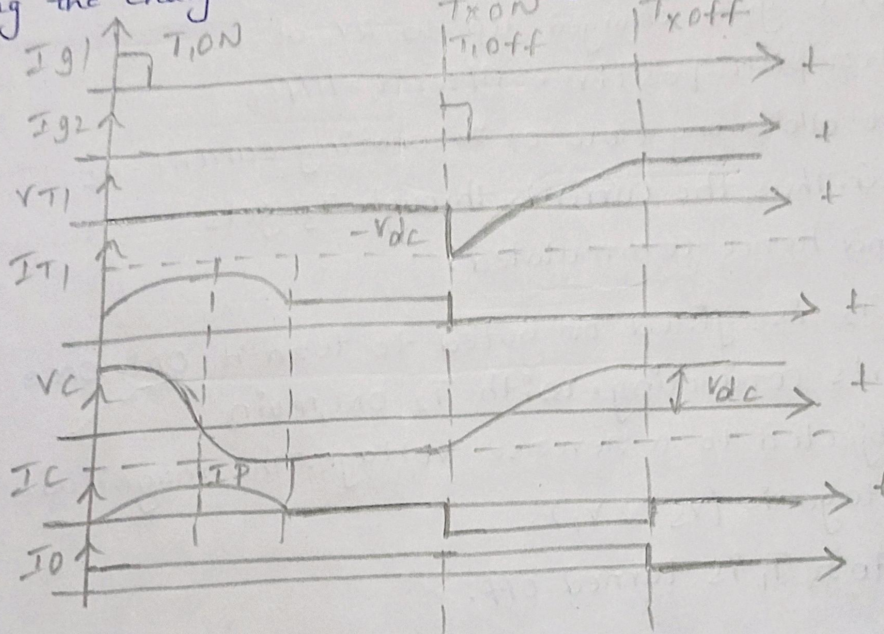


Now, as T_1 is in conducting state & we have to commutate T_1 thus, for this we need to trigger T_X i.e the auxiliary thyristor, T_1 to a reverse biased state and this will lead to turning the thyristor off

Thus, once T_1 gets turned off then the current through the circuit will flow in the manner

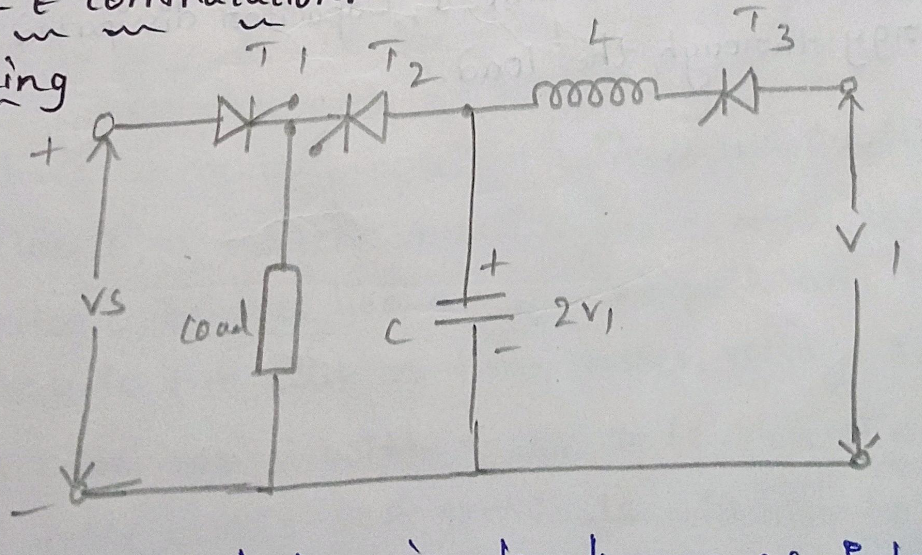


And this current will continue to flow till the time the capacitor is holding the charge of reverse polarity as the supply i/p



* Class - E commutation:-

Working



Class-E commutation is also known as External pulse commutation. This external current pulse is obtained from a seperate voltage source.

Initially thyristor T_1 is conducting & hence, load is being fed by main voltage source V_s Through V_1. Now, we want to turn off main SCR T_1.

For this, thyristor T_3 is fired or gated at any instant of time to turn it ON. Let us assume this time to be $t=0$ sec. Once T_3 is ON, it starts conducting at $t=0$ sec. A resonating circuit consisting of V_1, L and C is formed and resonating current starts flowing. Due to resonating current, Capacitor C gets charged up to $2V_1$ at $t=\pi/\sqrt{LC}$ with upper plate positive. After $t=\pi/\sqrt{LC}$ Capacitor will not allow any flow of resonating current as it is fully charged. Thus, the current through T_3 gets reduced to zero and hence commutated.

Now, thyristor T_2 is fired or gated to turn it ON. Once T_2 is ON, it starts conducting. With T_2 ON, main thyristor T_1 is subjected to a reverse voltage. The magnitude of his reverse voltage is $(V_S - 2V_1)$.

$\therefore$ main, thyristor T_1 is turned off.

After T_1 is turned off or commutated, Capacitor dissipated its stored energy through the load.

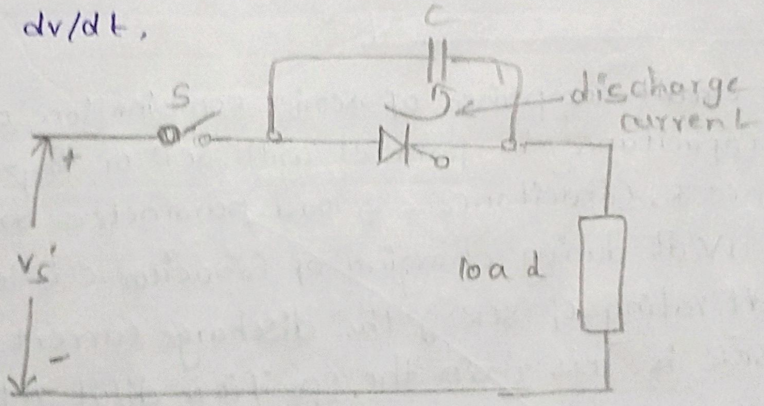
* Snubber circuit-purpose, Design and working:-

Purpose of Snubber circuit:-

The main purpose of Snubber circuit is to prevent the unwanted triggering of SCR or thyristor due to high rate of rise of voltage i.e dv/dt. We already know that if the rate of rise of anode to cathode voltage of SCR is high then it may lead to false triggering. This is commonly known as dv/dt trigerring. Thus we need to have some arrangement to protect SCR from such undesirable turning. Application of snubber circuit. Thus it is basically dv/dt protection of SCR.

Design and working principle of snubber circuit:-

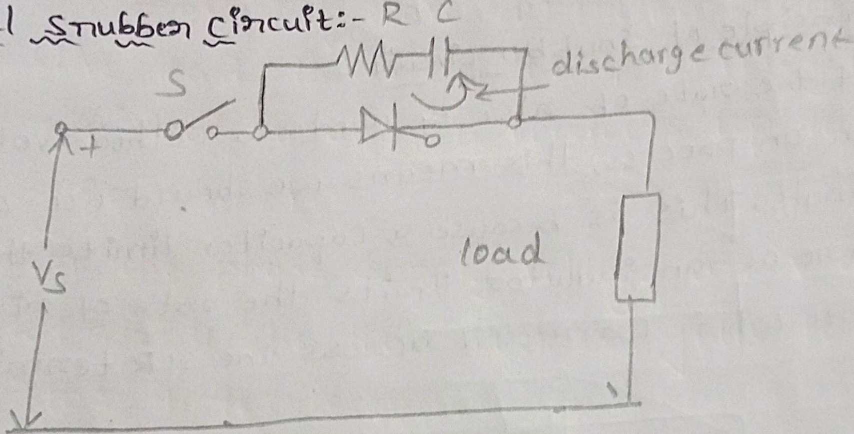
As we need to limit the rate of rise of anode to cathode voltage of SCR during its turn on process, this means we should use a capacitor the SCR terminals. This is because a capacitor limits the rate of rise of voltage where as an inductor limits the rate of rise of current. Thus a capacitor when connected across the SCR terminals, when limit dv/dt,



We have connected capacitor c in parallel with SCR. when switch S is closed, a sudden voltage appears across the circuit. Initially capacitor c behaves like a shorted path and hence the voltage across SCR is zero. But as time passes, voltage starts buildin up across capacitor C with a slow rate. Thus the rate of rise of voltage dv/dt across SCR terminals will also be slow and less than the specified dv/dt rating of SCR.

Before SCR is fired or triggered by applying gate pulse, the capacitor c is fully charged up to supply voltage V_s, As soon as SC is turned on by gate pulse, this charged capacitor C discharges through SCR. Hence a current having magnitude flows in the local path formed by SCR and capacitor C. Since the value of resistance of this local path is quite small, the magnitude of discharge current will be quite higher. This will lead to high value of di/dt which may exceed the specified di/dt rating of SCR. In order to limit the magnitude of the discharge current, a resistance should be connected in series with the capacitor C.

Actual Snubber circuit:-



Thus a snubber circuit comprises of series combination of resistance and capacitance in parallel with SCR or thyristor. Generally, resistance R, capacitance C & load parameters are so chosen that the dv/dt during charging of capacitor C is less than the specified dv/dt rating of SCR & the discharge current at the turn on of SCR is less than the specified di/dt rating.

PE

unit - II (P-16)

Many Industrial applications make use of "controllable DC power." Examples of Such applications are as fallows

(a). Steel-rolling mills, paper mills, printing presses and textile mills

(b) Traction systems working on DC.

(c) Electrochemical and electrometallurgical process.

(d) magnet power supplies

(e) portable hand tool drives

(f) HVDC transmission

Earlier DC power was obtained from Motor-Generator (M-G) Set or ac power was converted to DC power by means of mercury-arc rectifiers or thyratrons. Now a days those are replaced with phase Controlled Rectifiers

* In phase-controlled rectifiers, a thyristor is turned off as ac Supply voltage reverse biases it, provided anode current has fallen to a level below the holding current. The turning-off or Commutation of a thyristors by Supply voltage itself is called natural (or) line commutation.

* Therefore in phase-Controlled rectifiers no need of commutation circuitry. these are less expensive and are widely used in industries where controlled DC power is required.

** In the study of SCR Systems and Diodes are ass... ideal Switches which means that

(i) there is no voltage drop across them

(ii) no reverse current exists under reverse voltage conditions

(iii) holding current is zero.

Trigger circuits are not shown in SCR ckt for convenience

(0 to α): $V_0 = 0$, $I_0 = 0$

*Classification:-

Phase-controlled Rectifiers
- Single-phase
  - Half wave
    - loads:- R, RL, RLE
  - full wave
    - Half controlled (Semi converters)
      - mid-point (R, RL, RLE loads)
      - Bridge
        - Symmetrical (R, RL, ~~RLE~~)
        - Asymmetrical (R, RL, RLE)
    - fully controlled
      - mid point (R, RL, RLE)
      - Bridge type (R, RL, RLE)
- 3-phase
  - Halfwave
  - full wave
    - Semi Converter
    - fully controlled

In this unit we will study about 1-ϕ half controlled converter

In the next unit (4) we will study about 1-phase fully controlled converters

(0 to α):- (or) $0 \leq \omega t < \alpha$:-

$V_0 = 0$

$I_0 = 0$

$V_T = V_S = V_m \sin \omega t$

at $\omega t = \alpha$

$V_0 = V_m \sin\alpha$

$I_0 = \frac{V_0}{R} = \frac{V_m}{R} \sin\alpha$

$\alpha \leq \omega t \leq \pi$:-

$V_0 = V_S = V_m \sin \omega t$

$I_0 = \frac{V_0}{R}$

$V_T = 0$

at $\omega t = \pi$ thyristor(T) turn-OFF

$V_0 = 0$

$V_T = V_S$

$I_0 = 0$

The circuit turn-off time is given by

$$\boxed{t_c = \frac{\pi}{\omega} \text{ sec}} \quad (\because \omega = 2\pi f)$$

Average voltage V_0 across load R. is given by

$$V_0 = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t) \quad \left[\because V_{avg} = \frac{1}{T}\int_0^T f(t)dt\right]$$

$$V_0 = \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$V_0 = \frac{V_m}{2\pi}\left[-\cos\pi + \cos\alpha\right]$$

$$\therefore \boxed{V_0 = \frac{V_m}{2\pi}\left[1 + \cos\alpha\right]}$$

The maximum value of average o/p V_0 occures at $\alpha = 0°$

$$V_{om} = \frac{V_m}{2\pi}\left[1 + \cos 0°\right] = \frac{V_m}{\pi}$$

Average load current $\boxed{(I_0) = \frac{V_0}{R} = \frac{V_m}{2\pi R}(1 + \cos\alpha)}$

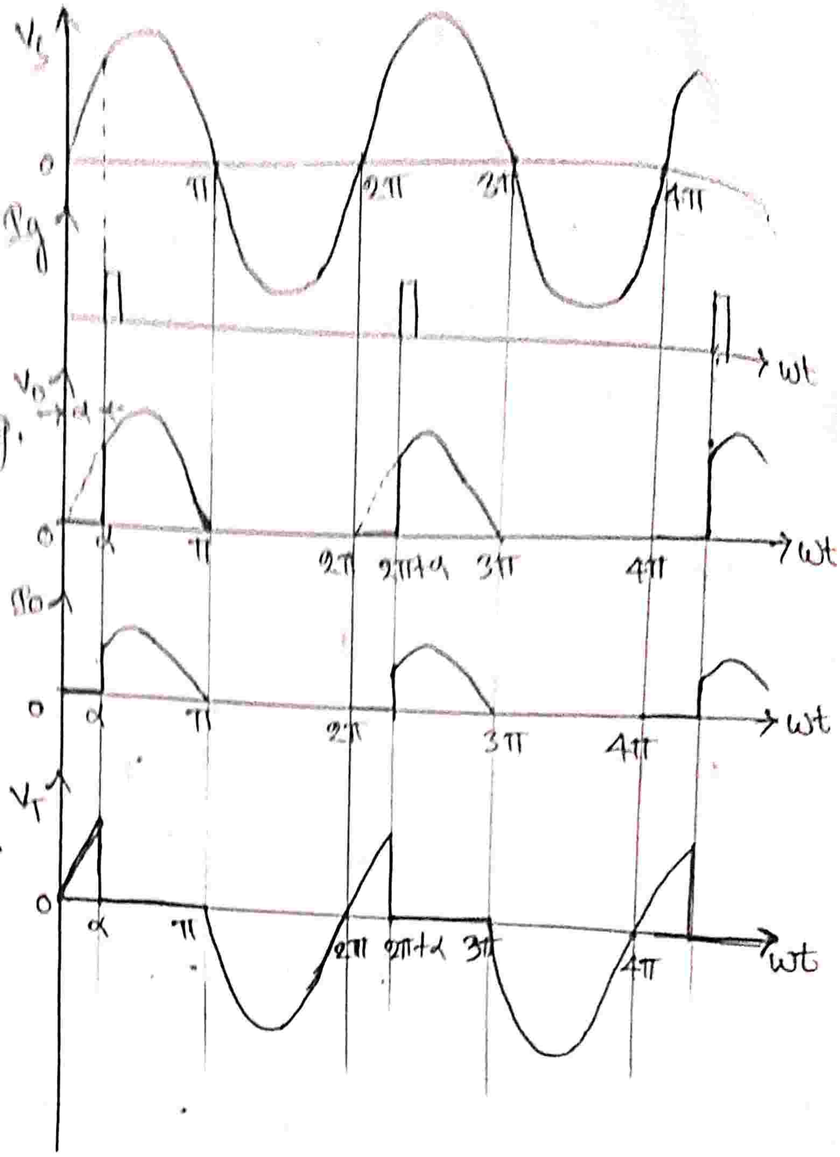
RMS voltage of load voltage is given by

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

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

$$\boxed{V_{or} = \frac{V_m}{2\sqrt{\pi}}\sqrt{[\pi - \alpha] + \frac{\sin 2\alpha}{2}}} \quad \& \quad \boxed{I_{or} = \frac{V_{or}}{R}}$$

Single-phase half-wave converter with R-load:-



1-ϕ half wave converter with R-load is shown in fig. The source voltage is

$V_s = V_m \sin \omega t$

An SCR can conduct only when Anode voltage is +ve and a gate signal is applied. Thyristor blocks the current i_o untill it is triggered at $\omega t = \alpha$ some delay angle Thyristor can be triggered. then V_o varies from 0 to $V_m \sin\alpha$ and output voltage follows the input from α to π.

* firing angle of a thyristor is measured from the instant it would start conducting if it were replaced by a diode. it would begin conduction at $\omega t = 0, 2\pi, 4\pi$ etc.

*** firing angle may be defined as the angle measured from the instant SCR gets forward biased to the instant it is triggered.

once the SCR is on, load current flows untill it is turned-off by reversal of voltage at $\omega t = \pi, 3\pi$ etc.... At these angles load current falls to zero & Thyristor is OFF.

$$V_{or} = \left[\frac{V_m^2}{4\pi}\int_{\alpha}^{\pi}(1-\cos 2\omega t)\, d(\omega t)\right]^{1/2}$$

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

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

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

The value of RMS load current I_{or} is

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

$$\therefore \boxed{I_{or} = \frac{V_m}{2\sqrt{\pi}(R)}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]^{1/2}}$$

power delivered to resistive load $= V_{or} \times I_{or} = \frac{V_{or}^2}{R} = I_{or}^2 R$

Input volt amperes $= V_s \times I_{or}$

$$= V_s \times \frac{V_m}{2\sqrt{\pi}}\left[(\pi-\alpha) + \tfrac{1}{2}\sin 2\alpha\right]^{1/2} \qquad \left[V_{rms} = \frac{V_m}{\sqrt{2}}\right]$$

$$\left[\therefore V_m = \sqrt{2} V_s\right]$$

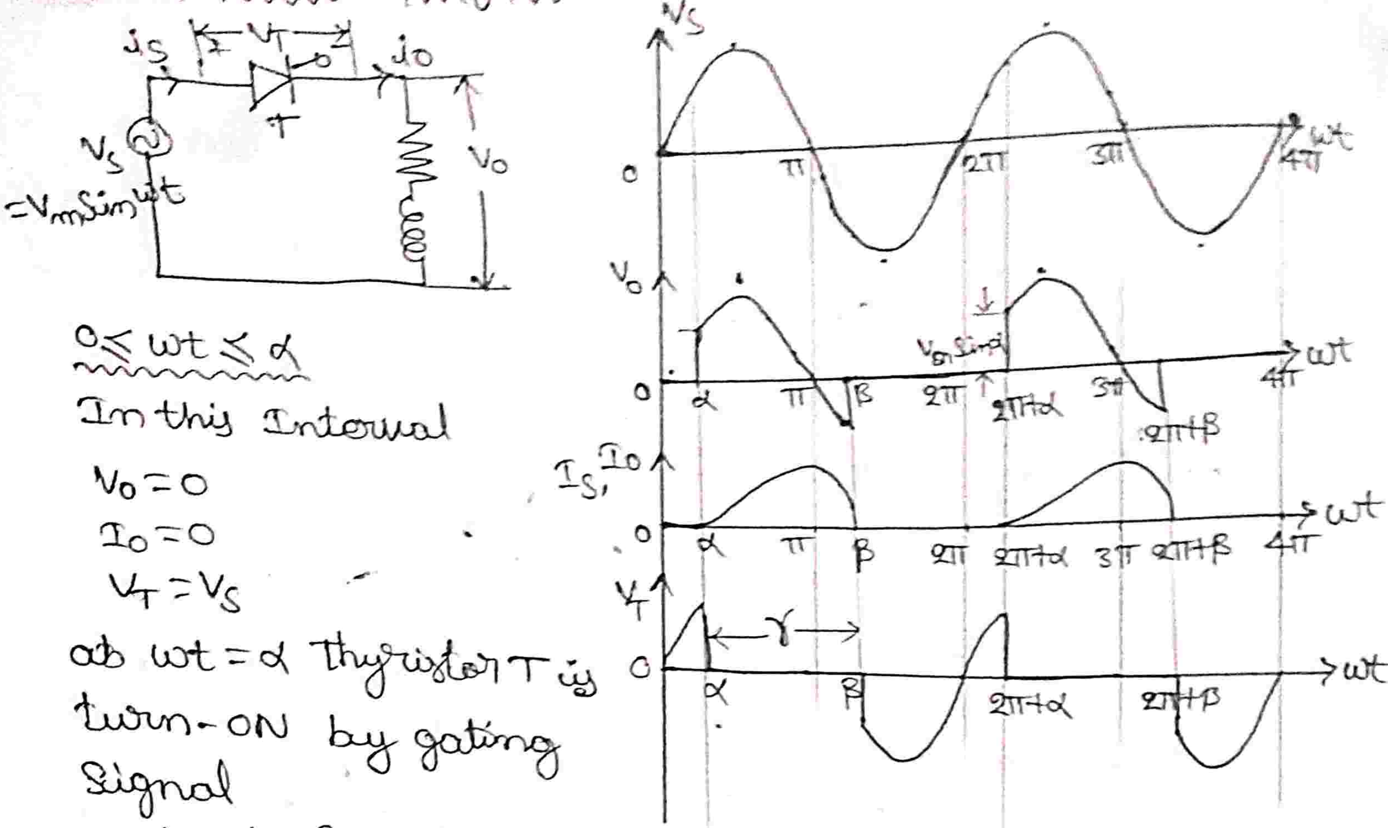
$$V_s I_{or} = \frac{\sqrt{2} V_s^2}{2R\sqrt{\pi}}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]^{1/2}$$

Input power factor $= \frac{\text{power delivered to load}}{\text{Input VA}}$

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

$$\therefore \boxed{\text{I/p P.f} = \frac{1}{\sqrt{2\pi}}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]^{1/2}}$$

Single-phase Half-wave circuit with RL Load:-



$0 \leq \omega t \leq \alpha$

In this Interval

$V_o = 0$

$I_o = 0$

$V_T = V_s$

at $\omega t = \alpha$ Thyristor T is turn-ON by gating Signal

$V_o = V_m \sin\alpha$

$I_o =$ Starts raising.

$\alpha \leq \omega t \leq \pi$:- O/p voltage $V_o = V_s$ current rises gradually after some time I_o reaches maximum & then begins to decreases

At $\omega t = \pi$ $V_o = 0$ but load current i_o is not zero because of the load inductor L. After $\omega t = \pi$. SCR is subjected to reverse anode voltage but it will not be turned off as load current is not less than the holding current. At some angle $\beta > \pi$, "i_o" reduced to zero and SCR is turned-off as it is already reverse biased.

After $\omega t = \beta$, $V_o = 0$ & $i_o = 0$ At $\omega t = 2\pi + \alpha$ SCR is triggered again, $V_o = V_s$.

Angle "β" is called the extinction angle and $\gamma = (\beta - \alpha)$ is called the Conduction angle.

Thus circuit turn-off time t_c

Conducting upto $\beta \Rightarrow \omega t_c = 2\pi - \beta$

$$\boxed{t_c = \frac{2\pi - \beta}{\omega}}$$

average load voltage is given by

$$V_{dc} = V_{avg} = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\beta}$$

$$\boxed{V_0 = V_{avg} = \frac{V_m}{2\pi}\left[\cos\alpha - \cos\beta\right]}$$

Average load current $I_0 = \frac{V_m}{2\pi R}\left[\cos\alpha - \cos\beta\right]$

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

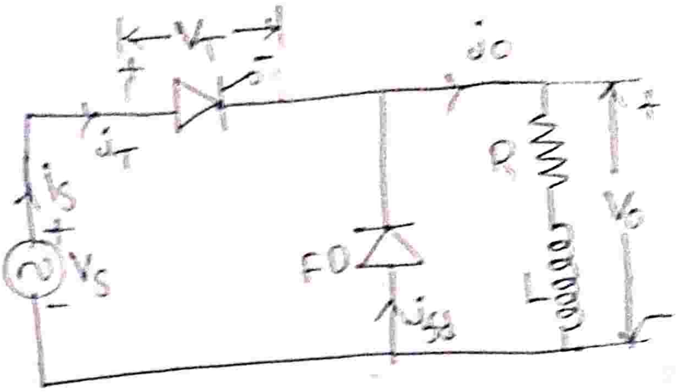
$$= \frac{V_m}{2\sqrt{\pi}}\left\{\int_{\alpha}^{\beta}(1 - \cos 2\omega t)\, d\omega t\right\}^{1/2}$$

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

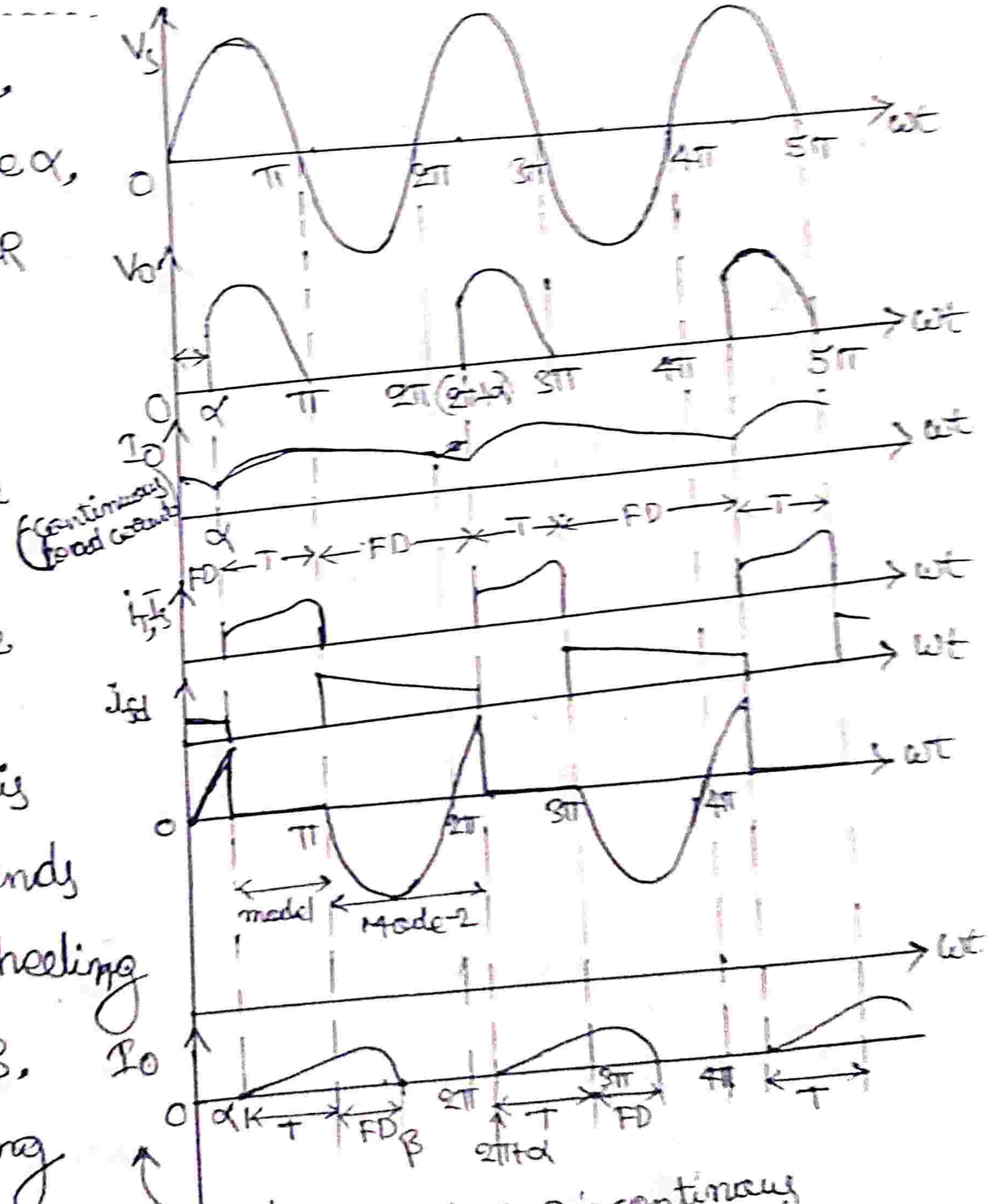
$$\therefore \boxed{V_{or} = \frac{V_m}{2\sqrt{\pi}}\left[(\beta - \alpha) - \frac{1}{2}(\sin 2\beta - \sin 2\alpha)\right]^{1/2}}$$

1-ϕ half-wave circuit with RL load & with freewheeling Diode :-

1-ϕ half wave circuit with RL load with freewheeling Diode as shown in fig.



"A freewheeling diode is also called by-pass or commutating diode.



At $\omega t = 0$ V_s is +ve, At some delay angle α, forward biased SCR triggered and Source Voltage appears across the load as V_0.

At $\omega t = \pi$ Source Voltage is zero and just after this instant, as V_s tends to reverse, Free-wheeling Diode (FD) is F.B. through conducting SCR. as a result load current is immediatly transferred from SCR to FD as V_s tends to reverse.

At the same time SCR is subjected to reverse voltage and zero current, it is turned off at $\omega t = \pi$.

* Assume that load current is continuous and I_o current does not decay to zero until the SCR is triggered again at $(2\pi + \alpha)$. Voltage drop across FD is taken almost zero, the load voltage V_o is therefore zero during freewheeling period.

As SCR is turn-off at $\omega t = \pi$, & reverse biased from π to 2π

$\therefore$ circuit turn-off time $t_c = \pi/\omega$ sec

i_s & I_T are same as shown in fig

Mode 1 (Conduction)

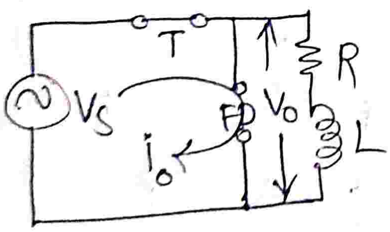
$\alpha \leq \omega t \leq \pi$

SCR-ON

$V_o = V_s$

$I_o = V_o/R$

$V_T = V_s$



Voltage Eq.

$$V_m \sin \omega t = R i_o + L \frac{di_o}{dt}$$

Sol. of above Eq.

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + \left[I_o - \frac{V_m}{Z} \sin(\alpha - \phi) \right] e^{-\frac{R}{L}(t - \alpha/\omega)}$$

Mode-2 (Freewheeling)

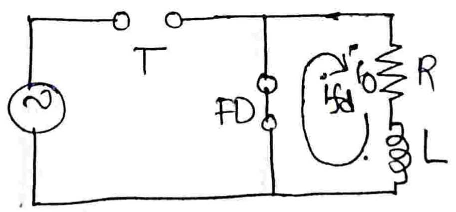
$\pi \leq \omega t \leq 2\pi + \alpha$

SCR-OFF

$V_o = 0$

$I_o = I_{fd}$

$V_T = V_s$



Voltage Eq

$$0 = R i_o + L \frac{di_o}{dt}$$

Sol. of above Eq.

at $\omega t = \pi$ $\quad i_o = I_{o1}$

$$i_o = I_{o1} e^{-R/L (t - \pi/\omega)}$$

Average load voltage V_0 is given by

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{2\pi}\int_{\alpha}^{\pi} \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_m}{2\pi}\left[-\cos\pi + \cos\alpha\right]$$

$$\boxed{V_0 = \frac{V_m}{2\pi}\left[1+\cos\alpha\right]} \longrightarrow (1)$$

Average load current $I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R}(1+\cos\alpha)$

* Load absorbs the power for α to π, but for π to $(2\pi+\alpha)$ energy stored in "L" is delivered to load "R" through the FD. Therefore power consumed by load is more.

$\therefore$ It can be concluded that power delivered to load for same firing angle is more when FD is used.

* <u>Advantages of freewheeling Diode</u>

(i) input P.f is improved

(ii) load current waveform is improved

(iii) as I_0 is increases load performance is better

(iv) as energy stored in L is transferred to "R" During freewheeling period, overall converter "η" increases.

(v) FD prevents the load voltage "v_0" from being negative.

(vi) with same firing angle the power delivered to load is increases with FD.

1-ϕ half wave converter thus introduces a DC compo into the supply line. This leads saturation of supply T/F and other difficulties (harmonics etc.)

This difficulties can be overcome with 1-ϕ full wave circuits.

* Disadvantages of 1-ϕ half wave converters:-

1-ϕ half wave ~~for~~ controlled rectifier gives

→ low DC o/p voltage

→ low DC o/p power & lower efficiency

→ higher ripple voltage & ripple current

→ higher ripple factor

→ low Transformer utilization factor

→ Input supply current has a DC component, which can result in saturation of T/F core.

* 1-ϕ full wave controlled Rectifiers:-

It produces two pulse o/p across the load. So some times it is also called as "2-pulse converter".

These are various types

(I) 1-ϕ full wave controlled rectifier (center tapped T/F)

(II) 1-ϕ " " (Bridge configuration)

(a) Half controlled bridge converter (Semi converter)

(b) fully controlled bridge converter (full converter)

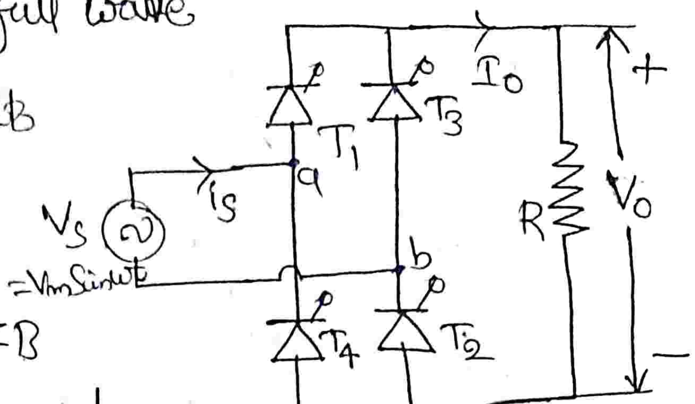
fully ϕ

I-ϕ

:- 1-ϕ full Converters :-

1-ϕ fully controlled bridge circuit with R-load :-

The below fig shows, 1-ϕ full wave converter in bridge circuit with R-load.



During the HC T_1 & T_2 are FB but those 2-SCRs in forward Blocking mode. $[0 \leq \omega t < \alpha,\ T_1 \& T_2 - \text{OFF}\ \ V_0 = I_0 = 0]$

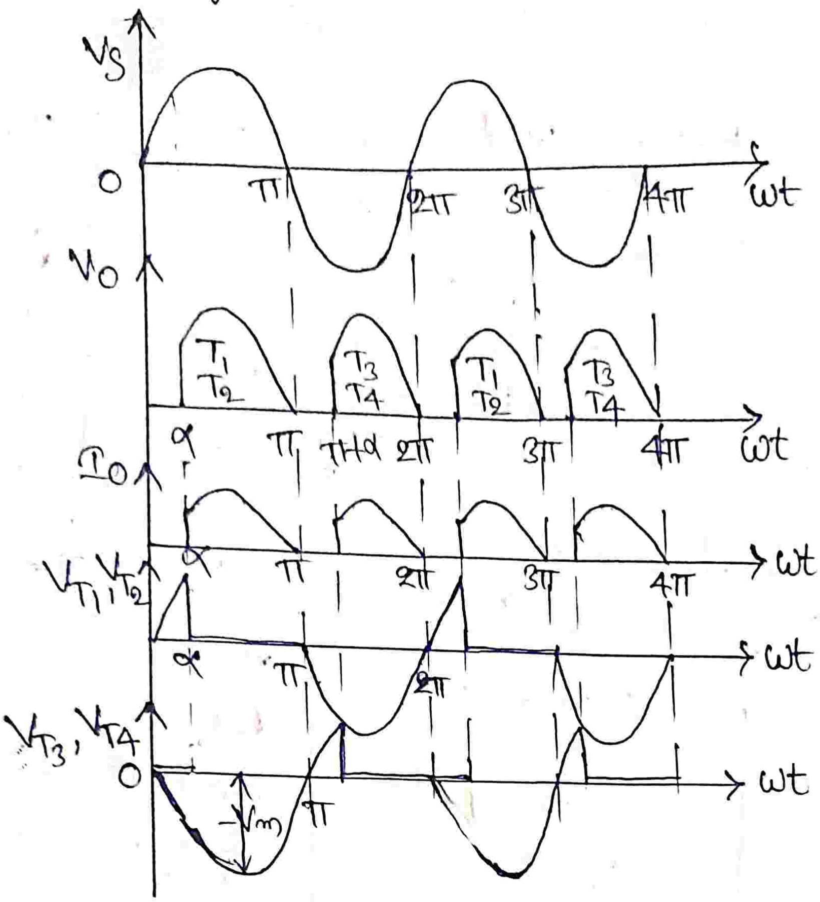
At $\omega t = \alpha$ both T_1 & T_2 triggered & Turned on. $V_0 = V_m \sin\alpha$ $I_0 = V_0/R$ $V_{T_2} = V_{T_1} = 0$	$\alpha \leq \omega t < \pi$ T_1 & T_2 − ON $V_0 = V_S$ $I_0 = V_0/R$ $V_{T_1} = V_{T_2} = 0$	at $\omega t = \pi$ due to natural commutation T_1 & T_2 − OFF

I-path: $V_S^+ - T_1 - R - T_2 - V_S^-$

During −ve Half Cycle T_3 & T_4 are in FBM

& at $\omega t = \pi + \alpha$ T_3 & T_4 are triggered & gets turned on. $V_0 = V_m \sin\alpha$ $I_0 = V_0/R$ $V_{T_3} = V_{T_4} = 0$	$\pi + \alpha \leq \omega t < 2\pi$ T_3 & $T_4 \Rightarrow$ ON $V_0 = V_S$ I_0-path :- $V_S^- - T_3 - R - T_4 - V_S^+$ $V_{T_3} = V_{T_4} = 0$	at $\omega t = 2\pi$ due to natural commutation T_3 & T_4 turned off.

* Waveforms:-



average o/p voltage $V_{DC} = V_{avg} = \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$

$$V_{DC} = \frac{V_m}{\pi} \left[-\cos\omega t \right]_{\alpha}^{\pi}$$

$$= \frac{V_m}{\pi} \left[-\cos\pi + \cos\alpha \right]$$

$$\boxed{V_{DC} = \frac{V_m}{\pi} \left[1 + \cos\alpha \right]} \longrightarrow ①$$

$$I_{DC} = \frac{V_{DC}}{R} = \frac{V_m}{\pi R} (1 + \cos\alpha) \longrightarrow ②$$

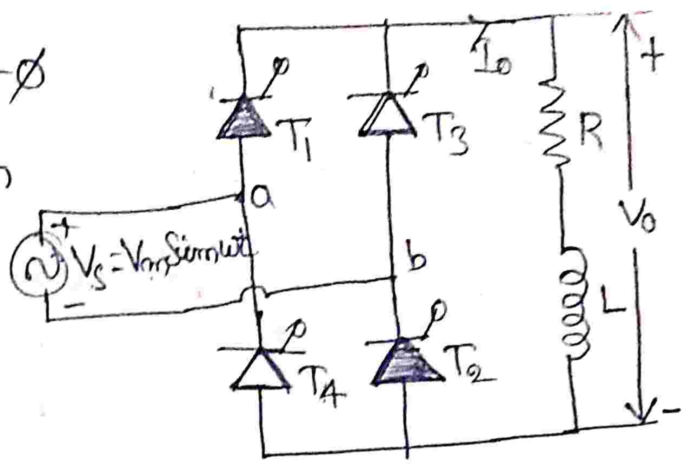
RMS output voltage $V_{orms} = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} (V_m \sin\omega t)^2 \, d(\omega t)}$

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

$$\boxed{V_{orms} = \frac{V_m}{\sqrt{2\pi}} \sqrt{(\pi - \alpha) + \frac{\sin 2\alpha}{2}}} \longrightarrow ③$$

$1-\phi$ fully controlled bridge converter with RL-load :-

The below fig shows the $1-\phi$ 2-pulse or full converter with RL load.



$$V_{ab} = -V_{ba} = V_m \sin\omega t$$

During the +ve H.C. $T_1 \& T_2 \Rightarrow$ FB &

$T_3 \& T_4 \Rightarrow$ RB

During -ve H.C. $T_3 \& T_4 \Rightarrow$ FB &

$T_1 \& T_2 \Rightarrow$ RB.

Assume that load inductance is larger enough and load current is being continuous. The wave-forms of full conver in continuous conduction mode as fallows.

ⓐ In continuous current conduction mode

$\beta \geq \pi + \alpha$, it holds good.

$0 \leq \omega t < \alpha$ $T_3 \& T_4$ - on & $T_1 \& T_2$ are in FBM.

at $\omega t = \alpha$ $T_1 T_2$ - on

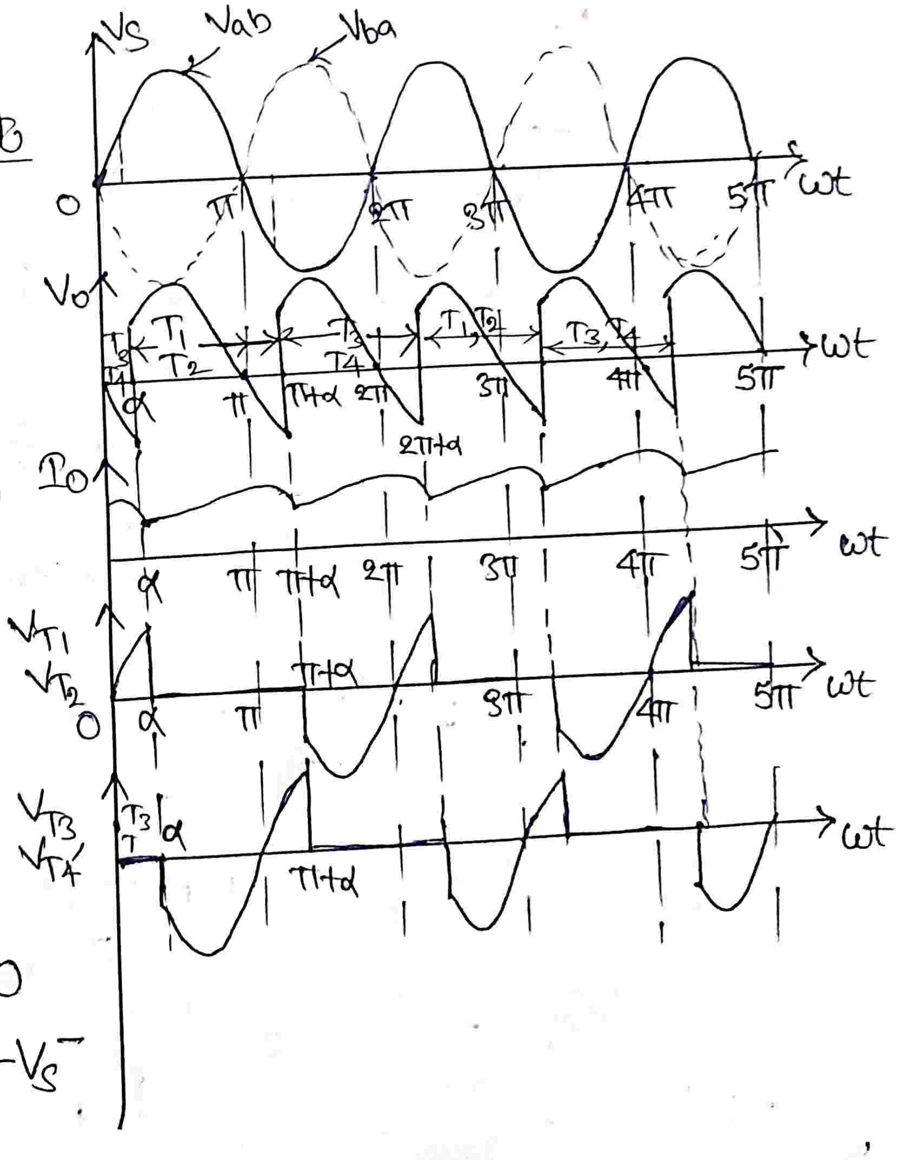
$\alpha \leq \omega t < \pi + \alpha$

$T_1 \& T_2$ - on

$T_3 \& T_4$ - OFF

$V_o = V_s$ $\quad V_{T_1} = V_{T_2} = 0$

I_o-path $V_s^+ - T_1 - R - L - T_2 - V_s^-$



At $\omega t = \pi + \alpha$ T_1 & T_2 - turned OFF &

T_3 & T_4 are gets triggered & turn-on.

$\therefore$ $V_0 = V_S$; $V_{T_3} = V_{T_4} = 0$

I_0 - path $\Rightarrow V_S^- - T_3 - R - L - T_4 - V_S^+$

average o/p voltage is derived as follows

$$V_{DC} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$$

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

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

$$= \frac{V_m}{\pi}\left[\cos\alpha + \cos\alpha\right]$$

$$\boxed{V_{DC} = \frac{2V_m \cos\alpha}{\pi}} \longrightarrow (1)$$

$$I_{DC} = V_{DC}/R = \frac{2V_m}{\pi R}\cos\alpha \longrightarrow (2)$$

Rms value of o/p voltage is derived as

$$V_{orms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}(V_m \sin\omega t)^2 d(\omega t)}$$

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

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

$$= \frac{V_m}{\sqrt{2\pi}}\left\{(\pi+\alpha-\alpha) - \frac{(\sin(2\alpha+2\pi) - \sin 2\alpha)}{2}\right\}^{1/2}$$

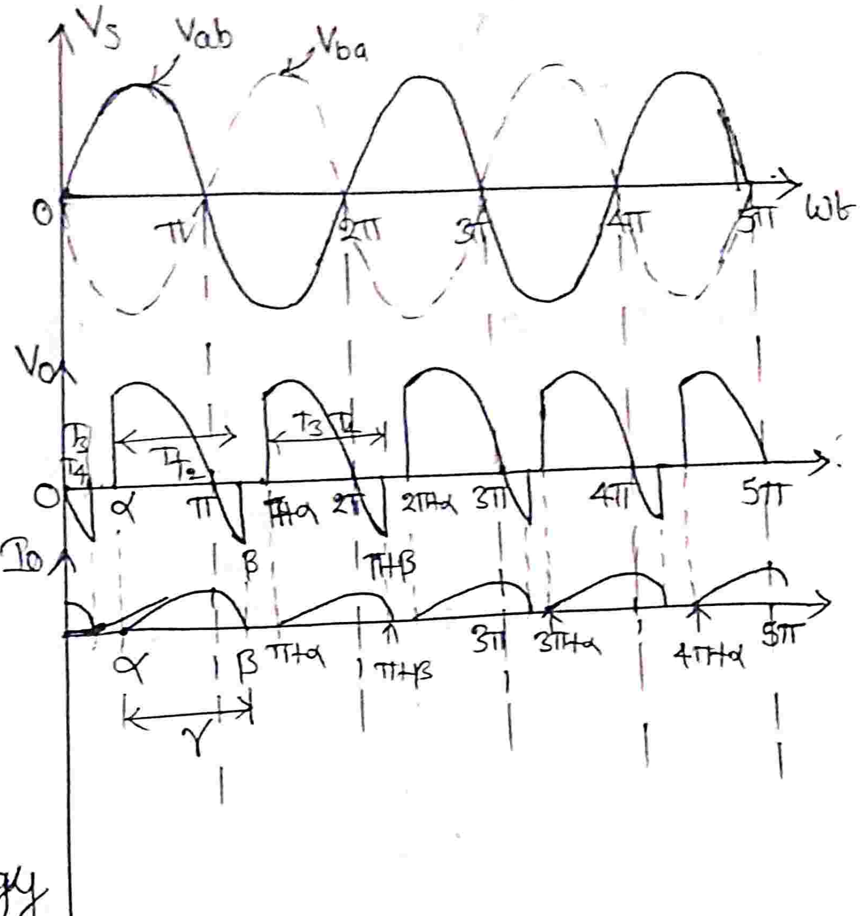
$$V_{orms} = V_m/\sqrt{2\pi}\left[\sqrt{\pi}\right] = V_m/\sqrt{2} \longrightarrow (3)$$

$$i/p \text{ P.f} = V_{orms}/V_{srms} = 1$$

(6) Discontinuous current Conduction mode :-

$\beta < \pi + \alpha$, its holds good (L - is small)

In discontinuous current conduction mode load current is made to zero before the $\pi+\alpha$ & $(\beta < \pi+\alpha)$ at extinction angle "β" after this instant inductor "L" will not have a sufficient energy to drive the load current.



$\therefore$ T_1 & T_2 Conducts up to β only

$\beta \leq \omega t \leq \pi+\alpha$ all the SCRs in OFF State. during This period $V_0 = 0$ & $I_0 = 0$

turn off time period of thyristors T_1 & T_2, T_3 & T_4 are increase from $\frac{\pi-\alpha}{\omega}$ to $\frac{\pi+\alpha-\beta}{\omega}$.

average o/p Voltage is derived as

$$V_{DC} = V_{oavg} = \frac{1}{\pi}\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\left[-\cos \omega t\right]_{\alpha}^{\beta}$$

$$V_{DC} = \frac{V_m}{\pi}\left[-\cos\beta + \cos\alpha\right]$$

$$\therefore \boxed{V_{DC} = \frac{V_m}{\pi}\left[\cos\alpha - \cos\beta\right]}$$

$$I_{DC} = \frac{V_{DC}}{R} = \frac{V_m}{\pi R}\left[\cos\alpha - \cos\beta\right]$$

RMS value of o/p voltage is

$$V_{o\,rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\beta}(V_m \sin\omega t)^2 \, d(\omega t)}$$

$$= \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\beta}(1 - \cos 2\omega t)\, d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\beta}}$$

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

$$\boxed{V_{o\,rms} = \frac{V_m}{\sqrt{2\pi}}\left\{(\beta - \alpha) + \frac{\sin 2\alpha - \sin 2\beta}{2}\right\}^{1/2}}$$

$$i/p \text{ P.f} = \frac{V_{o\,rms}}{V_{s\,rms}}$$

$$i/p \text{ P.f} = \frac{1}{\sqrt{\pi}}\left\{(\beta - \alpha) + \frac{\sin 2\alpha - \sin 2\beta}{2}\right\}^{1/2}$$

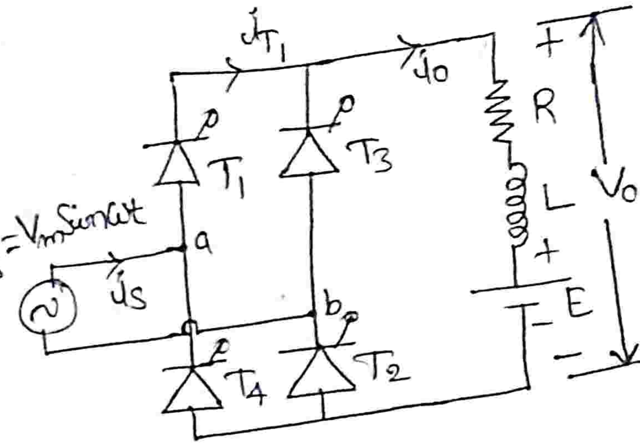
* Average thyristor current $= (I_T)_{avg} = \dfrac{I_{DC}}{2}$

* RMS value of thyristor current $(I_T)_{rms} = \dfrac{I_{o\,rms}}{\sqrt{2}}$

$\Big\}$ 1-φ full converter

1-ϕ full converter with RLE load:-

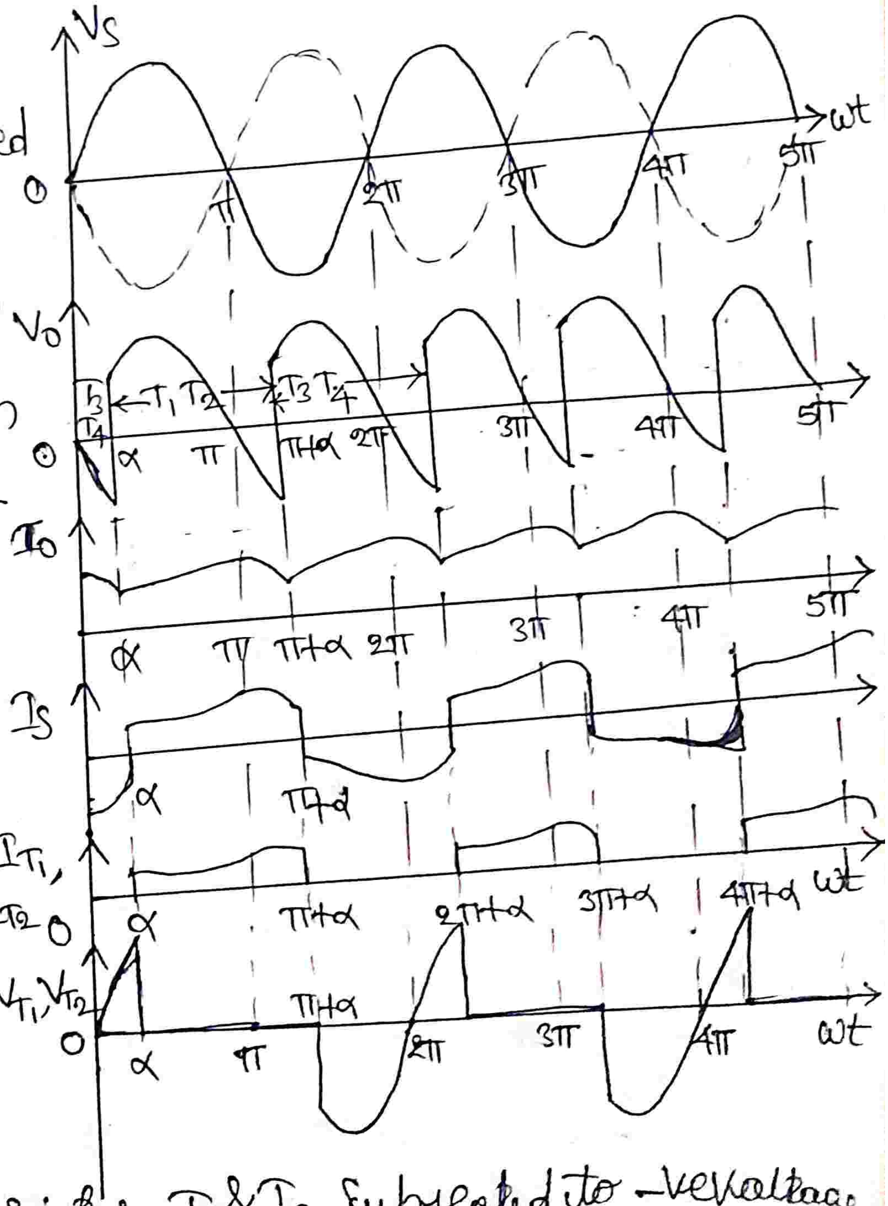
The below fig shows the full converter with RLE-load or motor load.



$V_{ab} = -V_{ba} = V_m \sin\omega t$

T_1, T_2 pair simultaneously triggered and π radians latter pair T_3, T_4 is gated together.

Load current I_0 is assumed to be continuous the waveforms as follows



at $\omega t = \alpha$ T_1 & T_2 triggered

$0 \leq \omega t < \alpha$ T_1 & T_2 - FB

T_3 & T_4 are in conduction

at $\omega t = \alpha$ T_1, T_2 are turn-on & T_3, T_4 are turned-off with reverse voltage of $V_m \sin\alpha$.

$\alpha \leq \omega t \leq \pi+\alpha$ T_1, T_2 - on

$V_0 = V_s$, I_0 path

$V_s^+ - T_1 - R - L - E - T_2 - V_s^-$

$\omega t = \pi+\alpha$ T_3 & T_4 are gated & turned on.

& already conducting thyristors T_1 & T_2 subjected to -ve voltage turned-off naturally.

$\pi+\alpha \leq \omega t < 2\pi+\alpha$ $T_3 \& T_4$ - On $T_1 \& T_2$ - OFF

$V_0 = V_s$ I_0 path $V_s^- - T_3 - R - L - E - T_4 - V_s^+$

average O/p Voltage $V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$

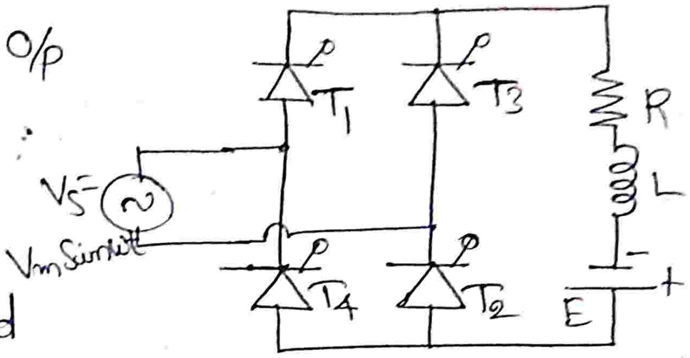
$$V_{DC} = \frac{2V_m}{\pi}\cos\alpha \qquad \{\because V_{DC} = i_{DC}R + E\}$$

$$I_{DC} = \left\{\frac{2V_m}{\pi R}\cos\alpha - E\right\}/R$$

$$V_{0rms} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}(V_m \sin\omega t)^2 d\omega t = \frac{V_m}{\sqrt{2}}$$

Inverter mode of operation:-

If firing angle $\alpha > 90°$, O/p Voltage V_{DC} is negative.



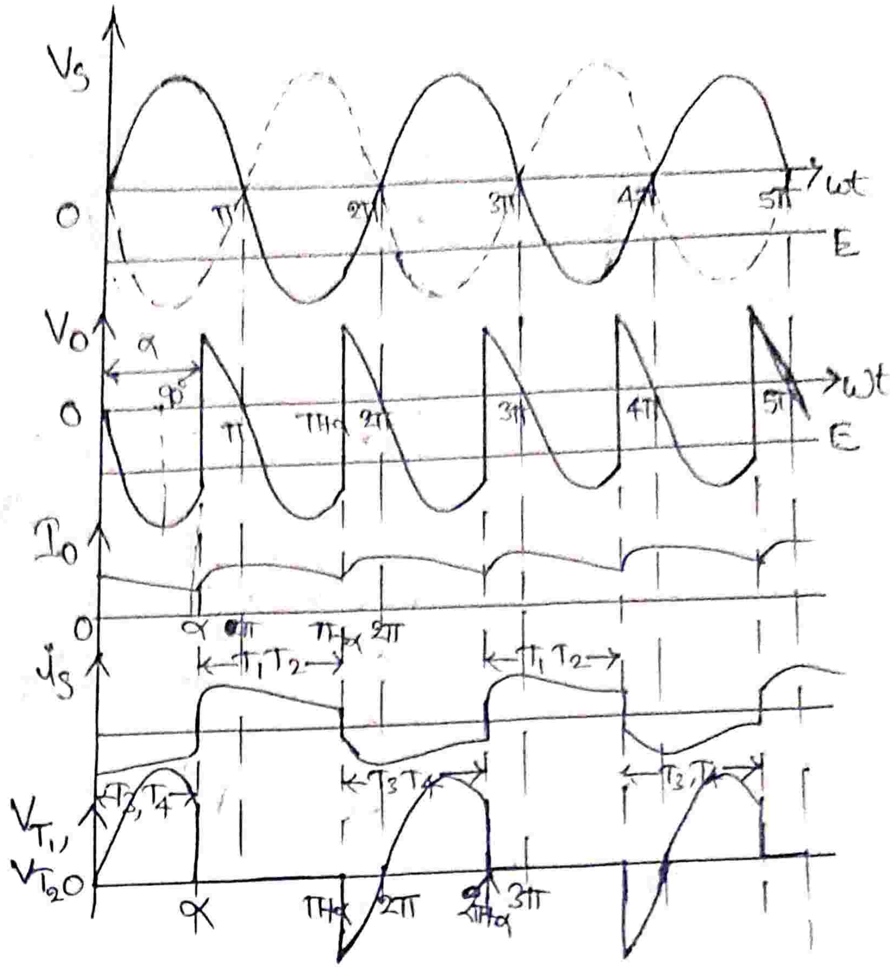
As V_0 is -ve, the load circuit emf E is reversed as shown in below fig.

* With $\alpha > 90°$ then this dc source E will feed power back to AC source. This mode of operation of full Converter is known as "Inverter operation". or full converter with $\alpha > 90°$ is called line "commutated inverter".

* The Voltage Source on the DC load side may be a battery, a photo voltaic source, a DC voltage produced by wind-generator system or counter emf of DC motor.

$0 \le \omega t < \alpha$

V_s is +ve but i_s is −ve, power therefore, flows from DC source to AC source.



$\alpha \le \omega t < \pi$

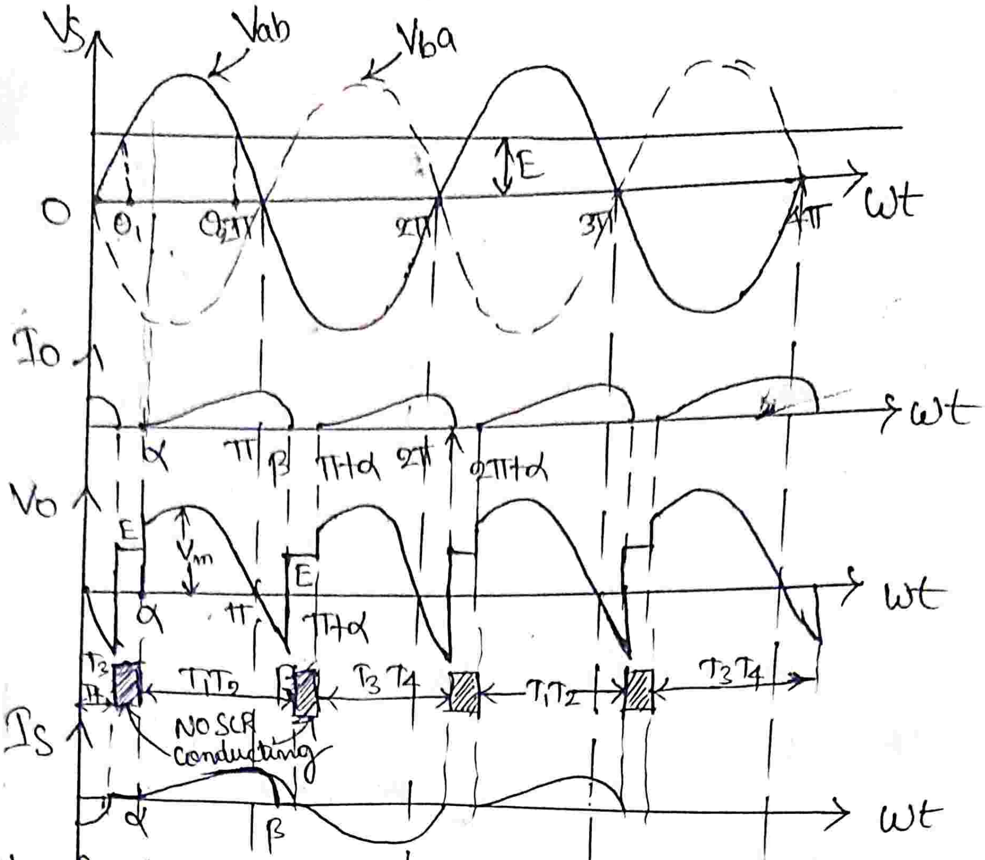
both V_s & i_s are +ve, power therefore, flows from AC source to DC source.

But the net power flow is from DC source to AC source because $(\pi - \alpha) < \alpha$ (from above fig)

* Both in converter mode ($0^\circ \le \alpha \le 90^\circ$) and inverter mode ($90^\circ < \alpha \le 180^\circ$), thyristors must be FB and current through SCRs must flow in same direction. as these are unidirectional devices.

* <u>1-ϕ full converter with Discontinuous current</u> :-

The load current being Discontinuous because of either small inductance or $\beta < \pi + \alpha$. or inductor should not have a sufficient energy to Drive the load. During this o/p wave forms are shown below.



from above wave forms

(i) Conduction period, $\alpha \leq \omega t < \beta$ T_1, T_2 Conducts & $V_0 = V_s$

& also $(\pi+\alpha) \leq \omega t < (\pi+\beta)$ T_3, T_4 Conducts and $V_0 = V_s$

(ii) Idle period $\beta \leq \omega t < \pi+\alpha$, no circuit element conducts and $v_0 = E$ & $I_0 = 0$

When the supply voltage is less than the DC voltage "E". in the circuits the SCRs are in reverse biasing condition. hence thyristors cannot conduct when the supply voltage less than DC Bus voltage "E".

Due to this firing angle control is limited to range θ_1 & θ_2 as shown in wave forms

$$V_m \sin \alpha = E$$

$$\therefore \boxed{\alpha = \sin^{-1}\left(\frac{E}{V_m}\right) = \theta_1}$$

$$\therefore \boxed{\theta_2 = \pi - \theta_1}$$

average o/p voltage is derived as

$$V_{oavg} = V_{DC} = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t\, d\omega t + \int_{\beta}^{\pi+\alpha} E\, d(\omega t)\right]$$

$$= \frac{1}{\pi}\left[V_m \left[-\cos\omega t\right]_{\alpha}^{\beta} + E\left[\omega t\right]_{\beta}^{\pi+\alpha}\right]$$

$$= \frac{V_m}{\pi}\left[\cos\alpha - \cos\beta\right] + \frac{E}{\pi}\left[\pi + \alpha - \beta\right]$$

$$\boxed{V_{oavg} = \frac{V_m}{\pi}\left[\cos\alpha - \cos\beta\right] + E\left[1 + \frac{\alpha-\beta}{\pi}\right]} \longrightarrow (1)$$

for i_{oavg}.

$$V_{DC} = i_o R + E$$

$$\boxed{I_{DC} = i_o = \frac{V_{DC} - E}{R}} \longrightarrow (2)$$

rms value of output voltage is derived as

$$V_{orms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\beta}(V_m \sin\omega t)^2 d\omega t + \int_{\beta}^{\pi+\alpha} E^2\, d(\omega t)}$$

$$= \left\{\frac{V_m^2}{2\pi}\left(\left[1 - \cos 2\omega t\right]_{\alpha}^{\beta}\right) + \frac{E^2}{\pi}\left[\omega t\right]_{\beta}^{\pi+\alpha}\right\}^{1/2}$$

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

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

$$\longrightarrow (3)$$

Effect of Source Inductance :-

If the Source having some Impedance and it is taken as pure inductive, since source resistance is very less when compared to inductor

The source inductance causes the both incomming and outgoing thyristors to conduct together.

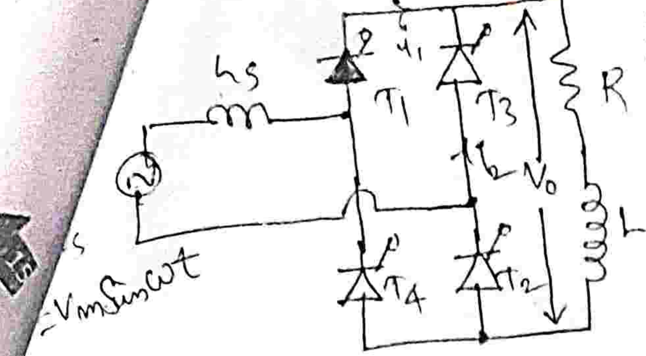
* overlap angle or commutation angle μ :-

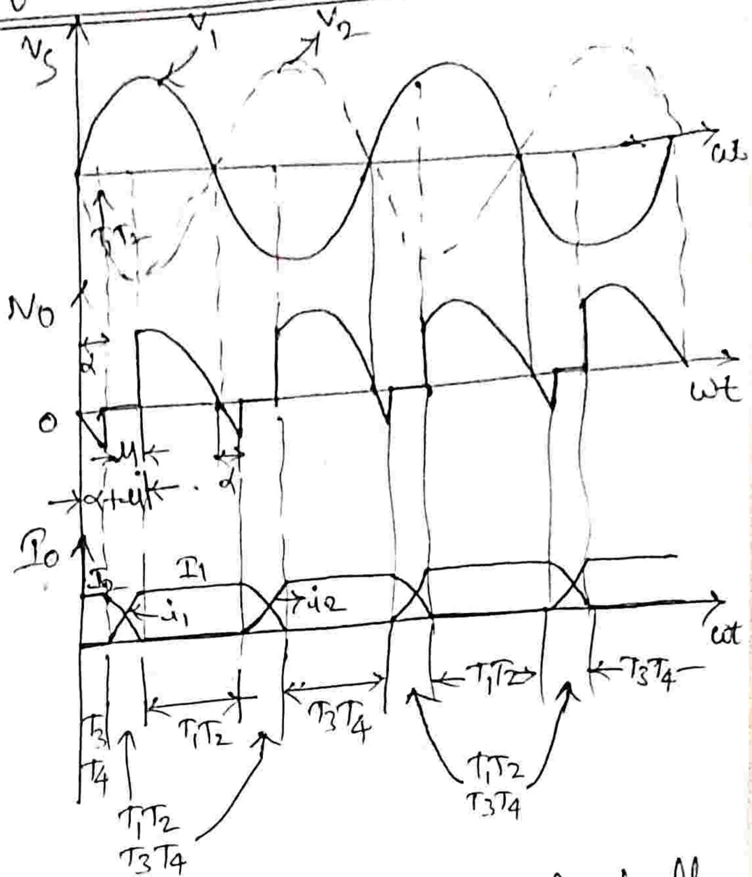
The angular period during which both the incoming & outgoing SCRs conducting together. Due to this

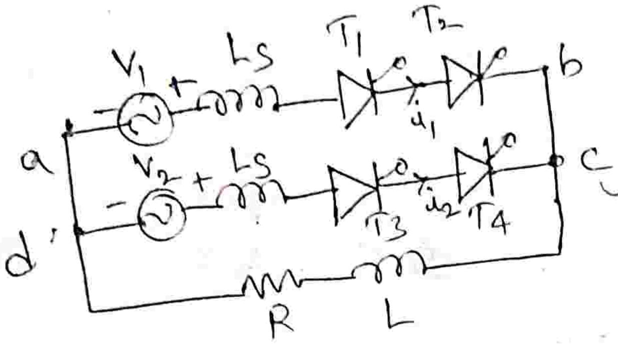
→ reduction in V_{avg}, modified performance characteristic

→ Distorted V, I waveforms

Effect of Source Inductance







when T_1T_2 are triggered at $\omega t = \alpha$

Commutation of T_3T_4 begans

Because of Source Inductance L_S

The current through outgoing Devices T_3T_4, decreases gradually to zero from its initial value of I_0.

where as in Incoming SCRs T_1, T_2 the current builds up gradually from zero to full value of load current I_0.

During the commutation of T_1T_2 & T_3, T_4 i.e during the overlap angle "μ"

KVL for the loop abcda

$\boxed{\mu - \text{commutation angle (or) overlap angle}}$ *

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

$$V_1 - V_2 = L_S\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right)$$

$V_1 = V_m \sin\omega t$ then

$V_2 = -V_m \sin\omega t$

$$\text{i.e } L_S\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right) = 2V_m \sin\omega t$$

The load current is assumed to be constant through

$$i_1 + i_2 = I_0$$

$$\frac{di_1}{dt} + \frac{di_2}{dt} = 0 \longrightarrow (1)$$

$$\frac{di_1}{dt} - \frac{di_2}{dt} = \frac{2V_m}{L_S} \sin\omega t \longrightarrow (2)$$

$$\therefore \frac{2di_1}{dt} = \frac{2V_m \sin\omega t}{L_S}$$

$$\frac{di_1}{dt} = \frac{V_m \sin\omega t}{L_S} \longrightarrow (3)$$

load current through T_1 & T_2 at $\omega t = \alpha$ $\quad I_0 = i_1 = 0$

at $\omega t = \alpha + u$ $\quad i_1 = I_0$

from Eq (3)

$$\int_0^{I_0} di_1 = \frac{V_m}{L_S} \int_{\alpha/\omega}^{(\alpha+u)/\omega} \sin\omega t \, d(\omega t)$$

$$\boxed{I_0 = \frac{V_m}{\omega L_S} \left[\cos\alpha - \cos(\alpha+u)\right]} \longrightarrow (4)$$

$V_0 = 0$ from $\omega t = \alpha$ to $\omega t = \alpha + u$

$$\therefore V_{dc} = V_{oavg} = \frac{1}{\pi} \int_{\alpha+u}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{\pi} \left[\cos\omega t\right]_{\alpha+u}^{\alpha+\pi}$$

$$V_0 = \frac{V_m}{\pi} \left[\cos\alpha + \cos(\alpha+u)\right].$$

from Eq (4)

$$\frac{I_0 \omega L_S}{V_m} = \cos\alpha - \cos(\alpha+u)$$

$$\cos(\alpha+u) = \cos\alpha - \frac{\omega L_S}{V_m} I_0 \longrightarrow (5)$$

Substitute Eq. (5) in V_0 then

$$V_0 = \frac{V_m}{\pi} \left[\cos\alpha + \left\{\cos\alpha - \frac{\omega L_S}{V_m} I_0\right\}\right]$$

$$* \boxed{V_0 = \frac{2V_m}{\pi} \cos\alpha - \frac{\omega L_S}{\pi} I_0} * \longrightarrow (6)$$

from Eq ④

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

$$\frac{I_o \omega L_s}{V_m} + \cos(\alpha+\mu) = \cos\alpha$$

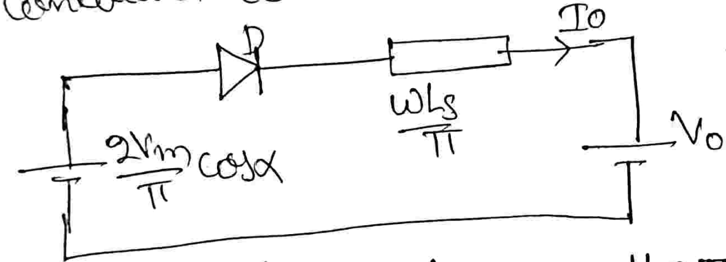
Sub "$\cos\alpha$" in Eq ⑥ then

$$V_o = \frac{2V_m}{\pi}\left[\frac{\omega L_s}{V_m} I_o + \cos(\alpha+\mu)\right] - \frac{\omega L_s I_o}{\pi}$$

$$= \frac{2\omega L_s}{\pi} I_o + \frac{2V_m}{\pi}\cos(\alpha+\mu) - \frac{\omega L_s I_o}{\pi}$$

$$* \boxed{V_o = \frac{2V_m}{\pi}\cos(\alpha+\mu) + \frac{\omega L_s}{\pi} I_o} *$$

from Eq ⑥ A DC Equivalent ckt for two-pulse 1-φ fully controlled converter can be drawn as



* Diode "D" indicates that load current is unidirectional.

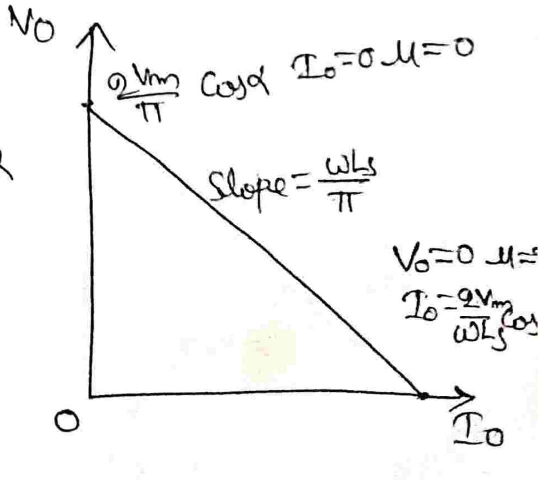
In 1-φ full converter as long as $\mu < \pi$

$$\boxed{V_o = \frac{2V_m}{\pi}\cos\alpha - \frac{\omega L_s}{\pi} I_o = \frac{2V_m}{\pi}\cos\alpha - 2fL_s I_o}$$

when $\mu = \pi$ the load will be permanently short ckted by SCRs and o/p voltage will be zero. because the overlap angle, all SCRs will be conducting

$$V_o = \frac{V_m}{\pi}(\cos\alpha + \cos(\alpha+\mu)) = \frac{V_m}{\pi}(\cos\alpha + \underbrace{\cos(\pi+\alpha)}_{-\cos\alpha})$$

$$= 0$$



If $\alpha = 0$ o/p voltage can be controlled over $\mu < \alpha < 180°$ and also max. firing angle can be "$180° - \mu$".

Harmonic factor or Total Harmonic Distortion

HF or THD is defined as follows

$$HF = THD = \sqrt{\left(\frac{1}{CDF}\right)^2 - 1}$$

where

CDF = Current Distortion factor = $\frac{I_{S1}}{I_S}$

I_{S1} - RMS value of fundmental current

I_S - RMS value of total i/p current

$$\therefore \boxed{THD = \sqrt{\left(\frac{I_S}{I_{S1}}\right)^2 - 1}}$$

$$* \boxed{i/p\ P.f = CDF \times DF} *$$

$$i/p\ P.f = \frac{I_{S1}}{I_S} \times \cos\alpha$$

...formance factors of Line commutated Converters

Input Displacement angle (ϕ_1) :-

It is defined as the angular displacement b/w the fudamental component of the a.c line current and the associated line to neutral voltage.

The fundamental component is either in phase or lags behind the voltage by an angle which depends upon the firing angle

② Input Displacement factor ($\cos\phi_1$) :-

The Input Displacement factor $\cos\phi_1$ is defined as the cosine of the input displacement angle or "$\cos\alpha$"

$\cos\theta_1 = \cos(-\alpha) = \cos\alpha$

③ Input power Factor (PF) :-

The input p.f is defined as the ratio of the total mean input power to the total RMS input VA (volt Amperes). Since only the fundamental components contributes the mean input power,

The p.f may be defined as $= \dfrac{V_1 I_1 \cos\phi_1}{V_{srms} I_{srms}}$

where $V_1 = V_{srms}$

I_1 - fundamental component of supply current

ϕ_1 - Displacement angle

(or)

$$\therefore \boxed{\text{Input P.f} = \frac{\text{power delivered to load}}{\text{Input VA}}}$$

④ DC Voltage Ratio (γ)

It is defined as the ratio of the mean DC terminal voltage at a given firing angle α, to the max. possible D.C terminal voltage (i.e V_0 at $\alpha=0$)

⑤ Input current Distortion Factor:-

The Distortion factor of the current in a given i/p line is defined as ratio of the RMS amplitude of the fundamental component, to the total RMS amplitude

⑥ Input Harmonic factor (I_H):-

The input Harmonic factor is defined as the ratio of the total harmonic content to the fundamental component

$$I_H = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1}$$

⑦ Form factor:-(FF)

It is defined as the ratio of output RMS voltage to the DC o/p voltage.

$$\text{form factor of voltage} = \frac{V_{ORms}}{V_{DC}} \text{ (or) } \frac{V_{orms}}{V_{o\,avg}}$$

$$\text{Form factor of current} = \frac{I_{orms}}{I_{dc}} \text{ (or) } \frac{I_{orms}}{I_{o\,avg}}$$

⑧ Voltage Ripple factor:-(K_V)

It is Defined as the ratio of the net harmonic content of the o/p voltage to the average o/p voltage

$$\boxed{K_V = \frac{\sqrt{V_{orms}^2 - V_{odc}^2}}{V_{odc}}} \Rightarrow \sqrt{\left(\frac{V_{orms}}{V_{oavg}}\right)^2 - \frac{V_{oavg}^2}{V_{oavg}^2}}$$

$$\therefore \boxed{K_V = \sqrt{(F.F)_{voltage}^2 - 1}}$$

⑨ Current Ripple factor (K_I):- It is defined as the ratio of net harmonic content of o/p current to the average output current

$$\boxed{K_I = \frac{\sqrt{I_{orms}^2 - I_{dc}^2}}{I_{dc}}} \text{ or } \boxed{K_I = \sqrt{(F.F)_{current}^2 - 1}}$$

given
de g
...ed

...tive power Input (P_I):-

It can be defined as

P_i = RMS line voltage X RMS fundamental component of current X Displacement factor

$$P_i = V_{orms} \times I_1 \times \cos\alpha$$

(11) Reactive power Input:-

$$Q_i = V_{rms} \times I_1 \sin\alpha$$

(12) Rectification efficiency:- (η)

It is defined as the ratio of DC power delivered to the load to Total ac input power.

i.e

$$\text{Rectification efficiency } \eta = \frac{P_{dc}}{P_{a.c}} \quad \left\{ \because P_{ac} \text{ is AC output power } \frac{V_{orm}^2}{R} \right\}$$

(13) peak Inverse voltage (PIV)

The maximum possible reverse voltage which is subjected to the SCRs in Reverse biase condition to Turn-off it naturally by the source

for mid point configuration (M-2) ⇒ PIV = $2V_m$

Bride " (B-2) PIV = V_m

(14) Transformer utilization factor (TUF):-

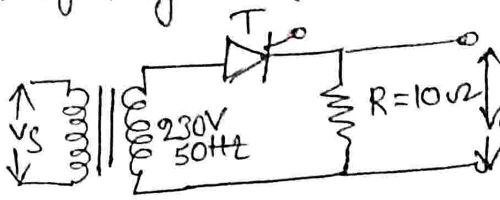
If V_s, I_s are the RMS voltage and RMS currents of the Secondary winding of input Transformer. then TUF is defined as

$$TUF = \frac{P_{dc}}{V_{srms} I_{srms}} = \frac{V_{odc} I_{odc}}{V_{srms} I_{srms}}$$

$$\therefore \boxed{TUF = \frac{P_{dc}}{\text{VA rating of T/F}}}$$

Set-1 (2012) Q-3(b)

① A 1-Ø T/F with secondary voltage of 230V f = 50Hz, delivers power to load R = 10Ω through half wave controlled rectifier ckt for a firing angle delay of 60° Determine
(i) Rectifier efficiency (ii) form factor (iii) voltage ripple factor
(iv) T/F utilization factor (TUF) (V) PIV of Thyristor.



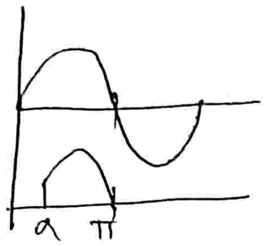
$V_{s\,rms} = 230V$

$V_m = V_{s\,rms} \times \sqrt{2} = 230 \times \sqrt{2}$

$= \underline{325.26}\ V$

$R = 10\Omega$

$\alpha = 60°$



$V_{dc} = \frac{V_m}{2\pi}(1+\cos\alpha)$

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

$= \frac{230 \times \sqrt{2}}{2\pi}(1+\cos 60°)$

$V_{dc} = \underline{77.65}\ V$

(i) Rectifier efficiency $= \frac{P_{dc}}{P_{ac}} = \frac{V_{dc} \times I_{dc}}{V_{s\,rms} I_{s\,rms}}$

$I_{dc} = \frac{V_{dc}}{R} = \frac{77.65}{10} = \underline{7.765}\ A$

$I_{o\,rms} = \frac{V_{o\,rms}}{R} = \frac{V_m}{R\,2\sqrt{\pi}}\left\{(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right\}^{1/2}$

$= \frac{230 \times \sqrt{2}}{10 \times 2 \times \sqrt{\pi}}\sqrt{\left\{(\pi - \pi/3) + \frac{\sin(2\times 60°)}{2}\right\}}$

$I_{o\,rms} = \underline{14.58}\ A$ & $I_{s\,rms} = I_{o\,rms}$

Rectifier efficiency $(\eta) = \frac{77.65 \times 7.765}{(I_{o\,rms}^2 R)} \times 100 = \frac{603.18}{2127.89}$

$\eta = \underline{28.33\ \%}$

(ii) Form factor $= \frac{V_{orms}}{V_{dc}} = \frac{145.8}{77.65} = 1.877$

Contd

(iii) voltage ripple factor $K_V = \sqrt{(F.F)^2 - 1}$

$= \sqrt{(1.877)^2 - 1}$

$= \underline{1.589}$

(iv) $TUF = \frac{P_{DC}}{V_S I_S} = \frac{V_{dc} I_{dc}}{V_{S\,Rms} \times I_{S\,rms}} = \frac{77.65 \times 7.765}{145.8 \times 14.58}$

$TUF = 0.2836$

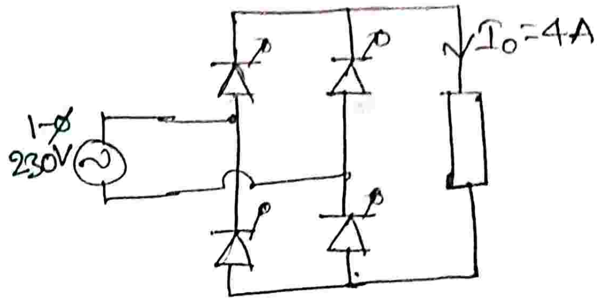
(v) PIV = peak reverse voltage on secondary side of i/p T/F

$= V_m = 230 \times \sqrt{2} = \underline{325.26}\ V$

(2012)

Set-2
Q-4(b)

(3) A 1-ϕ fully controlled bridge circuit is used for obtaining a regulated DC o/p voltage. The RMS value of the ac i/p voltage is 230V. and the firing angle is at $\pi/3$, so that the load current is 4A. Calculate
(i) The DC o/p voltage
(ii) Active and Reactive power i/p.



$V_{s\,rms} = 230V$

$I_o = 4A$

$\alpha = \pi/3 = 60^\circ$

(i) $V_{odc} = \dfrac{2V_m}{\pi}\cos\alpha$

$V_{odc} = \dfrac{2 \times 230 \times \sqrt{2}}{\pi}\cos 60^\circ = 103.54V$

given $I_{dc} = 4A = \dfrac{V_{odc}}{R}$

$R = \dfrac{V_{odc}}{I_{dc}} = 25.89\,\Omega$

Active power input $P_i = \dfrac{2V_m}{\pi} I_{dc}\cos\alpha$

$= \dfrac{2 \times 230 \times \sqrt{2}}{\pi} \times 4 \times \cos 60^\circ$

$P_i = 414.145W$

Reactive power input Q_i

$$Q_i = \frac{2V_m}{\pi} I_{dc} \sin\alpha$$

$$= \frac{2\times\sqrt{2}\times230}{\pi}\times4\times\sin 60^\circ$$

$$Q_i = 717.32 \text{ VARs}$$

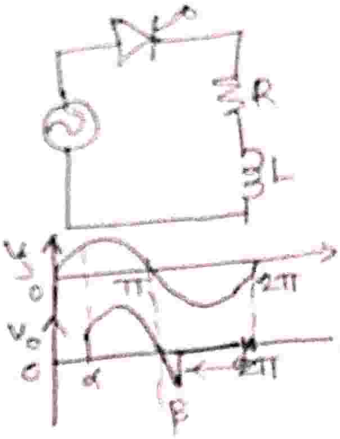
Set-3 (2012) (Q-3(b))

4) A 230V, 50Hz one pulse SCR controlled converter is triggered at a firing angle of 40° and the load current extinguishes at an angle of 210°. Find the circuit turn-off time, V_{oavg} & I_{oavg} for $R=5\Omega$ & $L=2mH$

$V_{srms} = 230V$, $f = 50Hz$

$\alpha = 40^\circ$

$\beta = 210^\circ$



(i) $T_{off} = ?$

$$\omega t_{off} = 2\pi - \beta$$

$$t_{off} = \frac{2\pi-\beta}{\omega} = \frac{2\pi - 210\times\left(\frac{\pi}{180}\right)}{2\times\pi\times f}$$

$$T_{off} = \frac{(2\pi - 1.167\pi)}{2\pi\times50} = 8.33 \text{ msec}$$

$$V_o = \frac{V_m}{2\pi}\int_\alpha^\beta \sin\omega t \, d\omega t$$

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

(ii) $$V_{oavg} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

$$V_{oavg} = \frac{230\times\sqrt{2}}{2\times\pi}(\cos40^\circ - \cos210^\circ) = 84.48\,V$$

$$I_{oavg} = \frac{V_{oavg}}{R} = \frac{84.48}{5} = 16.89A$$

Set-3 (2012)
Q - 4 (b)

(5) 1-ø full converter is made to deliver a const. load current. for $\alpha = 0^\circ$, $\mu = 15^\circ$. Calculate the overlap angle when firing angle is (i) 30° (ii) 45° & (iii) 60°

$\alpha = 0^\circ \quad \mu = 15^\circ$

$$I_0 = \frac{V_m}{\omega L_s}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

Let μ_1 be the overlap angle for firing angle α_1

i.e $\alpha_0 = 0 \quad \mu = 15^\circ$

$$\frac{V_m}{\omega L_s}\left[\cos\alpha - \cos(\alpha+\mu)\right] = \frac{V_m}{\omega L_s}\left[\cos\alpha_1 - \cos(\alpha_1+\mu_1)\right]$$

$$\cos 0^\circ - \cos(0+15^\circ) = \cos\alpha_1 - \cos(\alpha_1+\mu_1)$$

$$0.034 = \cos\alpha_1 - \cos(\alpha_1+\mu_1)$$

$$\boxed{\cos(\alpha_1+\mu_1) = \cos\alpha_1 - 0.034}$$

(i) at $\alpha = 30^\circ$

$$\cos(30^\circ+\mu_1) = \cos 30^\circ - 0.034$$

$$\cos(30^\circ+\mu_1) = 0.832$$

$$30^\circ + \mu_1 = 33.69^\circ$$

$$\boxed{\mu_1 = 3.7^\circ}$$

(ii) at $\alpha = 45^\circ$

$$\cos(45^\circ+\mu_2) = \cos 45^\circ - 0.034$$

$$45^\circ + \mu_2 = \cos^{-1}(0.6731)$$

$$\mu_2 = 47.7 - 45^\circ$$

$$* \boxed{\mu_2 = 2.7^\circ} *$$

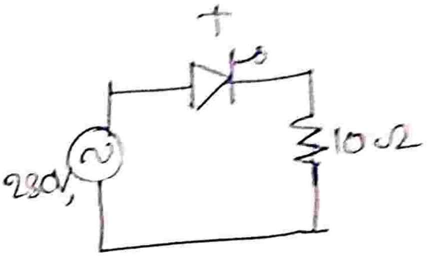
(iii) at $\alpha = 60^\circ$

$$\cos(60^\circ+\mu_3) = \cos 60^\circ - 0.034 = 0.466$$

$$\mu_3 = 62.22^\circ - 60^\circ$$

$$* \boxed{\mu_3 = 2.22^\circ} *$$

A 1-ϕ half wave controlled rectifier with $R = 10\Omega$ is supplied from 230V, 50Hz supply, Assume rms voltage is 50% of max. possible rms voltage, Determine (i) firing angle (ii) average DC o/p voltage (iii) average & rms current of SCR.



Sol:- given data

$$V_{s\,rms} = 230V$$

$$V_m = V_{s\,rms} \times \sqrt{2}$$

$$= 230 \times \sqrt{2} = \underline{325.27}\ V$$

$$R = 10\Omega$$

$$V_{o\,rms} = \frac{(V_{o\,rms})_{max}}{2}$$

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

$(V_{o\,rms})_{max}$ at $\alpha = 0$

$$\therefore (V_{o\,rms})_{max} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi + \frac{\sin 0}{2}} = \frac{V_m}{2}$$

$$\therefore \left(\frac{V_m}{2}\right)/2 = \frac{V_m}{2\sqrt{\pi}}\sqrt{(\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$\left(\sqrt{\pi}/2\right)^2 = (\pi-\alpha) + \frac{\sin 2\alpha}{2}$$

$$\pi/4 = \pi - \alpha + \frac{\sin 2\alpha}{2}$$

$$\alpha = \pi - \pi/4 + \frac{\sin 2\alpha}{2}$$

$$\alpha = 3\pi/4 + \frac{\sin 2\alpha}{2}$$

Solution is $\alpha = 114^\circ$ * trail & error method

(ii) average DC o/p voltage

$$V_{DC} = \frac{V_m}{2\pi}(1+\cos\alpha) = \frac{325.27}{2\pi}(1+\cos 114^\circ)$$

$$V_{DC} = 30.71\ V$$

$$I_{DC} = \frac{V_{DC}}{R} = \frac{30.71}{10} = 3.071\ A$$

(iii) $$I_{Tavg} = I_{DC_{avg}} = 3.071\ A$$

$$I_{Trms} = \frac{V_{orms}}{2}$$

$$V_{orms} = \left(\frac{V_m}{2}\right)\Big/_2 = \frac{325.27}{4} = \left(\frac{162.635}{2}\right) V$$

$$I_{orms} = \frac{162.635\cancel{V}}{20} = 8.131\ A$$

$$I_{Trms} = I_{orms} = 8.131\ A$$

80) 1-ϕ half wave controlled rectifier with $R = 10\Omega$ is supplied from 230V, 50HZ supply, if the average load current is 10A, determine (i) firing angle (ii) average DC o/p voltage (iii) rms voltage & current of SCR.

Sol:- given data

$$V_{s\,rms} = 230V$$

$$V_m = 230 \times \sqrt{2} = 325.27V$$

$$R = 10\Omega$$

$$I_{DC\,avg} = 10A$$

$$10 = \frac{V_m}{2\pi R}(1 + \cos\alpha)$$

$$\frac{10 \times 2\pi \times 10}{325.27} = 1 + \cos\alpha$$

$$\cos\alpha = 1.9316 - 1$$

$$\alpha = \cos^{-1}(0.9316)$$

$$\boxed{\alpha = 21.31^\circ}$$

(ii) average o/p voltage $V_{DC} = I_{DC} \times R$

$$= 100V$$

(iii) $V_{T\,rms}$ is difficult to find ?∴ $V_{o\,rms}$

$$V_{o\,rms} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(\pi - \alpha) + \frac{\sin 2\alpha}{2}}$$

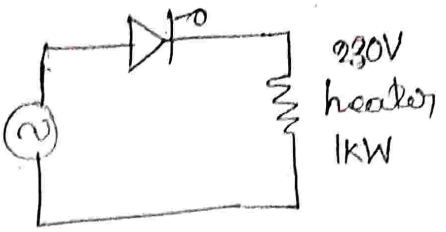
$$= \frac{325.27}{2 \times \sqrt{\pi}}\sqrt{\left(\pi - 21.31 \times \frac{\pi}{180^\circ}\right) + \frac{\sin 2 \times (21.31^\circ)}{2}}$$

$$= 91.756 \times 1.763$$

$V_{o\,rms} = 161.766V$ $\quad$ $I_{T\,rms} = I_{o\,rms} = 16.176A$

③ A 1-ϕ 230V, 1KW heater is connected across a 1-ϕ, 230V, 50Hz, Supply through an SCR. For the firing angle of 45° & 90°, find the power absorbed by heater element.

Sol:- $V_{s\,rms} = 230V$ $V_m = 230\times\sqrt{2}$
at $\alpha = 45°$ $= 325.27V$



$$V_{DC} = \frac{V_m}{2\pi}(1+\cos\alpha)$$

$$= \frac{325.27}{2\pi}(1+\cos 45°)$$

$$V_{DC} = 88.374V$$

$$P = I^2R = \frac{V^2}{R}$$

$$V_{o\,rms} = \frac{V_m}{2\sqrt{\pi}}\sqrt{(\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$= \frac{325.27}{2\sqrt{\pi}}\sqrt{(\pi - \pi/4) + \frac{\sin 90°}{2}}$$

$$V_{o\,rms} = 155.072V$$

we know that $\frac{V_{o\,rms}^2}{R} = P$

$$\frac{(230)^2}{R} = 1000W$$

$$R = \frac{(230)^2}{1000} = 52.9\,\Omega$$

∴ power consumed by heater at $\alpha = 45°$ is $= \frac{V_{o\,rms}^2}{R}$

$$\frac{(155.072)^2}{52.9} = 454.58W$$

at $\alpha = 90°$

$$V_{o\,rms} = \frac{325.27}{2\sqrt{\pi}}\sqrt{(\pi - \pi/2) + \cancel{\frac{\sin 180°}{2}} \to 0}$$

$$V_{o\,rms} = \frac{325.27}{2\sqrt{\pi}} \times \sqrt{\pi/2} = 115.0V$$

power consumed by heater element $= \frac{(115)^2}{52.9} = 250W$

Q) 1-ϕ full-converter feeds power to RLE load with $R = 6\Omega$, $L = 6mH$ and $E = 60V$. The ac source voltage is 230V, 50Hz. For continuous conduction, find the average value of load current for a firing angle delay of 50°.

In case one of the four SCRs gets open circuited due to a fault, find new value of o/p voltage and indicate the conduction of various SCRs (I_o continuous)

Sol:- 1-ϕ full-converter with RLE load

$V_{srms} = 230V$, $f = 50Hz$

$V_m = 230 \times \sqrt{2}\ V$

$\alpha = 50^\circ$

$R = 6\Omega$

$L = 6mH$

$E = 60V$

$$V_{DC} = \frac{2V_m}{\pi}\cos\alpha$$

$$= \frac{2 \times 230 \times \sqrt{2}}{\pi}\cos 50^\circ$$

$$V_{DC} = 133.084V$$

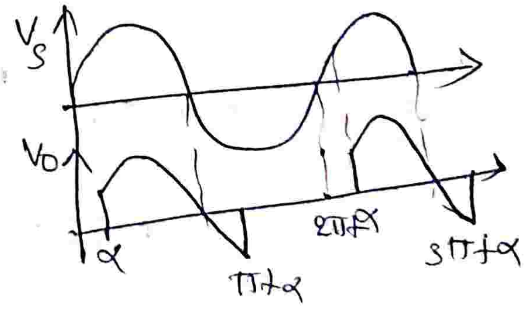
$$I_o = \frac{V_{dc} - E}{R} = \frac{133.084 - 60}{6}$$

$$\therefore \boxed{I_o = 12.181A}$$

due to fault let T_3 - gets damaged & it is open then

$$V_o = \frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, d(\omega t)$$

$$= \frac{V_m}{\pi}\cos\alpha$$



$$V_o = \frac{\sqrt{2} \times 230}{\pi}\cos 50^\circ = 66.542V$$

$$I_o = \frac{66.542 - 60}{6} = 1.0903A.$$

$\therefore$ load current reduced drastically.

⑤ A 1-ϕ full-converter, connected to 230V, 50Hz source, is feeding a load $R = 10\Omega$ in series with a large inductance that makes current ripple free. For a firing angle of 45°, calculate the i/p and o/p performance parameters of this converter.

$$V_0 = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times\sqrt{2}\times 230}{\pi}\cos 45^\circ$$

$$V_{DC} = 146.423V$$

$$I_{DC} = \frac{V_{DC}}{R} = \frac{146.423}{10} = 14.64A$$

$$V_{orms} = \frac{V_m}{\sqrt{2}} = V_s = 230V$$

for ripple free current $I_{or} = I_0 = 14.64A$

$$P_{dc} = V_{DC} I_{DC} = 146.423 \times 14.6423$$
$$= 2143.97W$$

$$I_{srms} = I_0 = I_{or} = 14.64A$$

$$P_{ac} = V_{or} \times I_{or} = 230 \times 14.6423$$
$$= 3367.73W$$

Rectification $\eta = \frac{P_{dc}}{P_{ac}} = \frac{2143.97}{3367.73} = 0.6366 = 63.66\%$

form factor $FF = \frac{V_{or}}{V_{DC}} = \frac{230}{146.423} = 1.5708$

$$VRF = \sqrt{FF^2 - 1} = \sqrt{(1.5708)^2 - 1}$$
$$= 1.2114$$

fundamental component of I_s * $\boxed{(I_{s_1}) = \frac{2\sqrt{2}}{\pi} \times I_{dc}}$ * $= \frac{2\sqrt{2}}{\pi} \times 14.6423$
$= 13.183A$

$$DF = \cos\alpha = \cos 45^\circ = 0.707$$

$$CDF = \frac{I_{S1}}{I_S} = \frac{13.183}{14.6423} = 0.90032$$

$$HF = THD = \sqrt{\left(\frac{1}{CDF}\right)^2 - 1}$$

$$= \sqrt{\left(\frac{1}{0.90032}\right)^2 - 1}$$

$$\boxed{HF = THD = 0.4834}$$

Active power $= V_{DC} \cdot I_{DC} = 2143.97\,W$

Reactive power $= \frac{2V_m}{\pi} I_{DC} \sin\alpha$

$$= \frac{2 \times 230 \times \sqrt{2}}{\pi} \times 14.6423 \times \sin 45^\circ$$

$$= 2143.963\ VARs$$

Input P.f $= CDF \times DF$

$= 0.90032 \times 0.707$

$= 0.63653$ lagging

parameter	full converter	Semi converter
Current Displacement factor (CDF) $= \frac{I_{S1}}{I_S}$	$\frac{2\sqrt{2}}{\pi}$	$\frac{2\sqrt{2}\cos\alpha/2}{\sqrt{\pi(\pi-\alpha)}}$
Harmonic factor (HF) or (THD) total harmonic Distortion	$THD = \sqrt{\frac{1}{CDF^2} - 1}$ $THD = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1}$	$THD = \sqrt{\frac{\pi(\pi-\alpha)}{8\cos^2\frac{\alpha}{2}} - 1}$ $DF = \cos\alpha/2$
Input P.F $= CDF \times DF$	$i/p\,Pf = \frac{2\sqrt{2}}{\pi}\cos\alpha$	$i/p\,Pf = \sqrt{\frac{2}{\pi(\pi-\alpha)}} \times (1+\cos\alpha)$

⑥ A 1-ϕ Semi converter with free-wheeling Diode across the load is operated from a 120V, 60Hz supply. The load current with an average value of I_a is continuous with negligible ripple contents. If the firing angle is $\pi/3$, calculate ⓐ HF of i/p current ⓑ Displacement factor ⓒ the input power factor.

Sol:- given Data

$V_{srms} = 120V$ | Let $R = 10\Omega$

$V_m = 120 \times \sqrt{2}$

$\alpha = \pi/3 = 60^\circ$

$$V_{DC} = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{\sqrt{2}\times 120}{\pi}(1+\cos\pi/3)$$

$V_{DC} = 81.03V$

$I_{DC} = 8.103A$

by neglecting ripple voltage or current

$I_{orms} = I_{DC} = I_{srms} = 8.103A$

$$CDF = \frac{2\sqrt{2}\cos\alpha/2}{\sqrt{\pi(\pi-\alpha)}} = \frac{2\sqrt{2}\cos 30^\circ}{\sqrt{\pi(\pi-\pi/3)}}$$

$CDF = 0.955$

ⓐ i/p current Harmonic factor $= \sqrt{\left(\frac{1}{CDF}\right)^2-1} = \sqrt{\left(\frac{1}{0.955}\right)^2-1}$

$THD = HF = 0.3108$

ⓑ Displacement factor $= \cos\alpha/2 = \cos 30^\circ = 0.866$

$DF = 0.866$

ⓒ i/p power factor $= CDF \times DF$

$= 0.955 \times 0.866$

$= 0.827$

The explanation for wave forms in the above fig. reveals the phase angle relation b/w Line voltages leads phase voltages by an angle 30°

Let V_a, V_b, V_c are phase voltages & $-V_a, -V_b, -V_c$ are corresponding negative phase voltages. & line voltages are $V_{ab}, V_{bc}, V_{ca}, V_{ba}, V_{cb}$ & V_{ac}.

Let $V_a = V_{mp}\angle 0^\circ$ $\qquad -V_a = V_{mp}\angle -180^\circ$

$V_b = V_{mp}\angle -120^\circ$ $\qquad -V_b = V_{mp}\angle -300^\circ$

$V_c = V_{mp}\angle -240^\circ$ $\qquad -V_c = V_{mp}\angle -60^\circ$

Line voltages can be related as

$$V_{ab} = V_a - V_b = V_{mp}\angle 0^\circ - V_{mp}\angle -120^\circ$$

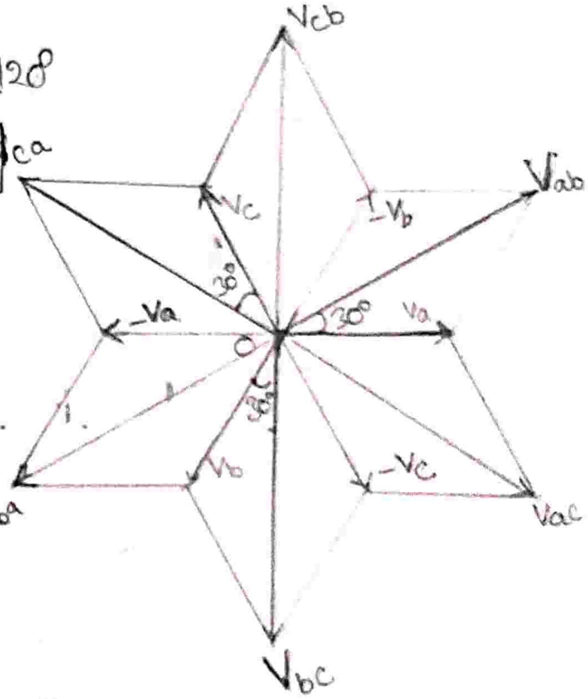
$$= V_{mp}[\sin\omega t - \sin(\omega t - 120^\circ)]$$

$$= V_{mp}\, 2\cos\left(\frac{\omega t + \omega t - 120^\circ}{2}\right) \times \sin\left(\frac{\omega t - \omega t + 120^\circ}{2}\right)$$

$$= 2V_{mp}\cos(\omega t - 60^\circ)\sin 60^\circ$$

$$= 2V_{mp}\sin(\omega t - 60 + 90^\circ) \times \frac{\sqrt{3}}{2}$$

$$= \sqrt{3}V_{mp}\sin(\omega t + 30^\circ)$$



$\left\{\sin C - \sin D = 2\cos\left(\frac{C+D}{2}\right)\sin\left(\frac{C-D}{2}\right)\right\}$

$V_{ab} = V_{ml}\sin(\omega t + 30^\circ)$ $\quad \therefore$ where $\boxed{V_{ml} = \sqrt{3}V_{mp}}$

$$\boxed{V_{ab} = V_{ml}\angle 30^\circ = \sqrt{3}V_{mp}\angle 30^\circ}$$

Illy $V_{bc} = \sqrt{3}V_{mp}\angle -90^\circ$. $\qquad V_{ba} = \sqrt{3}V_{mp}\angle -150^\circ$

$V_{ca} = \sqrt{3}V_{mp}\angle -210^\circ$ $\quad$ & $\quad V_{cb} = \sqrt{3}V_{mp}\angle +90^\circ$

$\qquad V_{ac} = \sqrt{3}V_{mp}\angle -30^\circ$

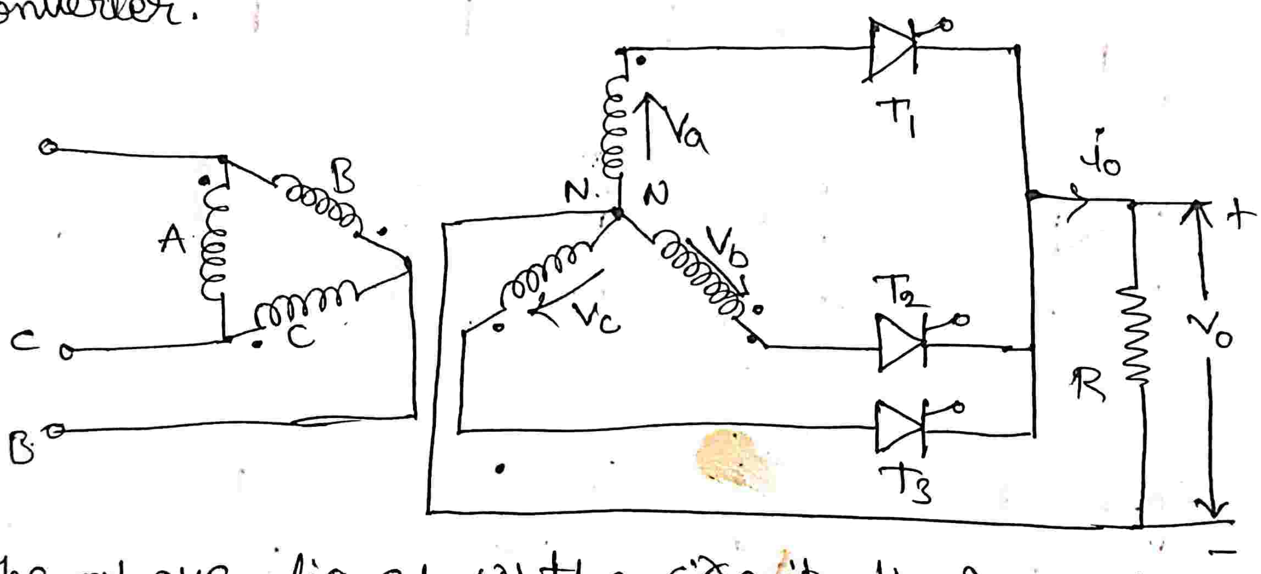
* Three phase Line Commutated Converters *

In general 3-Ø Δ-Y Transformer is employed for delivering power to 3-Ø Converters. All three-phase controlled converters use line commutation for the turning -off of SCRs

3-Ø thyristor converters may be classified as under
ⓐ 3-pulse converters.
ⓑ 6-pulse converters
ⓒ twelve-pulse converters

3-Ø Half-wave controlled converter (with R-load):-

It is also called 3-Ø 3-pulse converter or 3-Ø M-3 converter.



The above fig. shows the circuit diagram for 3-Ø Half wave (3-pulse M-3) Converter with R-load.

If firing angle is zero degrees, SCR T_1 would being conducting from $\omega t = 30°$ to $150°$, T_2 from $150°$ to $270°$ and T_3 from $\omega t = 270°$ to $390°$ and so on

each tyristor is conducts for $\frac{360°}{3\text{-Pulses}} = \underline{120°}$

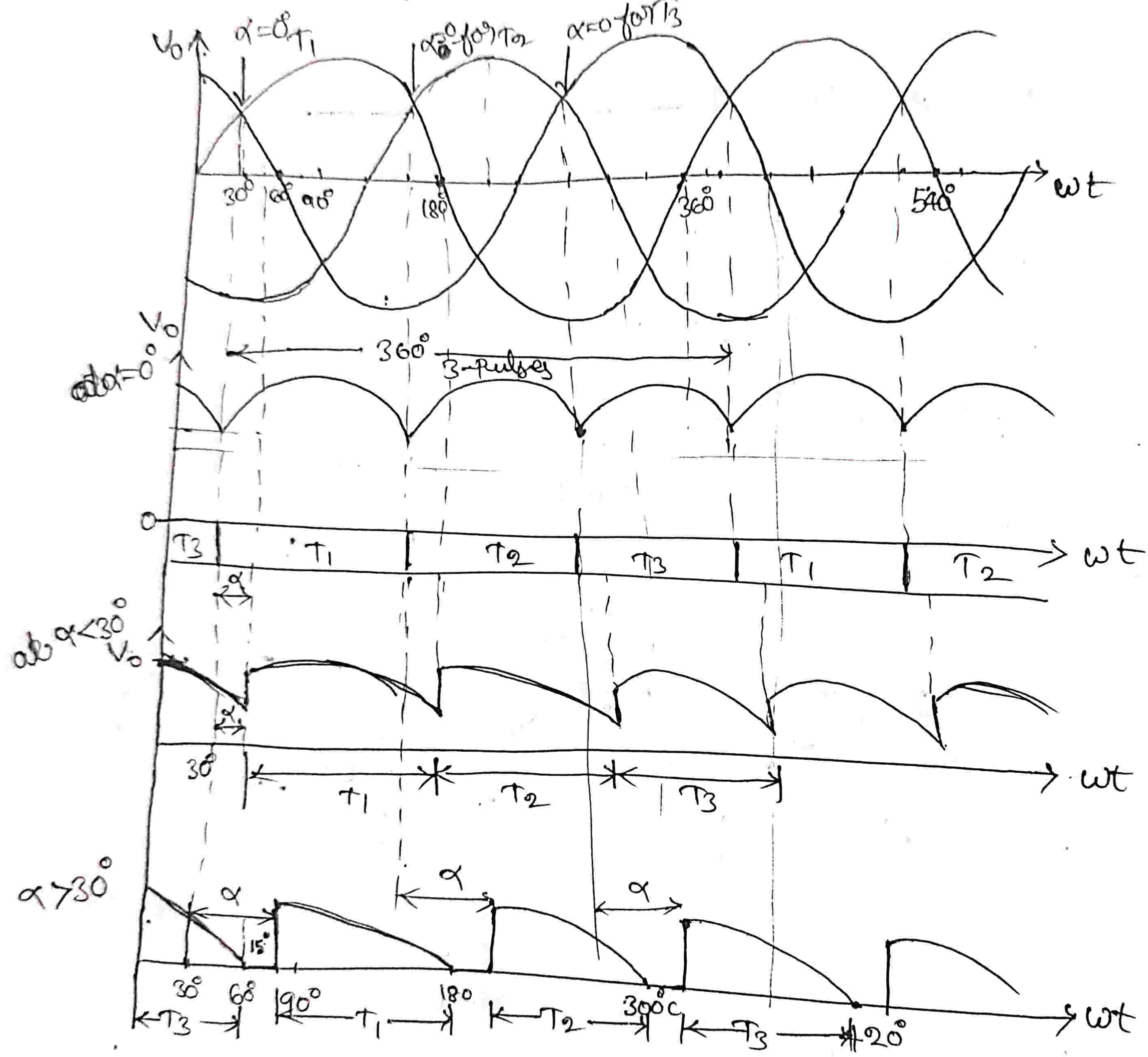
firing angle <30°:-

The o/p voltage wave form V_0 for $\alpha < 30°$

T_1 conducts from $\omega t = 30° + \alpha$ to $\omega t = 150° + \alpha$

T_2 " " $\omega t = 150° + \alpha$ to $\omega t = 270° + \alpha$

T_3 " " $\omega t = 270° + \alpha$ to $\omega t = 390° + \alpha$ - - -



from the o/p voltage wave forms for $\alpha < 30°$

average o/p voltage $$V_0 = \frac{3}{2\pi} \int_{\alpha + \pi/6}^{\alpha + 5\pi/6} V_{mp} \sin \omega t \, d(\omega t)$$

$$= \frac{3 V_{mp}}{2\pi} \left[-\cos \omega t \right]_{\alpha + \pi/6}^{\alpha + 5\pi/6}$$

$$V_o = \frac{3V_{mp}}{2\pi}\left[\cos(\alpha+\pi/6) - \cos(\alpha+5\pi/6)\right]$$

$$\boxed{V_o = \frac{3\sqrt{3}}{2\pi} V_{mp} \cos\alpha}$$

V_{mp} = maximum value of phase (Line-neutral) voltage

V_{ml} = max. value of line voltage = $\sqrt{3} \cdot V_{mp}$

α = firing-angle delay

$$\therefore \boxed{V_o = \frac{3V_{ml}}{2\pi} \cos\alpha} *$$

Average load current $I_o = \frac{V_o}{R} = \frac{3V_{ml}}{2\pi R} \cos\alpha$

RMS value of o/p load voltage is.

$$V_{or} = \left[\frac{3}{2\pi}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_{mp}^2 \sin^2\omega t \, d(\omega t)\right]^{1/2}$$

$$V_{orms}^2 = \frac{3V_{mp}^2}{4\pi}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} (1-\cos 2\omega t)\, d\omega t$$

$$= \frac{3V_{mp}^2}{4\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha+\pi/6}^{\alpha+5\pi/6}$$

$$= \frac{3V_{mp}^2}{4\pi}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2}\cos 2\alpha\right]$$

$$V_{orms} = V_{mp}\sqrt{\left[\frac{1}{2} + \frac{3\sqrt{3}}{8\pi}\cos 2\alpha\right]}$$

$$= \sqrt{3} V_{mp}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$$

$$\boxed{V_{orms} = V_{ml}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}}$$

Rms load current $I_{orms} = \frac{V_{orms}}{R} = \frac{V_{ml}}{R}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$

for $\alpha > 30°$:-

Half wave C

T_1 Conducts from $30°+\alpha$ to $180°$

T_2 " $150°+\alpha$ to $300°$

T_3 " $270°+\alpha$ to $420°$ - - -

at $\omega t = 180°$ current flows through T_1 is reaches to zero.

$\therefore$ T_1 is turned off at $\omega t = 180°$

it conducts for $150°-\alpha$ only

average o/p voltage is given by

$$V_0 = \frac{3}{2\pi}\int_{\alpha+\pi/6}^{\pi} V_{mp}\sin\omega t\, d(\omega t)$$

$$* \boxed{V_0 = \frac{3V_{mp}}{2\pi}\left[1+\cos(\alpha+30°)\right]} *$$

Rms value of o/p voltage $V_{orms} = \left[\frac{3}{2\pi}\int_{\alpha+\pi/6}^{\pi} V_{mp}^2 \sin^2\omega t\, d(\omega t)\right]^{1/2}$

$$V_{orms} = \frac{\sqrt{3}V_{mp}}{2\sqrt{\pi}}\left[\left(\frac{5\pi}{6}-\alpha\right)+\frac{1}{2}\sin(2\alpha+\pi/3)\right]^{1/2}$$

$$\boxed{V_{orms} = \frac{V_{mp}\sqrt{3}}{2\sqrt{\pi}}\left[\left(\frac{5\pi}{6}-\alpha\right)+\frac{1}{2}\sin(2\alpha+\pi/3)\right]^{1/2}}$$

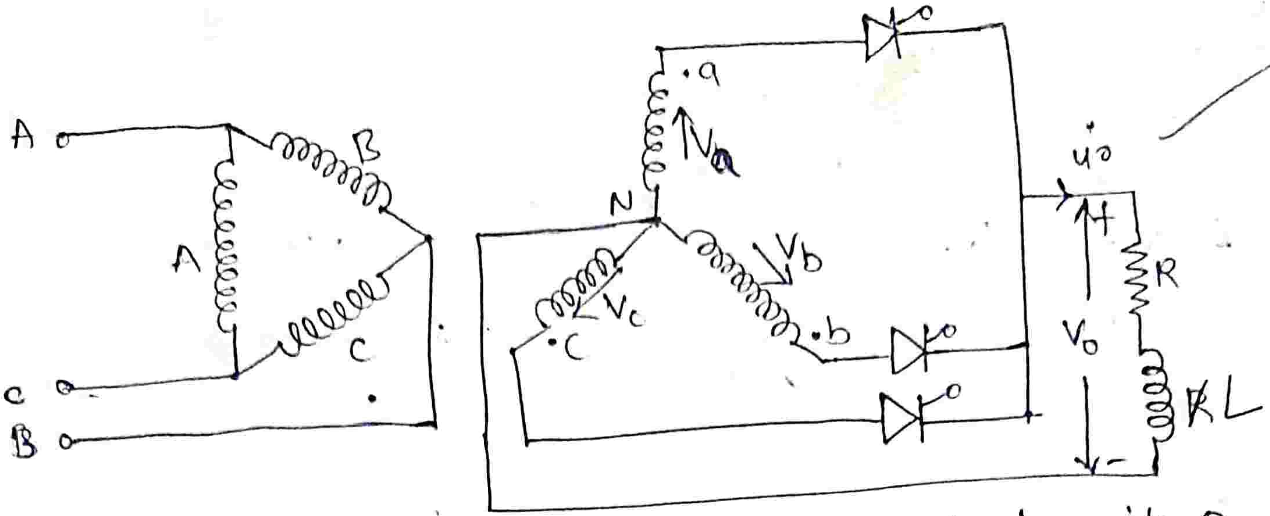
$$I_0 = \frac{V_0}{R}$$

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

or

$$\boxed{V_{orms} = \sqrt{3}V_{mp}\left[\frac{5}{24}-\frac{\alpha}{4\pi}+\frac{1}{8\pi}\sin(2\alpha+\pi/3)\right]^{1/2}}$$

Half wave Converter with RL load:- (3-phase)



The above fig. shows the 3-Ø M-3 converter with RL load for $\alpha < 30^\circ$ o/p voltages wave forms are similar to the R-load as discussed above for firing angles range of $30^\circ < \alpha < 90^\circ$ and $90^\circ < \alpha < 180^\circ$ this converter behaves differently

$30^\circ < \alpha < 90^\circ$:- $\boxed{\text{at } \alpha = 90^\circ \ V_{0avg} = 0}$

T_1 - conducts from $30^\circ + \alpha$ to $150^\circ + \alpha$ & T_2 from $150^\circ + \alpha$ to $270^\circ + \alpha$, T_3 from $270^\circ + \alpha$ to $390^\circ + \alpha$. Thus each SCR conducts for 120° for firing angle $\alpha = 45^\circ$

T_1 conducts from 75° to 195°, T_2 - 195° to 315° T_3 315°-435° ...

at $\omega t = \pi$ $V_0 = 0$ but SCR T_1 current i_{T_1} is not zero because of RL-load. Therefore, T_1 would be continue conducting beyond $\omega t = \pi$ $V_0 = V_a$ goes to -ve.

When T_2 is turn 'ON' at $\omega t = 150^\circ + \alpha$ (195°) load current shifts from T_1 to T_2 & T_1 - gets turn-off.

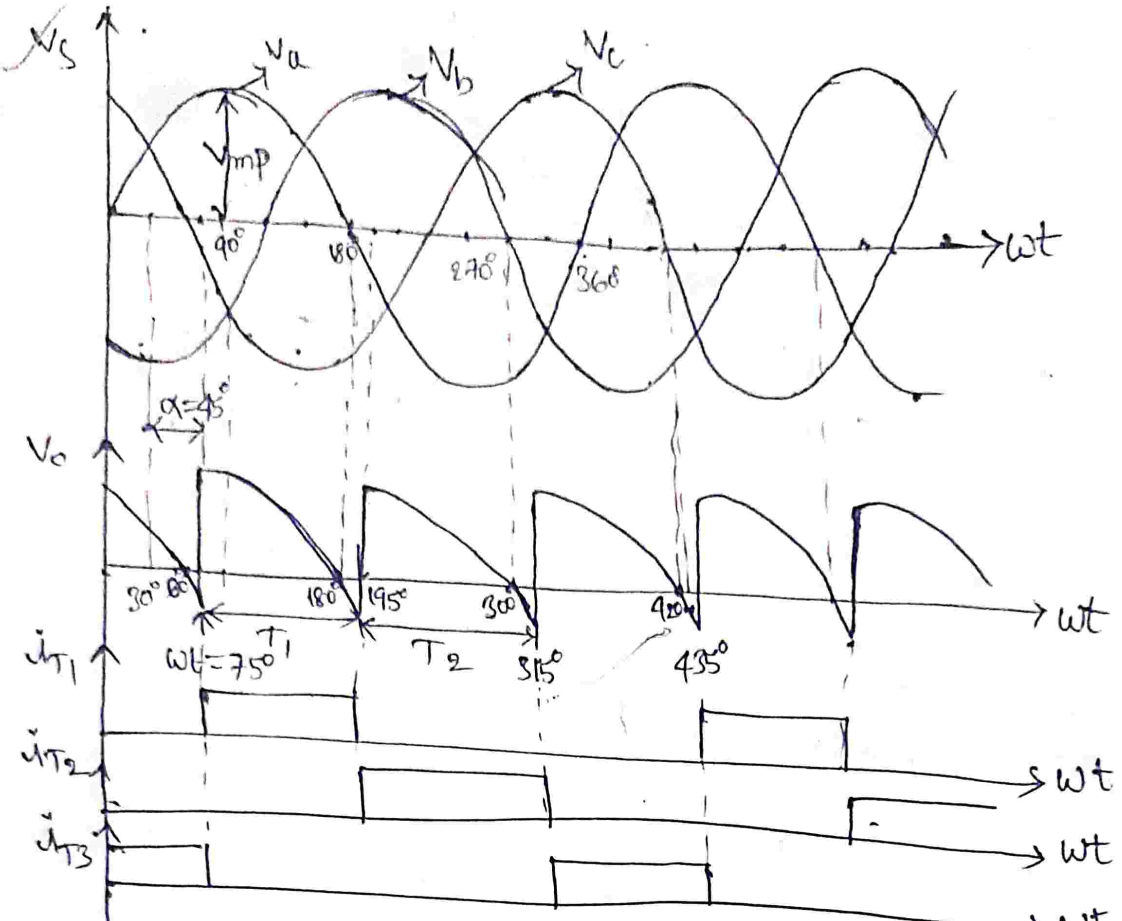
T_2 conducts for 120° there after T_3 for 120° then T_1 etc ---

The average value of o/p voltage is same as R-load

$$\boxed{V_0 = \frac{3V_{ml}}{2\pi}\cos\alpha} \ \& \ \boxed{V_{orms} = V_{ml}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}}$$

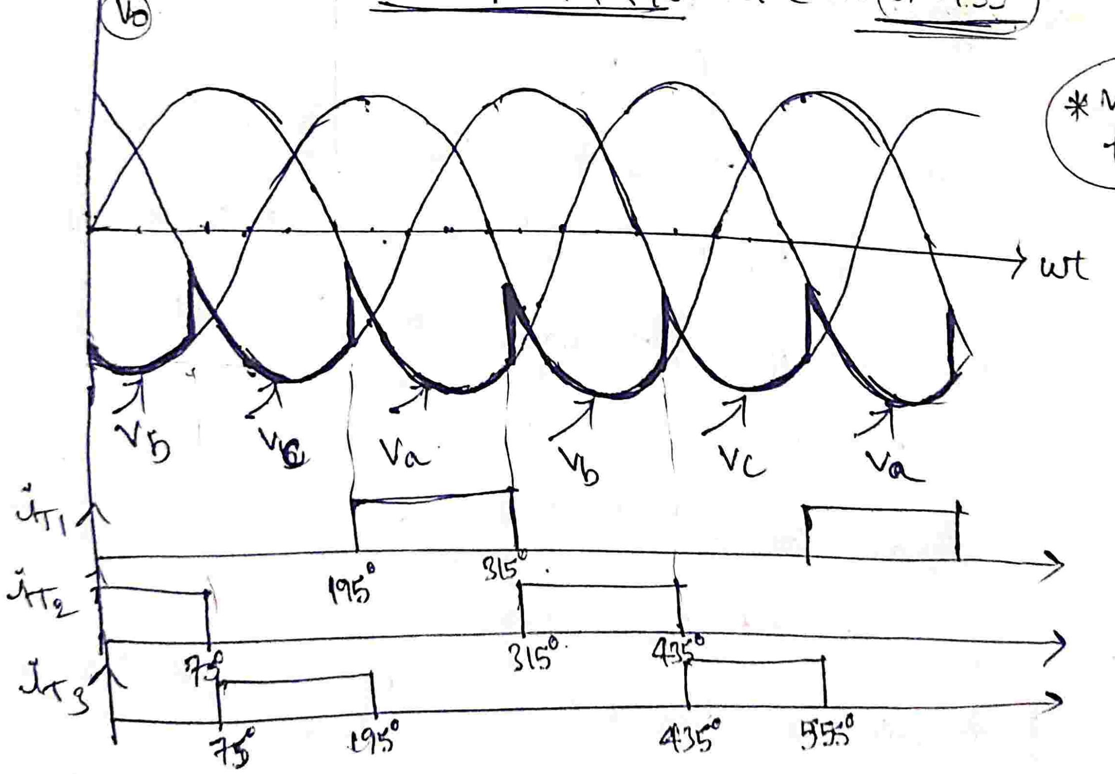
$$I_0 = \frac{V_0}{R} \quad \& \quad I_{orms} = \frac{V_{orms}}{R}$$

$30^\circ < \alpha < 90^\circ$ at $\alpha = 45^\circ$



If $90^\circ < \alpha < 180^\circ$ i.e at $\alpha = 135^\circ$

* Vo is -ve for $\alpha > 90^\circ$



$$I_m = I_a + I_b + I_c = I_o \text{ (load current)}$$

$$I_a = I_b = I_c = I_o/3$$

Sec. of T/R is connected in zig zag as a result core flux core losses & temp ↑ are unaffected.

THREE PHASE FULLY CONTROLLED BRIDGE CONVERTER

With Resistive Load

Three-phase fully controlled bridge rectifier with resistive load is shown in Fig. 6.44. For six-pulse operation, each SCR has to be fired twice in its conduction cycle, that is firing intervals should be 60°. As shown in Fig. 6.43 (b), there are six line to line phasors, each having a maximum conduction angle of 60°. The output voltage waveform for different values of 'α', i.e. α = 0°, 30°, 60°, 90° and 120° are shown in Fig. 6.45 (a).

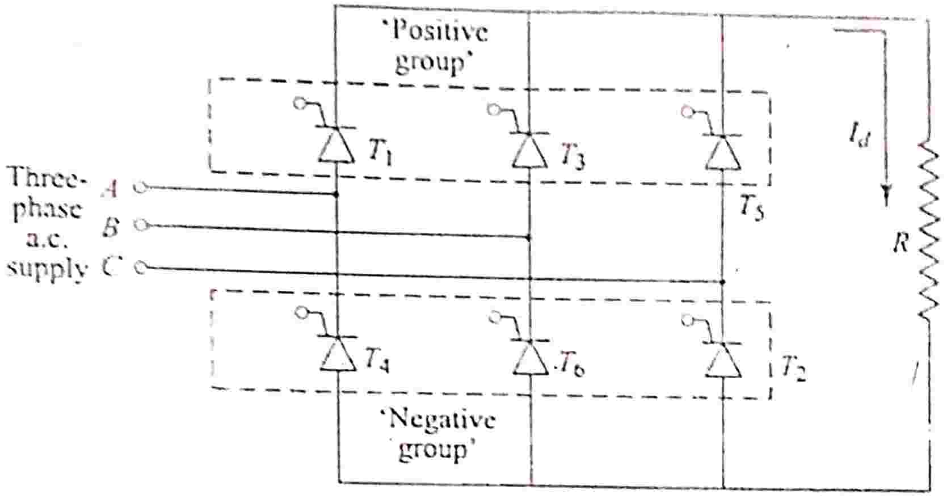


Fig. 6.44 *3-phase fully controlled bridge rectifier with resistive load*

The defining equations for phase and line voltages are:

$$E_{AN} = E_m \sin(\omega t) \qquad E_{BC} = \sqrt{3}\, E_m \sin(\omega t - 90°)$$

$$E_{BN} = E_m \sin(\omega t - 120°) \qquad E_{BA} = \sqrt{3}\, E_m \sin(\omega t - 150°)$$

$$E_{CN} = E_m \sin(\omega t + 120°) \qquad E_{CA} = \sqrt{3}\, E_m \sin(\omega t + 150°)$$

$$E_{AB} = \sqrt{3}\, E_m \sin(\omega t + 30°) \qquad E_{CB} = \sqrt{3}\, E_m \sin(\omega t + 90°)$$

$$E_{AC} = \sqrt{3}\, E_m \sin(\omega t - 30°)$$

The following points can be noted from Fig. 6.45 (a).

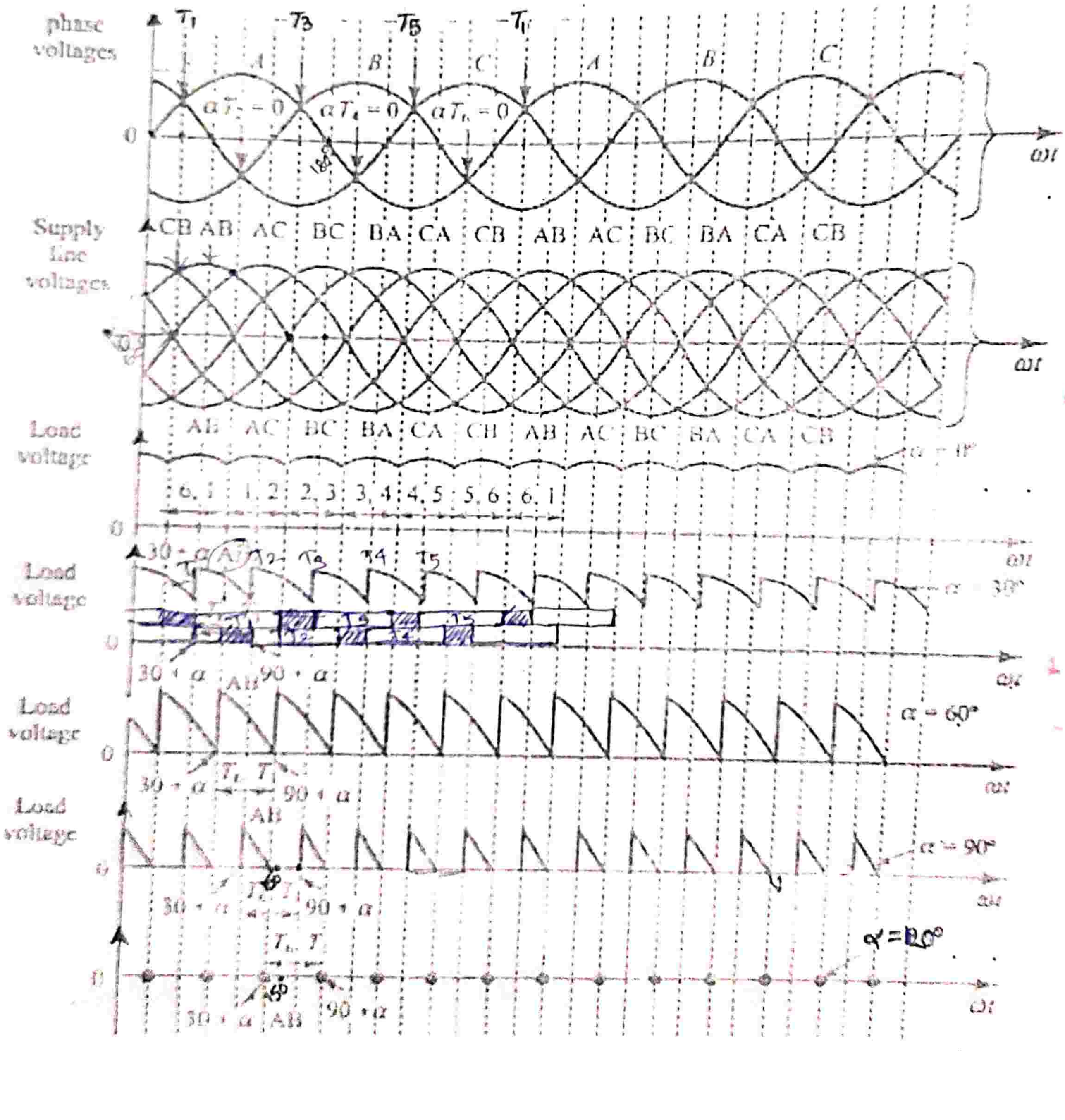
(i) The output voltage waveform for any value of α is a six pulse wave with a ripple frequency of 300 Hz.

(ii) *Continuous conduction mode* ($0 \le \alpha \le \pi/3$) When the phasor (A-B) is allowed to conduct at α between zero to $\pi/3$, it continuous to conduct by 60° when the phasor (A-C) is fired. The conduction is shifted from SCR T_6 to SCR T_2. T_6 is commutated off by the reverse-voltage of phase C and B across it. The phasor (A-C) conducts after another 60° after which it is replaced by phasor (B-C) when phase B voltage assumes greater value than C or A. Hence, load current is continuous for α between 0 to $\pi/3$.

(iii) ***Discontinuous conduction mode:*** ($\pi/3 \le \alpha \le 2\pi/3$) When $\pi/3 \le \alpha \le 2\pi/3$, the phasor (A-B) conducts upto an angle π after which both the thyristors T_1 and T_6 are commutated off because phase B becomes positive with respect to phase C and after 60°, when T_2 and T_1 are fired, phase (A-C) conducts also upto angle π, hence load current remains zero from angle π to the next firing pulse and becomes discontinuous, therefore, the fully-controlled bridge circuit produces a ripple frequency of six times the supply frequency at all trigger angles.

(iv) For $\alpha = 120°$, the output voltage is zero and hence $\alpha_{max} = 120°$ ($2\pi/3$).

Output Voltage Wave Forms: (R- Load)



The voltage and current relations for both the modes can be derived as follows:

(a) Continuous Conduction Mode: ($\alpha < 60°$) The general equation for the average load voltage is given by

$$E_{dc} = \frac{1}{2\pi} \int_{0}^{2\pi} E_{dc}(\omega t) \cdot d(\omega t)$$

Now for $\alpha < 60°$, and from Fig. 6.45 (a), we can write

$$E_{dc} = 6 \times \frac{1}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} E_{AB(\omega t)} \cdot d(\omega t)$$

where the line-to line-voltage E_{AB} is given by:

$$E_{AB} = \sqrt{3}\, E_m \sin(\omega t + \pi/6) \tag{6.48}$$

$$\therefore\ E_{dc} = \frac{3}{\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\, E_m \sin(\omega t + \pi/6)\, d(\omega t) = \frac{3\sqrt{3}\, E_m}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sin(\omega t) \cdot d\omega t$$

$$= \frac{3\sqrt{3}\, E_m}{\pi} (\cos \omega t)_{2\pi/3+\alpha}^{\pi/3+\alpha} = \frac{3\sqrt{3}\, E_m}{\pi} [\cos(\pi/3 + \alpha) - \cos(2\pi/3 + \alpha)]$$

$$= \frac{3\sqrt{3}\, E_m}{\pi} [\cos(\pi/3 + \alpha) + \cos(\pi/3 - \alpha)]$$

$$= \frac{3\sqrt{3}\, E_m}{\pi} (2 \cdot \cos(\pi/3) \cdot \cos \alpha) = \frac{3\sqrt{3}\, E_m}{\pi} \cos \alpha \tag{6.49 (a)}$$

Average load current:

$$I_d = \frac{3\sqrt{3}\, E_m}{\pi \cdot R} \cos \alpha \tag{6.49 (b)}$$

(b) Discontinuous Conduction Mode ($\alpha > 60°$)

From Fig. (6.45a),

$$E_{dc} = 6 \times \frac{1}{2\pi} \int_{\pi/6+\alpha}^{5\pi/6} \sqrt{3}\, E_m \sin\left(\omega t + \frac{\pi}{6}\right) = \frac{3\sqrt{3}\, E_m}{\pi} \int_{\pi/3+\alpha}^{\pi} \sin(\omega t)\, d\omega t$$

CCM:- $\alpha < 60^\circ$

Derivation of RMS Voltage

$$V_{orms} = \left\{ \frac{3}{\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} (V_{AB})^2 \, d\omega t \right\}^{1/2}$$

$$= \left\{ \frac{3}{\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} \left[\sqrt{3} V_{mp} \sin(\omega t + \pi/6)\right]^2 d\omega t \right\}^{1/2}$$

$$= \left\{ \frac{3}{\pi} \times (\sqrt{3} V_{mp})^2 \int_{\pi/3+\alpha}^{2\pi/3+\alpha} \sin^2(\omega t) \, d\omega t \right\}^{1/2}$$

$$V_{orms}^2 = \frac{9 V_{mp}^2}{\pi} \int_{\pi/3+\alpha}^{2\pi/3+\alpha} \left[\frac{1 - \cos 2\omega t}{2}\right] d\omega t$$

$$V_{orms}^2 = \frac{9 V_{mp}^2}{2\pi} \left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\pi/3+\alpha}^{2\pi/3+\alpha}$$

$$= \frac{9 V_{mp}^2}{2\pi} \left[2\pi/3 + \cancel{\alpha} - \pi/3 - \cancel{\alpha} - \frac{1}{2}\left[\sin(4\pi/3 + 2\alpha) - \sin(2\pi/3 + 2\alpha)\right]\right]$$

$$= \frac{9 V_{mp}^2}{2} \left[\frac{1}{3} - \frac{1}{2\pi}\left[-\frac{\sqrt{3}}{2} \cos 2\alpha + \left(-\frac{1}{2}\right) \cancel{\sin 2\alpha} - \left(\frac{\sqrt{3}}{2} \cos 2\alpha + \left(-\frac{1}{2}\right) \cancel{\sin 2\alpha}\right)\right]\right]$$

$$V_{orms}^2 = \frac{9 V_{mp}^2}{2} \left[\frac{1}{3} + \frac{1}{2\pi} \sqrt{3} \cos 2\alpha \right]$$

$$* \quad \boxed{V_{orms} = \frac{3 V_{mp}}{\sqrt{2}} \sqrt{\left(\frac{1}{3} + \frac{\sqrt{3}}{2\pi} \cos 2\alpha\right)}} \quad *$$

or

$$V_{orms} = \frac{3 V_{mp}}{2} \left[\frac{2}{3} + \frac{\sqrt{3}}{\pi} \cos 2\alpha \right]^{1/2}$$

$$\therefore \frac{3\sqrt{3}\,E_m}{\pi}(\cos\omega t)_{\pi}^{\pi/3+\alpha} = \frac{3\sqrt{3}\,E_m}{\pi}[1+\cos(\alpha+\pi/3)] \quad (6.50)$$

• For α_{max}, $E_{dc} = 0$, $\therefore \frac{3\sqrt{3}\,E_m}{\pi}[1+\cos(\alpha+\pi/3)] = 0$

Hence, $\alpha_{max} = 120°$

Average load current:

$$I_d = \frac{3\sqrt{3}\,E_m}{\pi R}[1+\cos(\alpha+\pi/3) \quad (6.51)$$

Detailed Waveforms (Operation) with R-Load for $\alpha = 30°$ Figure 6.45(b) shows the detailed waveforms for output voltage, output current, supply current, SCR current and voltage with $\alpha = 30°$. From these waveforms, following points can be noted:

(i) Output voltage and current waveforms are six pulse with ripple frequency of 300 Hz.

(ii) For $\alpha \le 60°$, the supply current waveforms are of 120° in each half cycle and for $\alpha > 60°$ (not shown in figure) it is less than 120°, i.e. $(180° - \alpha)$ in each half-cycle.

(iii) For $\alpha \le 60°$, the SCR waveform is 120° wide and for $\alpha > 60°$, it is $(180° - \alpha)°$ wide.

(iv) PIV rating of SCR is $\sqrt{3}\,E_m$.

RMS Voltage Derivation in DCM operation ($\alpha \geq 60°$)

$$V_{orms}^2 = \frac{1}{\pi/3}\int_{\pi/6+\alpha}^{5\pi/6}\left[\sqrt{3}\,V_{mp}\sin(\omega t+\pi/6)\right]^2 d\omega t$$

$$= \frac{3}{\pi}(\sqrt{3}V_{mp})^2\int_{\pi/3+\alpha}^{\pi}\sin^2(\omega t)\,d\omega t$$

$$= \frac{9V_{mp}^2}{\pi}\int_{\pi/3+\alpha}^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right)d\omega t$$

$$= \frac{9V_{mp}^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\pi/3+\alpha}^{\pi}$$

$$V_{orms}^2 = \frac{9V_{mp}^2}{2\pi}\left\{\left(\pi - \pi/3 - \alpha\right) - \frac{1}{2}\left(\cancel{\sin 2\pi}^{\,0} - \sin\left(\frac{2\pi}{3} + 2\alpha\right)\right)\right\}$$

$$V_{orms}^2 = \frac{9V_{mp}^2}{2\pi}\left\{\left(\frac{2\pi}{3} - \alpha\right) - \frac{1}{2}\left[-\frac{\sqrt{3}}{2}\cos 2\alpha - \left(-\frac{1}{2}\right)\sin 2\alpha\right]\right\}$$

$$\boxed{V_{orms} = \frac{3V_{mp}}{\sqrt{2}}\left\{\left(\frac{2}{3} - \frac{\alpha}{\pi}\right) + \frac{1}{4}\left[\sqrt{3}\cos 2\alpha - \sin 2\alpha\right]\right\}^{1/2}}$$

or

$$\therefore \boxed{V_{orms} = 3V_{mp}\left\{\left(\frac{1}{6} - \frac{\alpha}{4\pi} + \frac{\sqrt{3}}{16}\cos 2\alpha - \frac{1}{16}\sin 2\alpha\right)\right\}^{1/2}}$$

2018 Set
(4) Question

(1) A 3-ϕ full converter is connected to load resistance of 5Ω, It is supplied from a 220V, 50Hz ac supply, If the firing angle $\alpha = 30°$ Determine (i) Average output voltage and current (ii) RMS output voltage and current.

<u>given Data</u>:- 3-ϕ full converter with R-load

$R = 5\Omega$, $\alpha = 30°$

$$V_{mp} = \frac{V_{ml}}{\sqrt{3}}$$

$V_{Lrms} = 220V$

$V_{ml} = V_{Lrms} \times \sqrt{2} = 220 \times \sqrt{2}$

$$V_{mp} = \frac{220 \times \sqrt{2}}{\sqrt{3}} = 179.63V$$

(i) $$V_{DC} = \frac{3\sqrt{3}\,V_{mp}}{\pi}\cos\alpha = \frac{3\sqrt{3} \times 179.63}{\pi}\cos 30°$$

$V_{DC} = 257.3\,V$

$$I_{DC} = \frac{V_{DC}}{R} = 51.46A$$

(ii) $$V_{orms} = \frac{3V_{mp}}{2}\left[\frac{2}{3} + \frac{\sqrt{3}}{\pi}\cos 2\alpha\right]^{1/2}$$

$$= \frac{3 \times 179.63}{2}\left[\frac{2}{3} + \frac{\sqrt{3}}{\pi}\cos 60°\right]^{1/2}$$

$$\boxed{V_{orms} = 261.56\,V}$$

$$I_{orms} = \frac{V_{orms}}{R} = \frac{261.56}{5} = 52.31A$$

(2) 2018 - Set - 2 (4) Question

3-ϕ half wave Controlled rectifier with R load triggered at $\alpha = 60°$, supplied from 3-ϕ 220V, 50Hz ac supply. Determine (i) DC output voltage and current (ii) RMS output voltage and current. ($R = 10\Omega$)

Sol:-

$V_L = 220V$

$V_{mL} = 220 \times \sqrt{2}$

$V_{mp} = \frac{220 \times \sqrt{2}}{\sqrt{3}} = 179.63V$

$\alpha = 60°$ & $R = 10\Omega$

(i) $V_{dc} = \frac{3\sqrt{3} V_{mp} \cos\alpha}{2\pi} = \frac{3\sqrt{3} \times 179.63}{2\pi} \times \cos 60°$

$\boxed{V_{DC} = 74.27V}$

$I_{DC} = \frac{V_{DC}}{R} = \frac{74.27}{10} = 7.427A$

(ii) $V_{orms} = \sqrt{3} V_{mp} \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right]^{1/2}$

$= \sqrt{3} \times 179.63 \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos(120°) \right]^{1/2}$

$\boxed{V_{orms} = 113.13V}$

$I_{orms} = \frac{V_{orms}}{R} = \frac{113.13}{10}$

$\boxed{I_{orms} = 11.313A}$

R-16
2019 Set-I
Q 4(b)

4(b)

A 3-ϕ full converter is connected to a resistive load of 10Ω. If the firing angle of SCR is $\alpha = 45^\circ$ and it feeds 4KW power to a resistive load determine the amplitude of maximum line input voltage.

Sol:- given Data

$$R = 10\Omega \quad , \alpha = 45^\circ$$

$$P = 4KW \qquad V_{ml} = ?$$

$\alpha < 60^\circ$ $\therefore$ It is operated in CCM.

$$V_{o\,rms} = \frac{3V_{mp}}{2}\left[\frac{2}{3} + \frac{\sqrt{3}}{\pi}\cos 2\alpha\right]^{1/2} \longrightarrow (1)$$

$$V_{o\,rms} = \sqrt{P.R} = \sqrt{4 \times 10^3 \times 10} = 200V$$

$$200 = \frac{\sqrt{3}V_{ml}}{2}\left[\frac{2}{3} + \frac{\sqrt{3}}{\pi}\cancel{\cos 90^\circ}^{\,0}\right]^{1/2} \quad (\because V_{ml} = \sqrt{3}V_{mp})$$

$$200 = \frac{\cancel{\sqrt{3}}V_{ml}}{\cancel{2}_{\sqrt{2}}}\sqrt{\frac{\cancel{2}}{\cancel{3}}}$$

$$\therefore V_{ml} = 200\sqrt{2} = 282.8V$$

$$\therefore \boxed{V_{ml} = 282.8V}$$

4(b) A 3-phase half-wave converter is supplying a load with a continuous constant current of 40A over a firing angle from 0° to 75°. What will be the power dissipated by the load at these limiting values of firing angle. The supply voltage is 415V (line)

Sol:- In 3-ϕ half wave converter CCM operation for R-load (0-30°) only.

Here (0-75°) load current is continuous and constant then, the load is (RL or RLE) type.

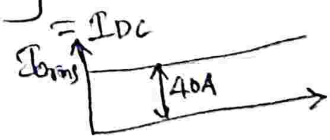
In CCM:- $V_0 = \frac{3V_{ml}}{2\pi}\cos\alpha$ $V_{orms} = \sqrt{3}V_{mp}\left[\frac{1}{6}+\frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$

$V_{Lrms} = 415V$

$V_{mp} = \frac{415\times\sqrt{2}}{\sqrt{3}}$ & $V_{ml} = 415\times\sqrt{2}$
$= 586.89$

At $\alpha = 0°$

$V_{orms} = 586.89\left[\frac{1}{6}+\frac{\sqrt{3}}{8\pi}\cos 0°\right]^{1/2}$



$V_{orms} = 284.86V$

given $I_{DC} = I_{orms} = 40A$ ($\because$ current is continuous & constant)

$\therefore$ Power delivered to the load at $\alpha = 0° = V_{orms} I_{orms}$

$P_{\alpha=0°} = 284.86\times 40 = 9954.4W$

$\boxed{P_{\alpha=0°} = 9.9544KW}$

At firing angle $\alpha = 75°$

$$V_{orms} = V_{ml}\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{1/2}$$

$$= 586.89\left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos(2\times 75°)\right]^{1/2}$$

$$V_{orms} = 191.96\,V$$

power dessipated to the load at $\alpha = 75°$ $= V_{orms} I_{orms}$

$$= 191.96 \times 40$$
$$= 7678.4$$
$$P_{\alpha=75°} = 7.6784\,KW$$

R-16 Set-3 (2019) Q 4(b)

3-ø full Converter fed by 230V, 50Hz, 3-phase supply. the average load current is 25A and the load is highly inductive. For firing angle of 60° find RMS, average and peak currents through SCR's

Sol:- For highly inductive load load current is continuous and constant (at $\alpha = 60°$) $I_{DC} = I_{orms} = 25A$

(i) Average current through SCR's $= I_{TA} = \frac{I_{DC}}{3} = \frac{25}{3} = 8.33A$

$$\boxed{I_{TA} = 8.33A}$$

(ii) RMS current through SCR's $= I_{Trms} = \frac{I_{orms}}{\sqrt{3}} = \frac{25}{\sqrt{3}}$

$$\boxed{I_{Trms} = 14.43A}$$

(iii) peak current flowing through SCR's $= I_{Trms} \times \sqrt{2}$

$$= 14.43 \times \sqrt{2} = 20.4A$$

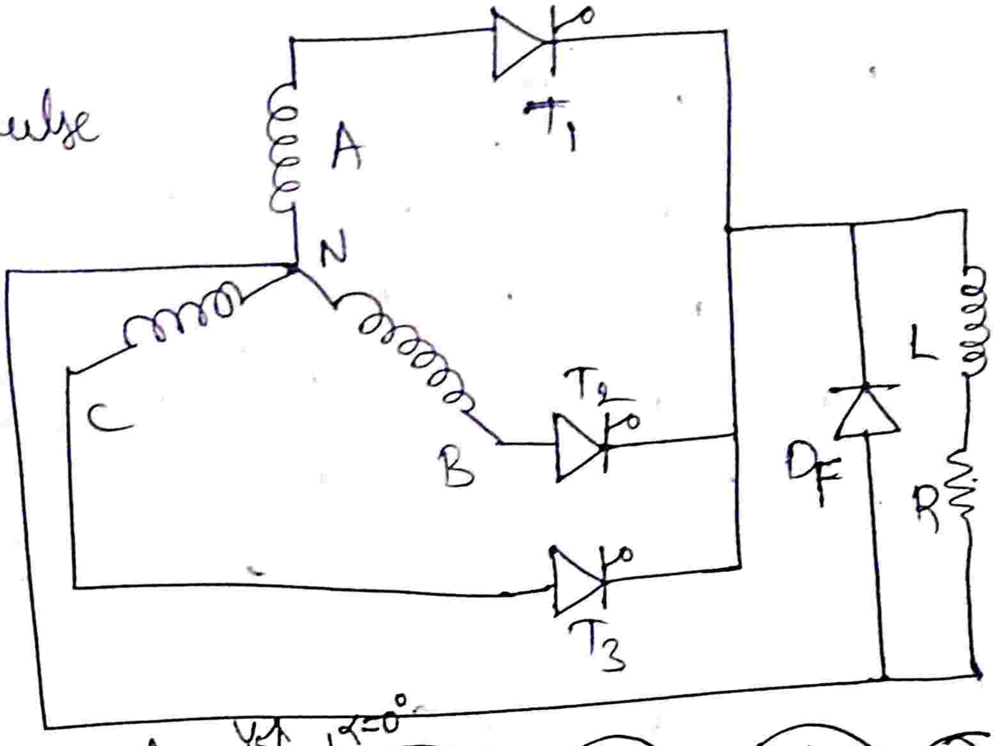
Q 4 2019 (R-16)

2019 (R-16)

A 3-ϕ three pulse controlled rectifier with free wheeling Diode D_F is fed from a 3-ϕ, 400V, 50Hz. ac Supply and it is connected with a constant current load of 90A at firing angle of $\alpha = 45^\circ$. Calculate DC output voltage, rms output voltage, Average and RMS currents of freewheeling Diode.

given Data:-

3-phase 3-pulse Converter



$V_{L\text{-}rms} = 400V$

$\alpha = 45^\circ$

$I_{DC} = 90A$

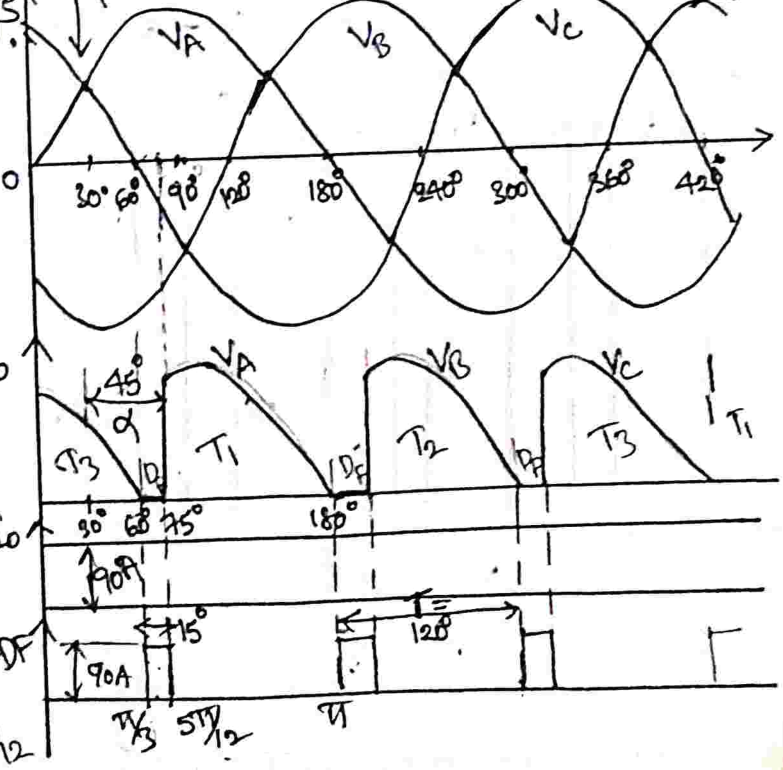
D_F is present in circuit means load is "(RL)". or RLE load.

$\alpha = 45^\circ (\nless 30^\circ)$

(a) $V_{DC} = \dfrac{3V_{mp}}{2\pi}\left[1+\cos(\alpha+30^\circ)\right]$

$V_{mp} = 400\sqrt{2/3} =$

$$\boxed{V_{mp} = 326.6V}$$



$\frac{\pi}{3} = 60^\circ$, $30^\circ = \frac{\pi}{6}$, $15^\circ = \frac{\pi}{12}$

$75^\circ = 60^\circ + 15^\circ = \pi/3 + \frac{\pi}{12} = \frac{4\pi+\pi}{12} = 5\pi/12$

$$V_{DC} = \frac{3 \times 326.6}{2\pi}\left(1+\cos(45^\circ+30^\circ)\right)$$

$$\boxed{V_{DC} = 196.3\,V}$$

ⓑ $$V_{orms} = \sqrt{3}\,V_{mp}\left[\frac{5}{24} - \frac{\alpha}{4\pi} + \frac{1}{8\pi}\sin\left(2\alpha + \pi/3\right)\right]^{1/2}$$

$$= \sqrt{3} \times \left(400\sqrt{\frac{2}{3}}\right)\left[\frac{5}{24} - \left(\frac{\pi/4}{4\pi}\right) + \frac{1}{8\pi}\sin(90^\circ+60^\circ)\right]^{1/2}$$

$$\boxed{V_{orms} = 230.29\,V}$$

ⓒ Average free wheeling Diode current

periodicity $T = 120^\circ = 2\pi/3$

$$I_{DF\,avg} = \frac{1}{2\pi/3}\int_{\pi/3}^{5\pi/12} (I_{DC})\,d\omega t = \frac{3 I_{DC}}{2\pi}\left[\omega t\right]_{\pi/3}^{5\pi/12}$$

$$= \frac{3 I_{DC}}{2\pi}\left[5\pi/12 - \pi/3\right] = \frac{\cancel{3} I_{DC}}{2\cancel{\pi}}\left[\frac{\cancel{\pi}}{\cancel{12}_{\,4}}\right]$$

$$I_{DF\,avg} = \frac{90}{8} = 11.25A$$

ⓓ RMS value of free wheeling Diode current $= I_{Drms}$

$$I_{Drms} = \left\{\frac{3}{2\pi}\int_{\pi/3}^{5\pi/12}(I_{DC})^2\,d\omega t\right\}^{1/2} = \left\{\frac{3(I_{DC})^2}{2\pi}\left[\omega t\right]_{\pi/3}^{5\pi/12}\right\}^{1/2}$$

$$= \sqrt{\frac{\cancel{3} I_{DC}^2}{2\cancel{\pi}}\left(\frac{\cancel{\pi}}{\cancel{12}_{\,4}}\right)} = \frac{I_{DC}}{2\sqrt{2}} = \frac{90}{2\sqrt{2}}$$

$$\boxed{I_{Drms} = 31.82A}$$

DUAL CONVERTER

Dual converter, the name itself says two converters. One will perform as a rectifier and the other will perform as an inverter. 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 figure-1.

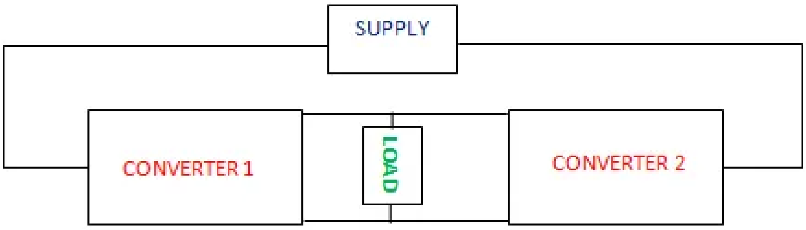


Figure 1

Modes of Operation of Dual Converter

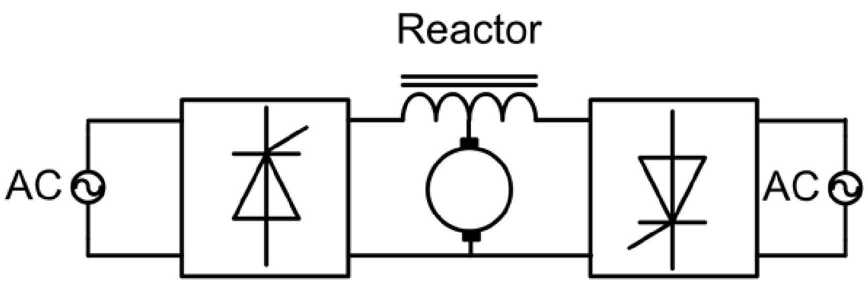
There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

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

Let say converter-1 acts as a rectifier and supplying the load current. At this instant, converter-2 is blocked by removing the firing angle. For inversion operation, converter-1 is blocked and converter-2 is supplying the load current. The pulses to the converter-2 are applied after a delay time to avoid circulating currents. The delay time is around **10 to 20 msec**.

Circulating Current Mode



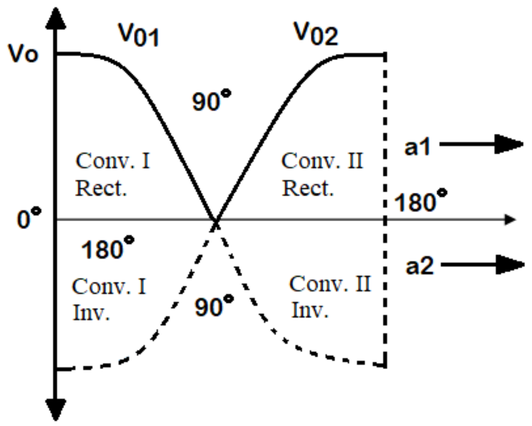
Two converters will be in the ON condition at the same time. So circulating current is present. A **current limiting reactor** is connected between the DC terminals of both converters. The firing angle of the converters is regulated by a control circuit. So, the DC voltages of both converters are equal in magnitude and opposite in polarity. This makes possible to drive current in reverse direction through the load. This makes the minimum amount of circulating current flow through the reactor.

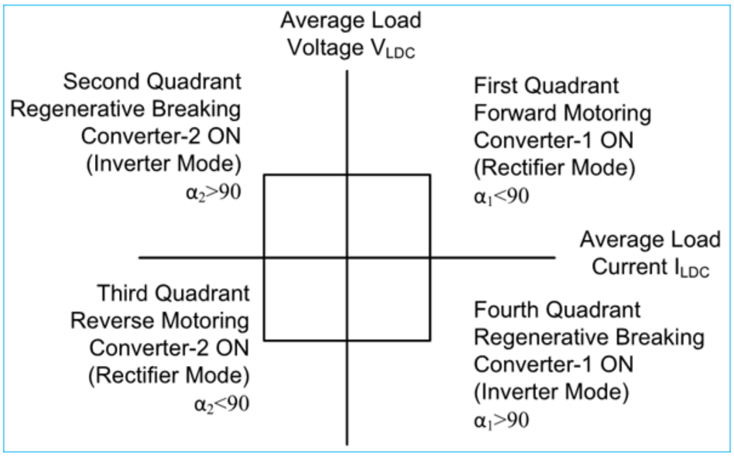
- Average output voltage of Single-phase converter = $2V_m \,COS\alpha/ \pi$
- Average output voltage of Three-phase converter = $3V_m \,COS\alpha/ \pi$

- For converter 1, the average output voltage, $V_{01}= V_{max}\ COS\alpha_1$
- For converter 2, the average output voltage, $V_{02}= V_{max}\ COS\alpha_2$
- The Output voltage is given by,

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

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





The advantage of this scheme is that we can get smooth operation of the converter at the time of inversion. Time response of the scheme is very fast. The normal delay period is 10 to 20 msec in the case of circulating current free operation is eliminated.

The disadvantage of this scheme is that, the size and cost of reactor high. Because of the circulating current, the power factor and efficiency are low. To handle the circulating current, the thyristors with high current ratings are required.

Types of Dual Converters

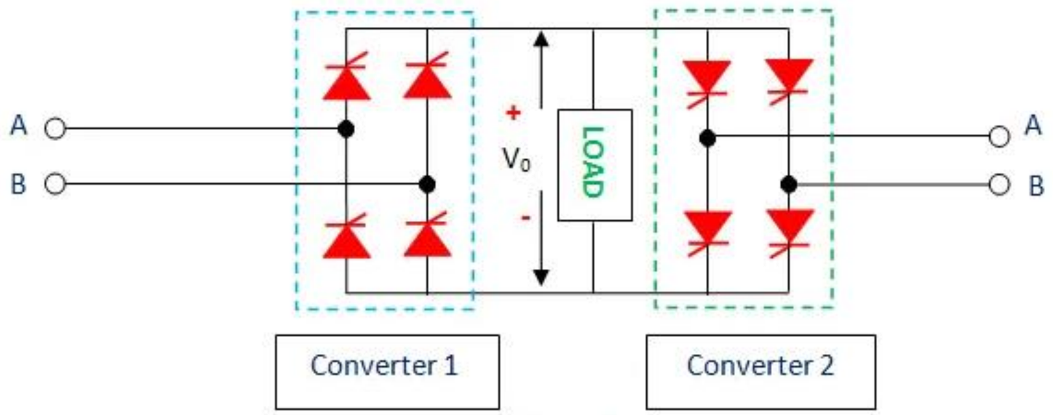
They are of two types of Dual converters:

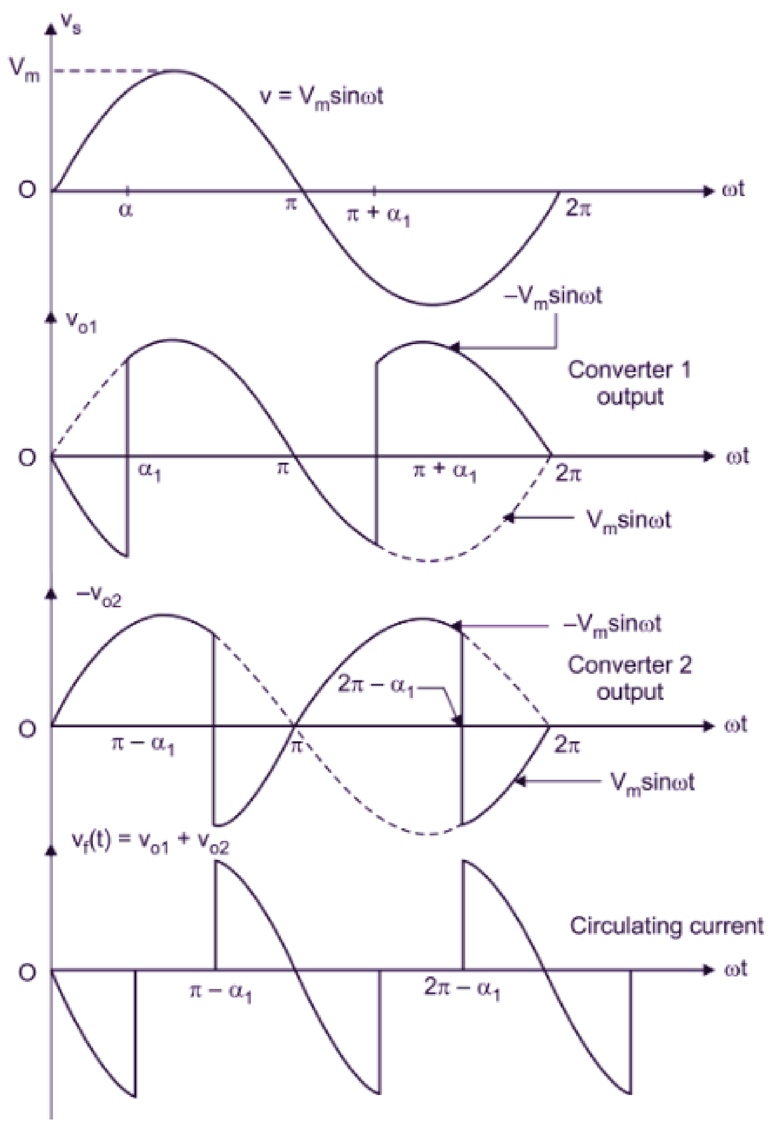
1. **Single-phase dual converter**
2. **Three-phase dual converter**.

According to the **type of load, single-phase and three-phase dual converters are used**.

Single Phase Dual Converter

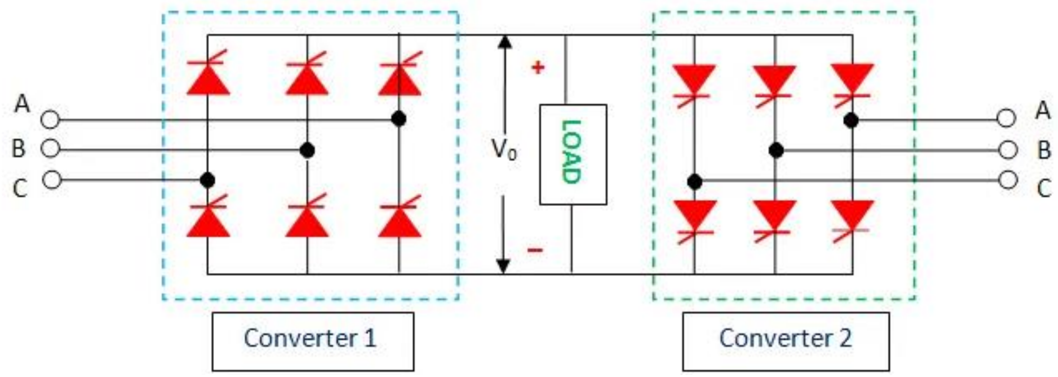
Consider, a single phase dual converter with non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs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





Three Phase Dual Converter

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



Application of Dual Converter

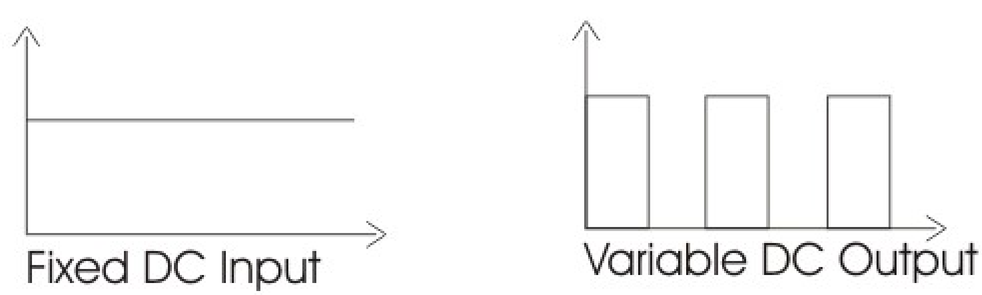
- Direction and speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Differences between circulating and Non-circulating current modes:

S. No	With Circulating Current	Without Circulating Current
1.	Reactors are required to limit the circulating current. These reactors may be costly and bulky and consume lot of power.	Reactors are not required for normal operation but sometimes may have to be used to make the load current continuous.
2.	Losses increase due to circulating current and hence efficiency decreases.	Efficiency is higher.
3.	The converter current is due to presence of circulating current.	Converter current can be discontinuous.
4.	Less response time, therefore fast response.	Response time is more so slow response.
5.	Transfer characteristics are linear.	Transfer characteristics are nonlinear due to discontinuous current.
6.	The fault circulating current, due to undesired firing of converters is limited by the current reactor.	Simultaneous firing of both the converter due to faulty signals will create a short circuit condition.
7.	The converter current is higher than the load current, due to circulating current.	The converter current is the same as output current.

Unit-III
Chopper | DC to DC Converter

DC to DC converter is very much needed nowadays as many industrial applications are dependent upon DC voltage source. The performance of these applications will be improved if we use a variable DC supply. It will help to improve controllability of the equipments also. Examples of such applications are subway cars, trolley buses, battery operated vehicles etc. We can control and vary a constant DC voltage with the help of a **chopper**.
Chopper is a basically static power electronics device which converts fixed DC voltage/power to variable DC voltage or power. It is nothing but a high speed switch which connects and disconnects the load from source at a high rate to get variable or chopped voltage at the output.



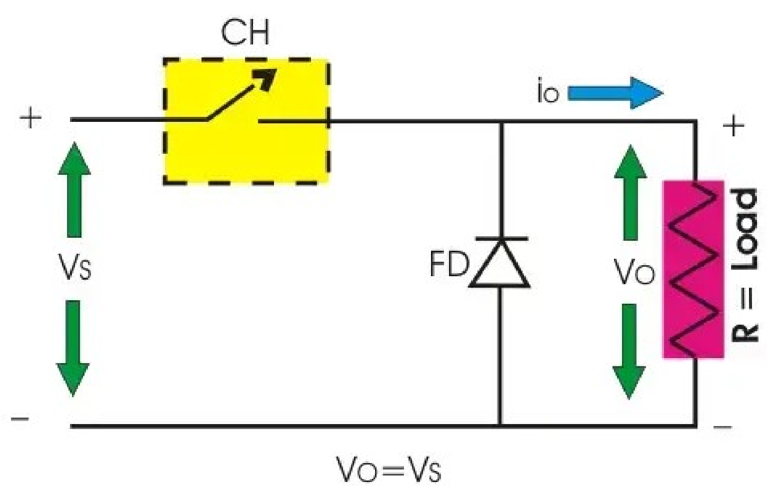
Chopper can increase or decrease the DC voltage level at its opposite side. So, chopper serves the same purpose in DC circuit transfers in case of ac circuit. So it is also known as DC transformer.

Devices used in Chopper

Low power application: GTO, IGBT, Power BJT, Power MOSFET etc.
High power application: Thyristor or SCR.
These devices are represented as a switch in a dotted box for simplicity. When it is closed current can flow in the direction of arrow only.

Operation of Step Down Chopper with Resistive Load

When CH is ON, $V_o = V_S$
When CH is OFF, $V_o = 0$



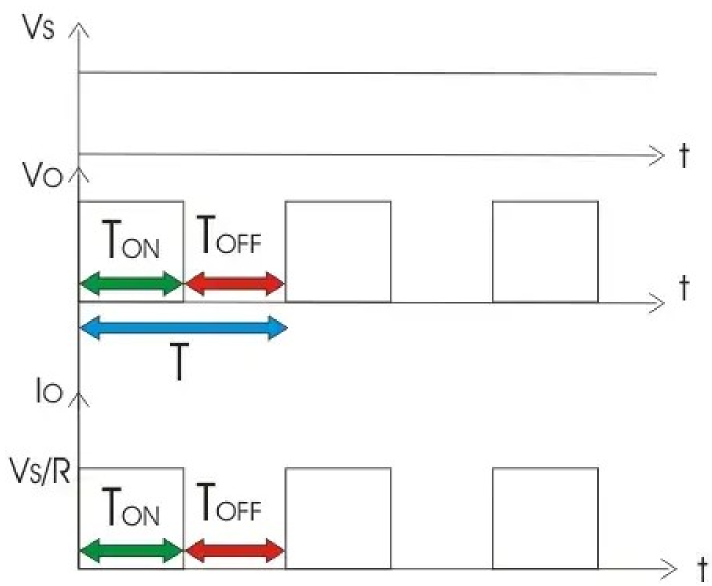
$$Average\ output\ voltage\ V_O = \frac{1}{T}\int_0^{T_{ON}} V_s dt = \frac{V_s T_{ON}}{T} = DV_s$$

Where, D is duty cycle = T_{ON}/T.
T_{ON} can be varied from 0 to T, so $0 \leq D \leq 1$. Hence output voltage V_o can be varied from 0 to V_S.

$$RMS\ output\ voltage\ V_{or} = \sqrt{\frac{1}{T}\int_0^{T_{ON}} V_s^2 dt} = V_s\sqrt{\frac{T_{ON}}{T}} = \sqrt{D}V_s$$

$$Therefore, Effective\ input\ resistance\ R_i = \frac{V_s}{T_{savg}} = \frac{V_s}{DV_s/R} = \frac{R}{D}$$

So, we can conclude that output voltage is always less than the input voltage and hence the name step down chopper is justified. The output voltage and current waveform of step down chopper with resistive load is shown below.



Operation Of Step Down Chopper with Inductive Load

When CH is ON, $V_o = V_S$

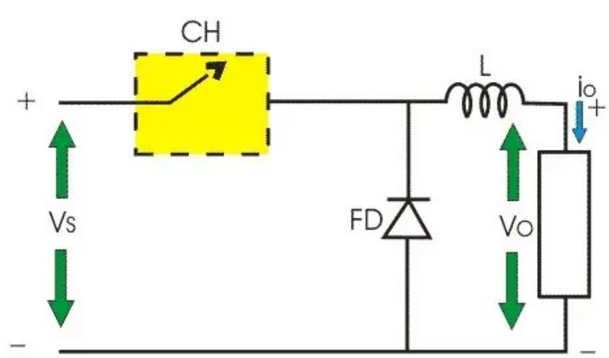
When CH is OFF, $V_o = 0$

During ON time of Chopper

$$V_s = V_L + V_o \Rightarrow V_L = V_s - V_o \Rightarrow L\frac{di}{dt} = V_s - V_o \Rightarrow L\frac{\Delta I}{T_{ON}} = V_s - V_o$$

Therefore, peak to peak load current,

$$\Delta I = \frac{V_s - V_o}{L} T_{ON} \cdots\cdots\cdots (i)$$



During OFF Time of Chopper

If inductance value of L is very large, so load current will be continuous in nature. When CH is OFF inductor reverses its polarity and discharges. This current freewheels through diode FD.

$$Therefore,\ L\frac{di}{dt} = V_o$$

$$L\frac{\Delta I}{T_{OFF}} = V_0 \Rightarrow \Delta I = V_0\frac{T_{OFF}}{L} \cdots\cdots\cdots (ii)$$

By equating (i) and (ii)

$$\frac{V_s - V_o}{L}T_{ON} = \frac{V_o}{L}T_{OFF}$$

$$\frac{V_s - V_o}{V_o} = \frac{T_{OFF}}{T_{ON}}$$

$$\frac{V_s}{V_o} = \frac{T_{ON} - T_{OFF}}{T_{ON}}$$

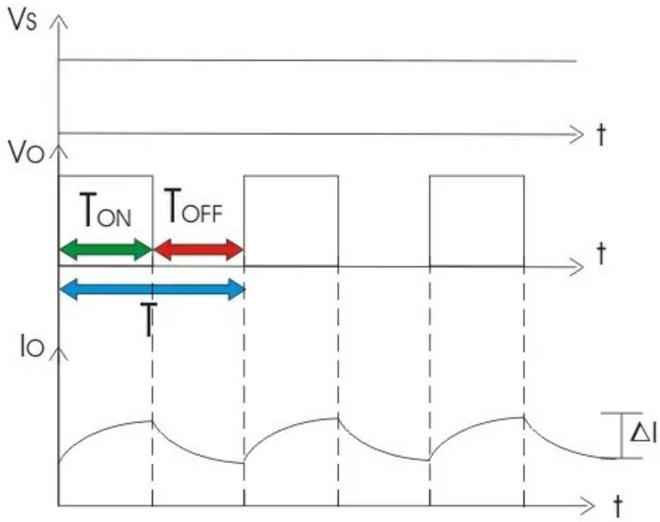
$$Therefore,\ V_o = \frac{T_{ON}}{T}V_s = DV_s$$

So, from (i) we get,

$$\Delta I = \frac{V_s - DV_s}{L}DT \left[Since,\ D = \frac{T_{ON}}{T}\right]$$

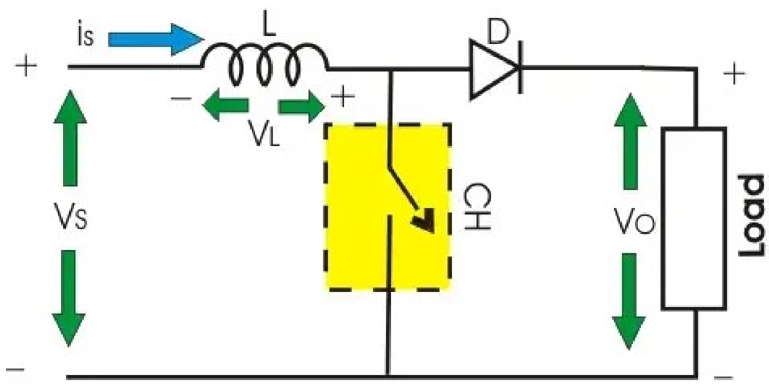
$$= \frac{V_s(1 - D)D}{Lf}\left[f = \frac{1}{T} = Chopping\ Frequency\right]$$

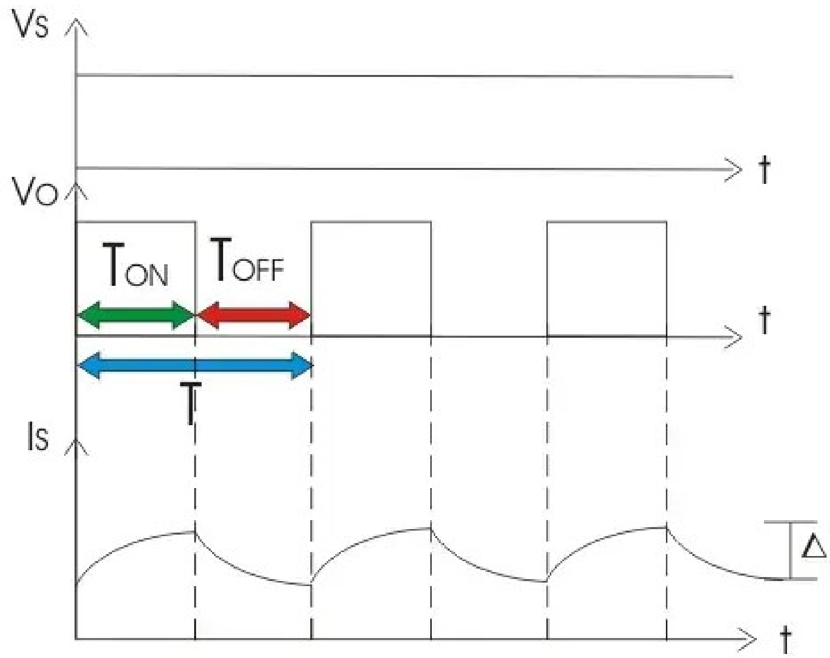
The output voltage and current waveform of step down chopper with inductive load is shown below



2) Step up Chopper or Boost Converter :

Step up chopper or boost converter is used to increase the input voltage level of its output side. Its circuit diagram and waveforms are shown below in figure.

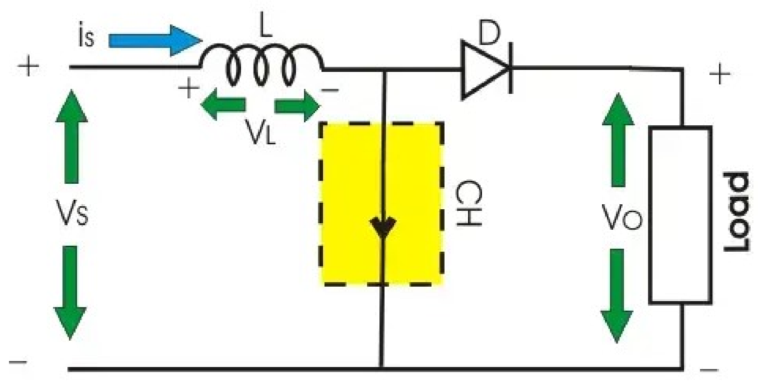




Operation of Step up Chopper

When CH is ON it short circuits the load. Hence output voltage during T_{ON} is zero. During this period inductor gets charged. So, $V_S = V_L$

$$L\frac{di}{dt} = V_s \Rightarrow \frac{\Delta I}{T_{ON}} = \frac{V_s}{L} \Rightarrow \Delta I = \frac{V_s}{L}T_{ON} \cdots (iii)$$

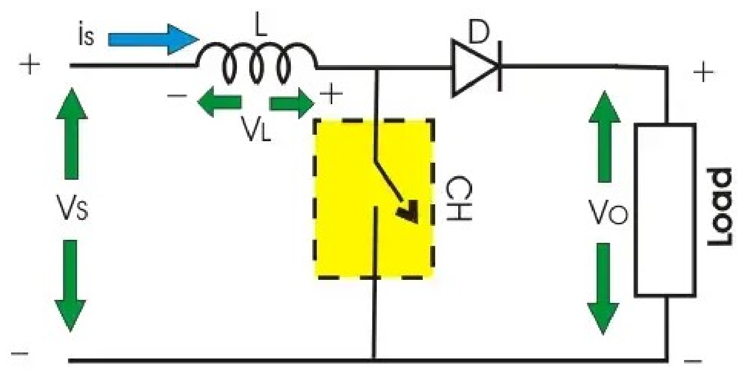


Where, ΔI is the peak to peak inductor current.

When CH is OFF inductor L discharges through the load. So, we will get summation of both source voltage V_S and inductor Voltage V_L as output voltage, i.e.

$$V_o = V_s + V_L \Rightarrow V_L = V_o - V_s \Rightarrow L\frac{di}{dt} = V_o - V_s$$

$$\Rightarrow L\frac{\Delta I}{T_{OFF}} = V_o - V_s \Rightarrow \Delta I = \frac{V_o - V_s}{L}T_{OFF} \cdots \cdot (iv)$$



Now, by equating (iii) and (iv),

$$\frac{V_s}{L}T_{ON} = \frac{V_o - V_s}{L}T_{OFF} \Rightarrow V_s(T_{ON} + T_{OFF}) = V_o T_{OFF}$$

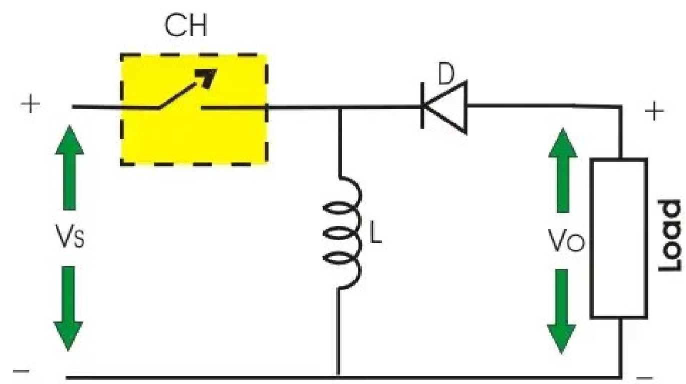
$$\Rightarrow V_o = \frac{TV_s}{T_{OFF}} = \frac{V_s}{(T - T_{ON})/T}$$

$$Therefore,\ average\ output\ voltage,\ V_o = \frac{V_s}{1 - D}$$

As we can vary TON from 0 to T, so $0 \leq D \leq 1$. Hence V_O can be varied from V_S to ∞. It is clear that output voltage is always greater than the input voltage and hence it boost up or increase the voltage level.

Buck-Boost Converter or Step Up Step Down Converter

With the help of Buck-Boost converter we can increase or decrease the input voltage level at its output side as per our requirement. The circuit diagram of this converter is shown below.



Operation of Buck-Boost Converter

When CH is ON source voltage will be applied across inductor L and it will be charged.

So $V_L = V_S$

$$L\frac{di}{dt} = V_s \Rightarrow \Delta I = \frac{V_s}{L}T_{ON}$$

$$\Rightarrow \Delta I = \frac{V_s}{L}T\frac{T_{ON}}{T}$$

$$\Delta I = \frac{DV_s}{Lf}\left[Since, \frac{T_{ON}}{T} = D\ and\ \frac{1}{T} = f = Chopping\ Frequency\right]\cdots\cdot(v)$$

When chopper is OFF inductor L reverses its polarity and discharges through load and diode, So.

$$V_o = -V_L$$

$$L\frac{di}{dt} = -V_o \Rightarrow L\frac{\Delta I}{T_{OFF}} = -V_o \Rightarrow |DeltaI = -\frac{V_o}{L}T_{OFF}\cdots\cdot(vi)$$

By evaluating (v) and (vi) we get,

$$\frac{DV_s}{fL} = -\frac{V_0}{L}T_{OFF} \Rightarrow DV_s = -V_o T_{OFF} f$$

$$DV_s = -V_o \frac{T - T_{ON}}{T} = -V_o \left(1 - \frac{T_{ON}}{T}\right) \Rightarrow V_o = -\frac{DV_s}{1 - D}$$

$$\left[Since, D = \frac{T_{ON}}{T} = \frac{T - T_{OFF}}{T}\right]$$

Taking magnitude we get,

$$V_o = \frac{DV_s}{1 - D}$$

D can be varied from 0 to one.

When, D = 0; $V_o = 0$

When D = 0.5, V_o = VS

When, D = 1, $V_o = \infty$

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

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