Introduction

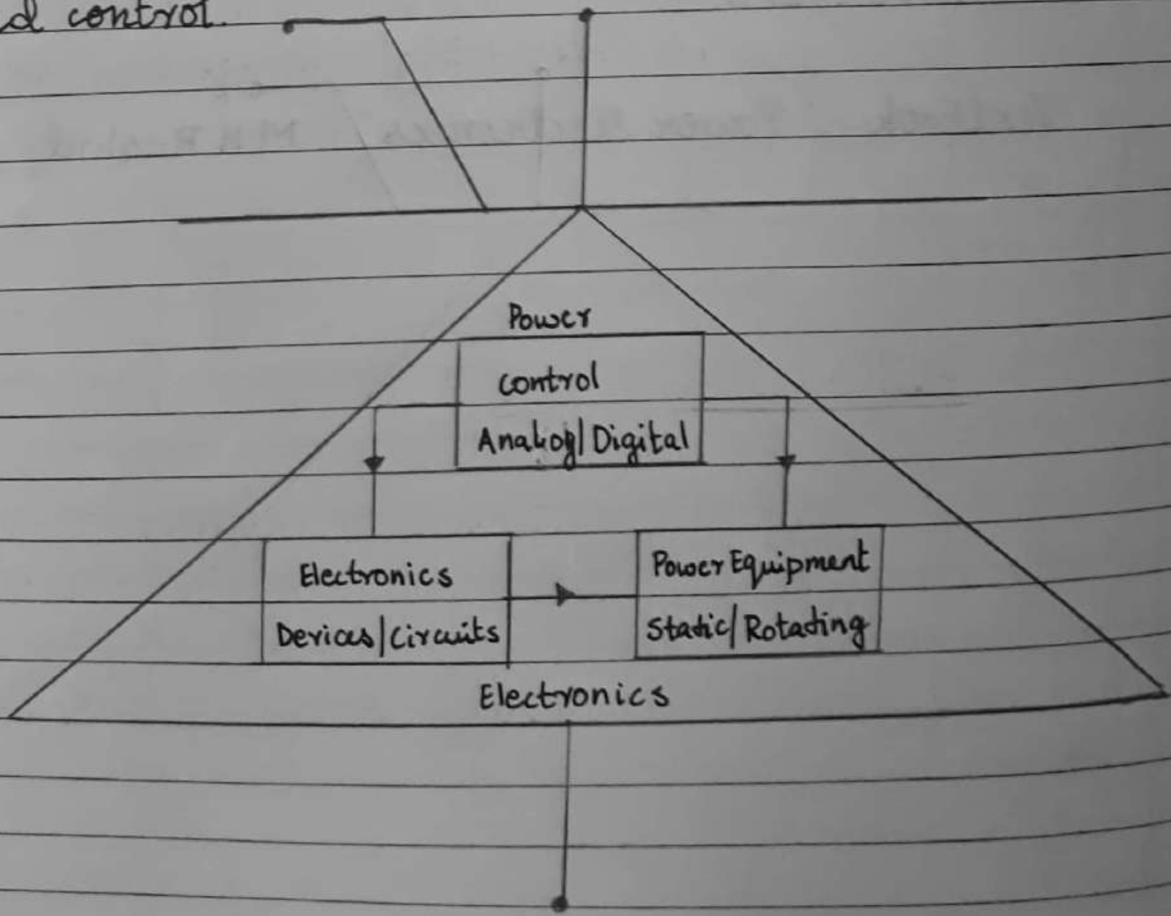
- Power electronics combine power, electronics and control.

  a. Power deals with the static and rotatory power equipment for the generation, transmission and distribution of electrical energy.

  b. Electronics deals with the solid-state devices and circuits for signal processing.

  c. Control deals with the steady state and dynamic characteristics of closed-loop systems.

- Interrelationship of power electronics with power, electronics and control.



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Unit - 1

POWER SEMICONDUCTOR DEVICES

* Power Semiconductor Devices:

Power semiconductor devices are broadly classified as:

1. Power Diodes
2. Thyristors
3. Power Bipolar Junction Transistors (BJT's)
   (high voltage and current rating)
4. Power Metal Oxide Semiconductor Field-Effect Transistors (MOSFET's)
   (high switching speed)
5. Insulated-gate Bipolar Transistors (IGBT's)
   (both high voltage and current rating and high switching speed)

and Static Induction Transistors (SIT's)

* Thyristors:

Thyristors can be further classified into eight types

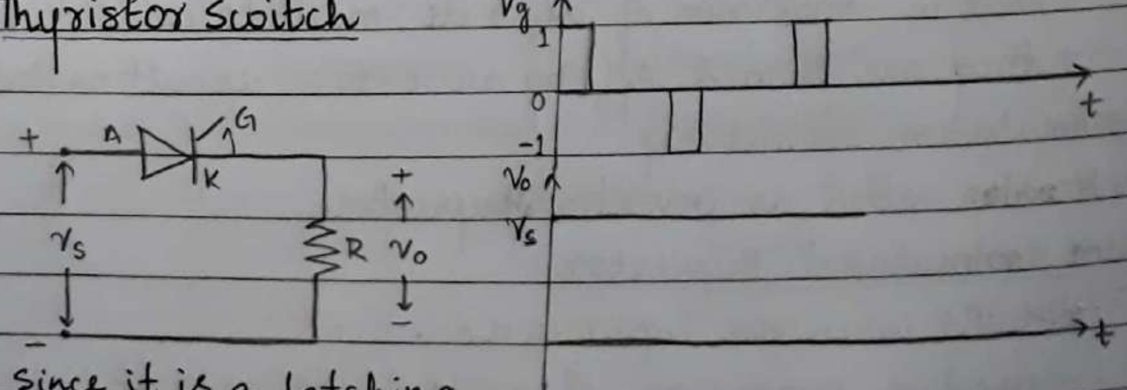
1. Forced Commutated Thyristor
   - used when the input is dc.
   - used in conversion of dc to dc or dc to ac
   - they are turned off by an extra circuit called commutation circuitary.
   - also called as inverter thyristor.
2. Line Commutated Thyristor
   - used when the input is ac.
   - used in conversion of ac to dc or ac to ac.
   - they are turned off due to the sinusoidal nature of input.
   - also called as phase control thyristor.
3. Gate turn-off Thyristor (GTO's)
   - They are self-turned off thyristors.

- They are turned on by applying a short positive pulse to the gates and are turned off by applying a short negative pulse to the gates.
- They donot require any commutation circuit.

4. Reverse-Conducting Thyristors: (RCT'S)
   - high speed switching
   - they conduct in both the directions.
5. Static Induction thyristors: (SIT'S)
   - they are similar to GTO's.
6. Gate-Assisted turn-off Thyristors: (GATT's)
   - they are similar to RCT'S.
7. Light Activated Silicon controlled Rectifier (LASCR's)
   - the input to LASCR's is light and not current.
8. MOS turn-off Thyristors (MTO's)
   - it is a combination of a GTO and a MOSFET which together overcome the limitations of the GTO turn off ability.
   - they are similar to GTO's. (high current and high voltage)

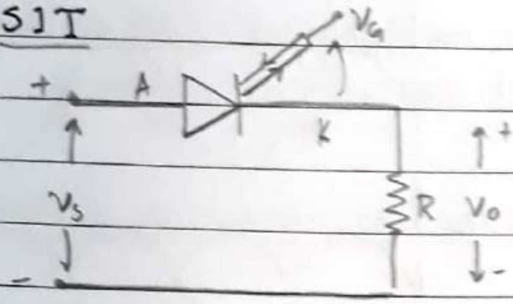
* Control Characteristics of Power Devices:

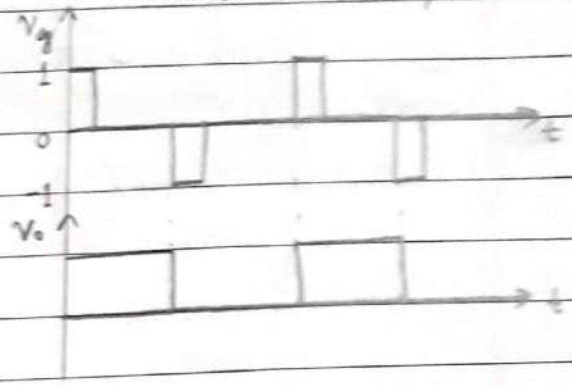
1. Thyristor switch



Since it is a latching device, once turned on there will be no effect of gate similar to GTO's, MTO's

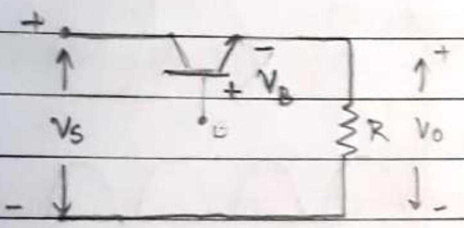
2. SJT

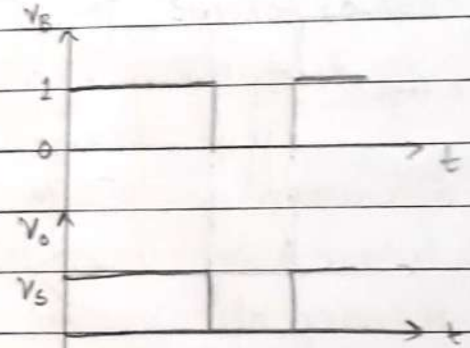




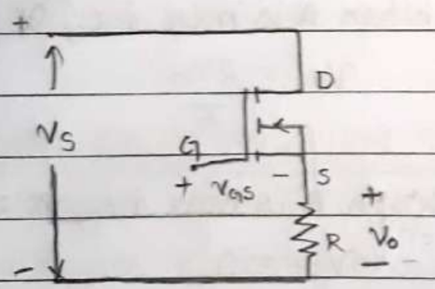
turns on - positive gate pulse
turns off - negative gate pulse

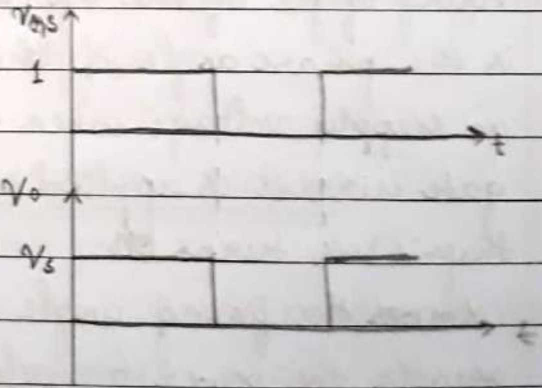
3. Transistor switch





4. MOSFET | IGBT as switch

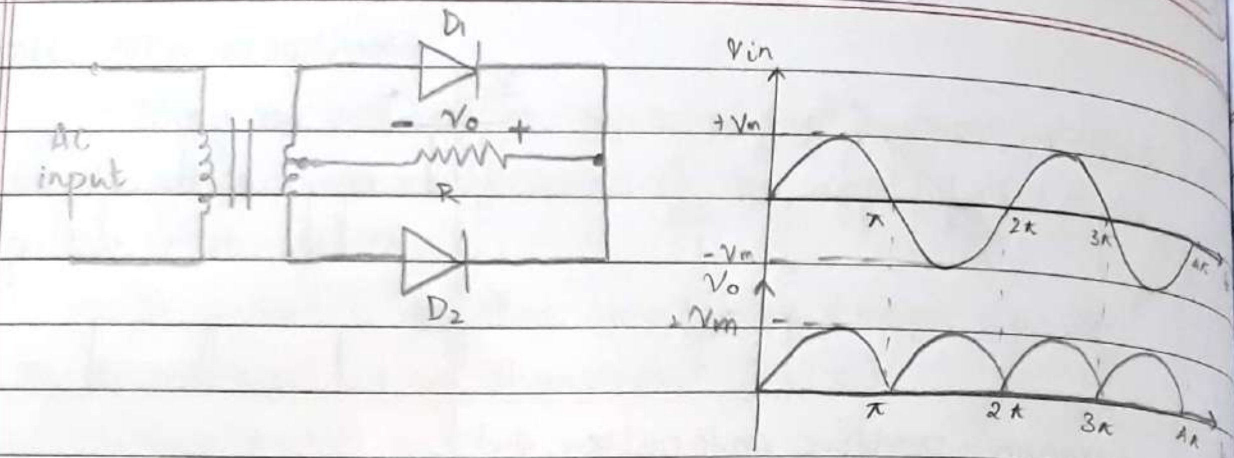




when V_{GS} is zero, MOSFET is in cut off hence switched off.
similar BJT, but MOSFET has higher switching speed.

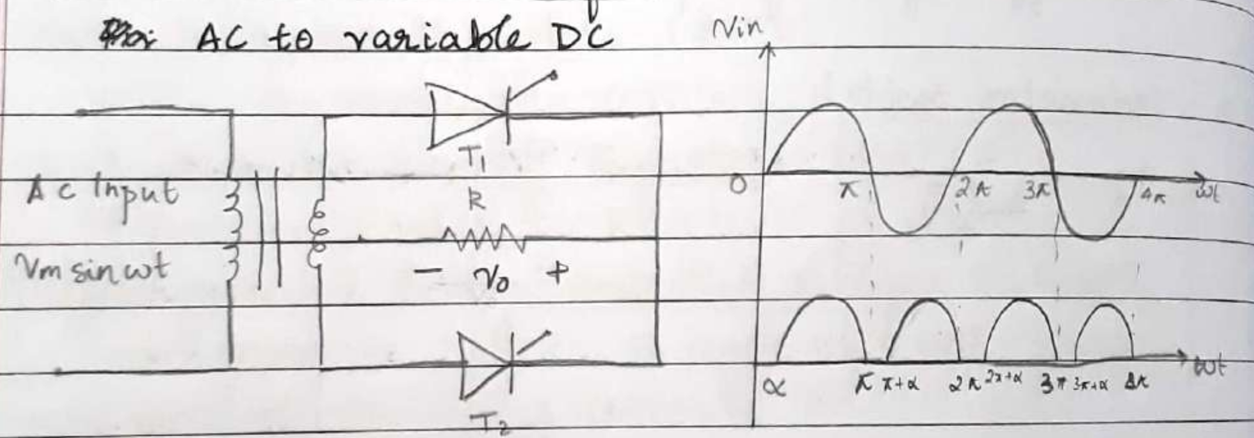
★ Types of Power Electronic circuits:

1. AC to DC : Diode rectifier
AC to pulsating DC by full wave rectifier



2. AC – DC controlled Rectifiers

AC to variable DC



Firing angle : $\alpha_1 = \alpha_2 = \alpha$

Firing angle of the thyristor is the phase angle of the ac supply voltage when the gate current is applied and thyristor turns on.

Lower the firing angle greater the power transfered to the load.

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

When α is min i.e., $\alpha = 0$

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

When α is max i.e., $\alpha = \pi$

$$V_{DC} = 0$$

$\Rightarrow$ α is inversely proportional to V_{DC}

3. DC to AC : Inverters

Fixed DC to AC.

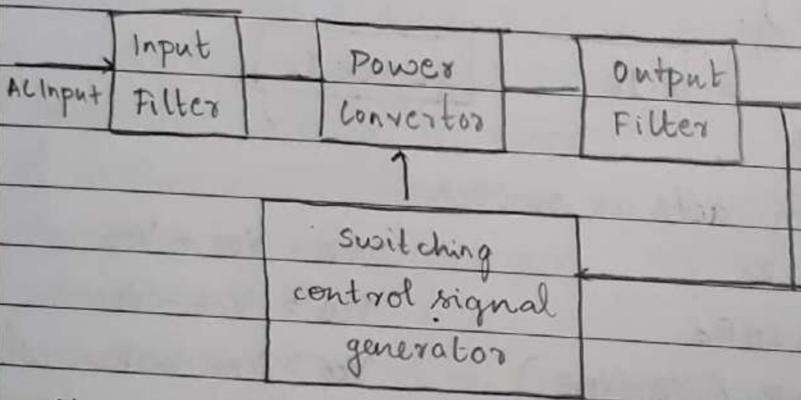
Used in UPS.

For faster switching MOSFET is used.

4. DC to DC : Choppers
Fixed DC to variable DC   textbook pg 31

5. Static Switches : contractors

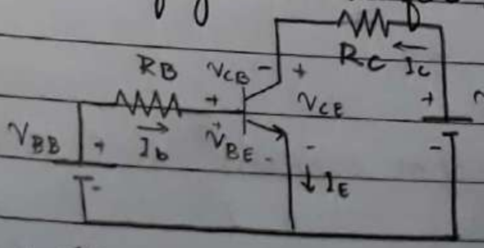
★ Peripheral Effects:
When Power converters are used Harmonic Distortion and RF Interference is induced which is unwanted.

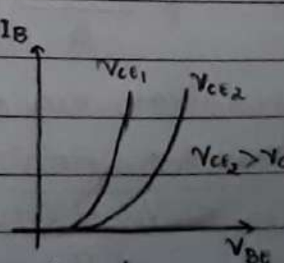


Grounded shielding
- thin metal foil connected to ground.

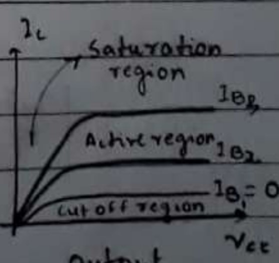
Along with output filter even grounded sheilding helps reducting these peripheral effects.

★ BIPOLAR JUNCTION TRANSISTORS (BJT's):
- Types of BJT's : npn and pnp
- Types of configurations : CE, CB, CC configurations.
CE configuration for switches





Input characteristics



Output characteristics

at cut off region - open switch
at saturation region it acts as a switch.

$\boxed{I_E = I_C + I_B}$; $I_C = \beta I_B$

$\Rightarrow I_E = (1+\beta) I_B$

$I_C = \beta I_B + I_{CBO}$ where I_{CBO} : leakage current in collector base junction.

$\therefore I_E = I_B(1+\beta) + I_{CBO}$

since I_{CBO} is very small it is neglected.

$\Rightarrow \boxed{I_E = I_B(1+\beta)}$

$I_E = \frac{I_C}{\beta}(1+\beta) = I_C\left(1 + \frac{1}{\beta}\right)$

$$I_E = I_C\left(\frac{1+\beta}{\beta}\right)$$

$\Rightarrow I_C = \frac{I_E\beta}{1+\beta} = \alpha I_E \quad \therefore \boxed{I_C = \alpha I_E}$

When transistor acts as switch

$V_{CE} = V_{CC} - I_C R_C$

$V_{CE} = V_{CC} - \beta I_B R_C$

$V_{CE} = V_{CC} - \beta R_C\left(\frac{V_B - V_{BE}}{R_B}\right)$

$V_{CE} = V_{BE} + V_{CB}$

$V_{CB} = V_{CE} - V_{BE}$

$V_{CE} > V_{BE}$ when collector base junction is reverse biased

Maximum collector current in active region is when $V_{CB} = 0 \Rightarrow V_{CE} = V_{BE}$

$$I_{C_{max}} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC} - V_{BE}}{R_C}$$

Maximum corresponding base current

$$I_{B_{max}} = \frac{I_{C_{max}}}{\beta}$$

Saturaturation region

I_{CS} - saturation collector current

$$\boxed{I_{CS} = \frac{V_{CC} - V_{CE(sat)}}{R_C}}$$

corresponding saturation base current

$$\boxed{I_{BS} = \frac{I_{CS}}{\beta_{min}}} \qquad I_B > I_{BS}.$$

β_{min} because $I_B \propto \frac{1}{\beta}$

over drive factor (ODF)

It is the ratio of I_B to I_{BS}

$$\boxed{ODF = \frac{I_B}{I_{BS}}}$$

Total ON state Power loss

$P_T = V_{BE_{sat}} I_B + V_{CE_{sat}} I_{C_{sat}}$

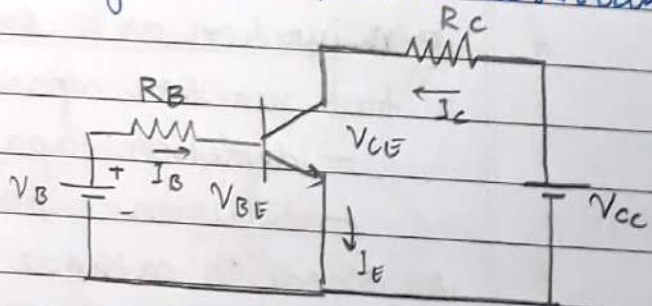
it is terms of w or kW.

Forced β

It is the ratio of I_{CS} to I_B

$$\boxed{\beta_f = \frac{I_{CS}}{I_B}}$$

Q: For the circuit shown β is in range 8 to 40, load resistance $R_C = 11\Omega$, dc supply $V_{CC} = 200V$, input base voltage $V_B = 10V$. If V_{CE} at saturation is 1V, V_{BE} at saturation is 1.5V calculate:



i. value of R_B that results in saturation with an over drive factor is 5.

ii. forced β.

iii. total power loss.

sol: Given: $\beta = 8 - 40$ $\quad V_{CE\,sat} = 1V$

$R_C = 11\Omega$ $\quad V_{BE_{sat}} = 1.5V$

$V_{CC} = 200V$ $\quad ODF = 5$

$V_B = 10V$ $\quad \beta_{max} = 40 \quad \beta_{min} = 8$

@ saturation

$$I_{CS} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{200-1}{11} = 18.09A$$

$$I_{BS} = \frac{I_{CS}}{\beta_{min}} = \frac{18.09}{8} = 2.26A$$

$$ODF = \frac{I_B}{I_{BS}} \Rightarrow I_B = ODF \times I_{BS} = 5 \times 2.26 = 11.3A$$

i. $R_B = \dfrac{V_B - V_{BEsat}}{I_B} = \dfrac{10-1.5}{11.3} = \underline{\underline{0.75\Omega}}$

ii. Forced β

$$\beta_f = \frac{I_{CS}}{I_B} = \frac{18.09}{11.3} = \underline{\underline{1.6}}$$

iii. Total power loss.

$$P_T = V_{BE_{sat}} I_B + V_{CE_{sat}} I_{C_{sat}}$$

$$\underline{\underline{P_T = 35.04}}$$

* **P-n junction as a switch**

two junction capacitance

- depletion capacitance
- diffusion capacitance

As anode to cathode voltage increases the depletion capacitance decreases and almost acts as short circuit.

* **Switching characteristics**

→ Forward biased pn junction diode has two parallel capacitances

- depletion capacitance
- diffusion capacitance

Reverse biased pn junction diode

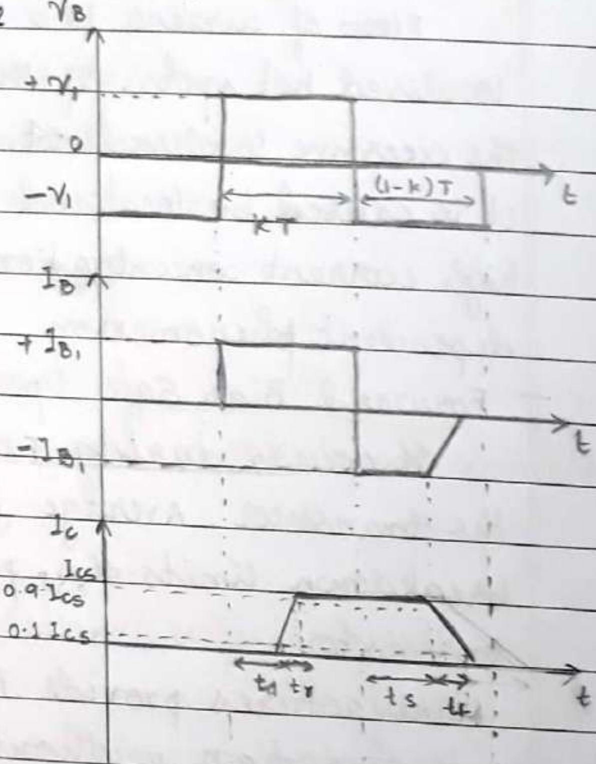
- depletion capacitance.

→ Under steady state conditions capacitance donot play any role but under transient conditions they influence the turn on and turn off behaviour of the transistor.

Lower the TON and TOFF, faster is the switching.

- t_d - delay time
  time required to charge base emitter junction capacitance and base emitter junction is forward biased.
- t_r - Raise time
  time constant is determined by base emitter junction capacitance.
- t_s - charge storage time
  time required to remove the stored charge.
- t_f - fall time
  time constant of reverse biased base emitter junction capacitance.

Switching characteristics of transistor



Turn ON Time

$$T_{ON} = t_d + t_r$$

Turn OFF Time

$$T_{OFF} = t_s + t_f$$

Due to internal capacitance transistor does not turn on immediately.

As input voltage $V_B \uparrow$ from $0 - V_1$, the base current $I_{B_1} \uparrow$ but the collector current does not respond immediately : delay time t_d.

After this delay the collector current $I_C \uparrow$ to steady state value of I_{CS}. The rise time t_r depends on the time constant determined by the base emitter junction capacitance.

As input voltage is reversed from V_1 to $-V_1$, the base current reduces to $-I_{B_1}$ but the collector current doesnot change for a time t_s: storage time. Higher the I_C, higher the t_s.

Once the storage charge is removed, the base emitter junction capacitance charges to $-V_1$ and $I_{B_1} = 0$. The fall time t_f depends on the time constant determined by the reverse biased base emitter junction capacitance.

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* Switching limits:

- Secondary breakdown

Flow of current to a small portion of base, produces localised hot spots. If the energy in these hot spots is sufficient the excessive localised heating may damage the transistor. Thus it is caused by localised thermal runaway resulting from high current concentrations. It is basically a energy dependent phenomenon.

- Forward Bias Safe Operating Area (FBSOA)

It occurs during Turn on or ON state condition of the transistor. Average junction temperature or secondary breakdown limits the power handling capacity of the transistor.

Manufactures provide FBSOA curves (I_C versus V_{CE}) for safe operation without damaging the transistor.

- Reverse Bias Safe Operating Area (RBSOA)

Occurs during turn off condition of the transistor, a high current and high voltage must be sustained by the transistor in most cases with the Base Emitter junction reverse biased. The V_{CE} must be held to a safe level at or below a specified value of I_C. The manufacturers provide the $I_C - V_{CE}$ limits during reverse biased turn off as RBSOA

Power derating: Power derating is the operation of a device at less than its rated maximum capacity in order to prolong its life.

- Break down voltages.

It is defined as the absolute maximum voltage between two terminals with the third terminal open, shorted or biased either forward or reverse direction. At breakdown the voltage remains relatively constant whereas the current rises rapidly

★ POWER MOSFET:

- It is a voltage controlled device and requires very small input current.
- High switching speed. (nseconds)
- High frequency low power applications.
- Secondary breakdown does not occur.

Limitations.

- electrostatic discharge
- requires special care or handling.
- difficult to protect MOSFET under short circuit conditions.

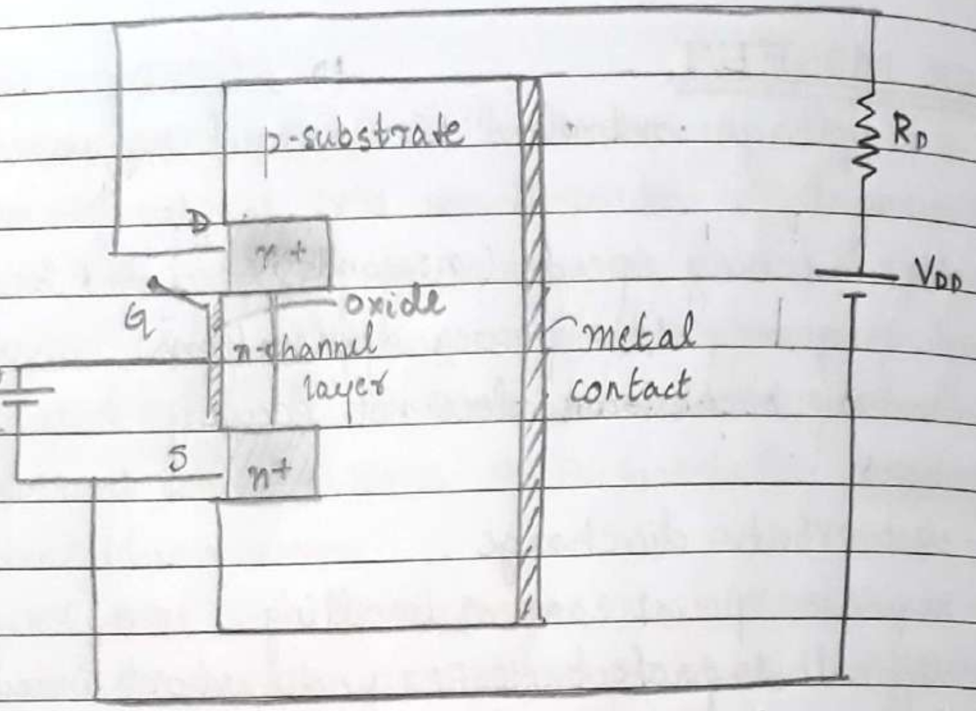
= Types of power MOSFET's.

a. Depletion type:
  - physical layer of channel is present.
  - it is classified into
    1. n-channel
    2. p-channel
  - It requires an additional layer so not preffered usually

b. Enhancement type:
  - virtual layer of channel is present, hence no physical layer of channel is present.
  - it is classified into
    1. n-channel
    2. p-channel
  - As no extra layer for channel is required, it is usually preffered.

★ n-channel Depletion MOSFET:

A physical n-channel is present. It is connected to metal contact through metal oxide layer between the channel and the metal contact.



Input voltage is applied across gate and source terminal.
When V_{GS} is negative it is reverse biased. Hence the electrons of the n channel get repelled due to which depletion region is created below the oxide layer.

- As V_{GS} is made more negative the width of the depletion region increases, reducing the channel width. At a point no current flows from Drain to Source

$$I_{DS} = 0 \text{ and } R_{DS} \text{ is maximum.}$$

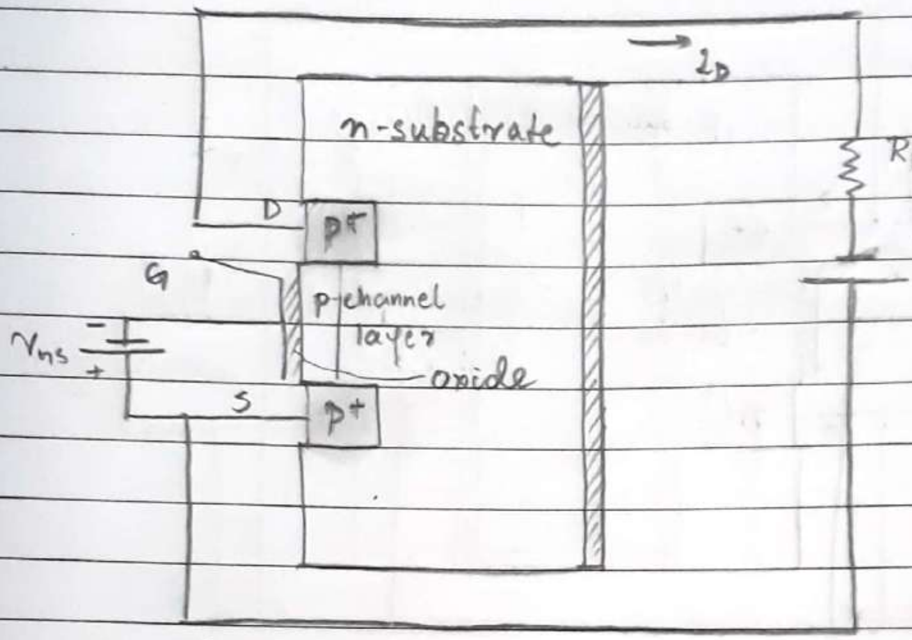
The value of V_{GS} at which I_{DS} is reduced to zero is called pinch off voltage.

- As V_{GS} is made positive the width of the depletion region decreases, increasing the channel width. in turn increasing current I_{DS} as R_{DS} reduces.

* p-channel Depletion MOSFET:

A physical p-channel is present. It is connected to a metal contact through metal oxide.

A physical layer is required hence enhancement type is preferred than depletion type MOSFET.

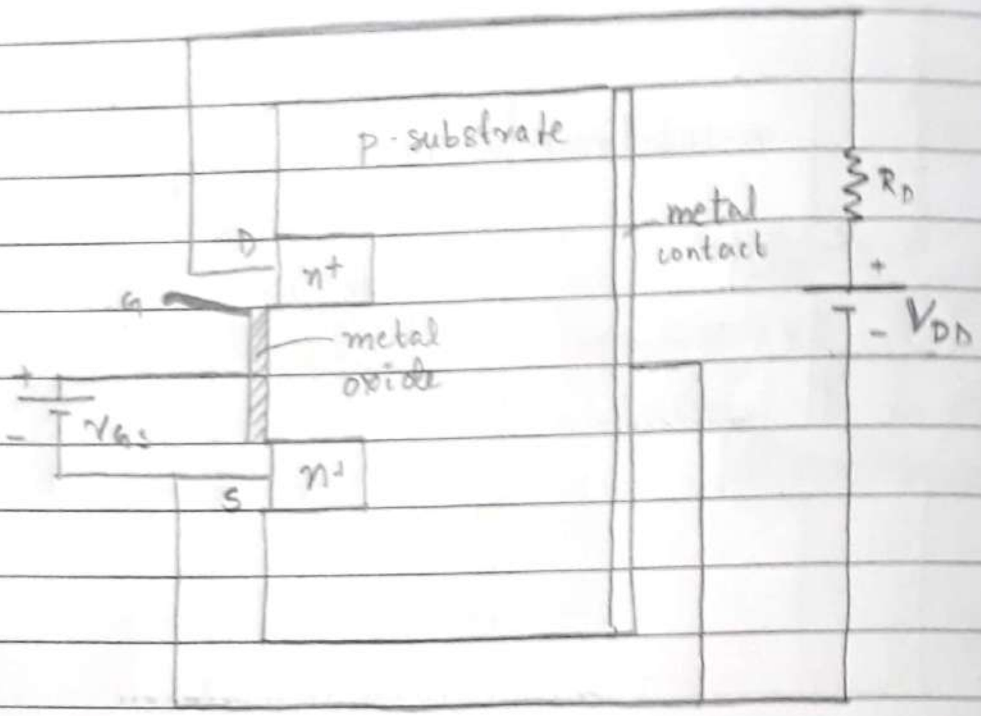


Input voltage is applied across gate and source terminal (V_{GS})
When V_{GS} is negative it is reverse biased. Hence the holes of the p-channel get repelled due to which depletion region is created below the oxide layer.

- As V_{GS} is made negative the width of the depletion region increases, reducing the channel width.
At a point no current flows from drain to source.
$I_{DS} = 0$ and R_{DS} is maximum.
The value of V_{GS} at which I_{DS} is reduced to zero is called the pinch off voltage.

- As V_{GS} is made positive the width of the depletion region decreases, increasing the channel width in turn increasing current I_{DS} as R_{DS} reduces.

* n-channel Enhancement MOSFET:
No physical layer of n-channel is present there is only a virtual n-channel.
Power MOSFET is generally Enhancement type as it is cost effective as no extra layer for channel is required.



Input voltage is applied across gate and source terminal. When V_{GS} is positive it is forward biased. The minority charge carriers present in the p-substrate (i.e., electrons) accumulate below the metal oxide layer forming a virtual layer of n-channel. This causes flow of electrons i.e., current flows from drain to source terminal, when $V_{GS} \geq V_T$ (threshold voltage).

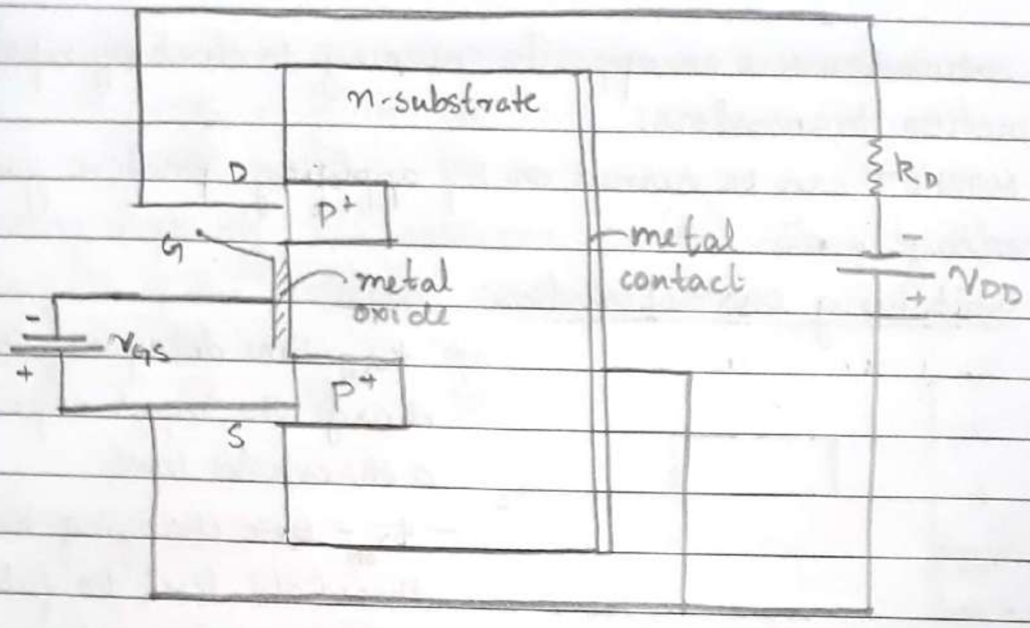
The formation of the n-channel is due to the induced voltage.

★ p-channel Enhancement MOSFET:

No physical layer of p-channel is present, there is only formation of a virtual channel.

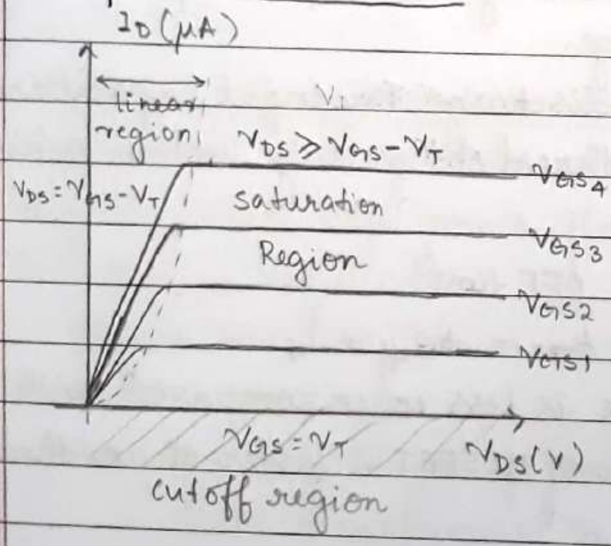
Input voltage is applied across gate and source terminal. When V_{GS} is positive it is forward biased. The minority charge carriers (holes) present in the n-substrate accumulates below the metal oxide layer forming a virtual layer of p-channel. This causes flow of current from drain to source terminal when $V_{GS} \geq V_T$ (threshold voltage).

The formation of the p-channel is due to the induced voltage



Steady State Characteristics of MOSFET:

Output Characteristics



The MOSFET conducts only when $V_{GS} \geq V_T$ (threshold voltage).
Assuming there is no effect of junction capacitances
It has three regions

1. cut off region
   $I_D = 0$, channel is narrow depletion is wide, hence the MOSFET is off.
   that is $V_{GS} \leq V_T$

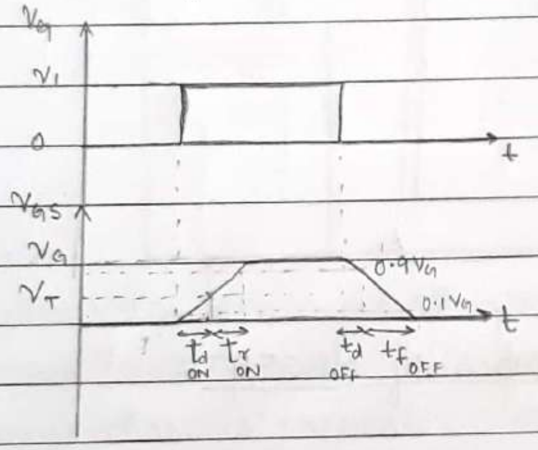
2. Linear region
   Switching action can be observed as I_D varies in proportion with V_{DS}.

3. Saturation region
   The drain current is almost constant, hence the MOSFET is on. It is also known as pinch off region (even if $I_D \neq 0$ as it is constant it is called as pinch off region)

Saturation has an opposite meaning to that of bipolar junction transistors.

MOSFET can be turned on by applying positive gate voltage.

Switching characteristics:



- $t_{d_{ON}}$ – time delay required to charge the input capacitance to a threshold level.
- $t_{r_{ON}}$ – Gate charging time from threshold level to full gate voltage to drive transistor to linear region. It is called the rise time.
- $t_{d_{OFF}}$ – time required to discharge the input capacitance from V_1 to pinch off voltage.
- $t_{f_{OFF}}$ – time required to discharge the input capacitance from pinch off voltage to threshold voltage below which the transistor is off.

On time

$$t_{ON} = t_{d_{ON}} + t_r$$

OFF time

$$t_{OFF} = t_{d_{off}} + t_f$$

The on time and off time is less when compared with BJT's. Hence the switching action of MOSFET is faster than that of BJT.

* **di/dt and dv/dt limitations:**

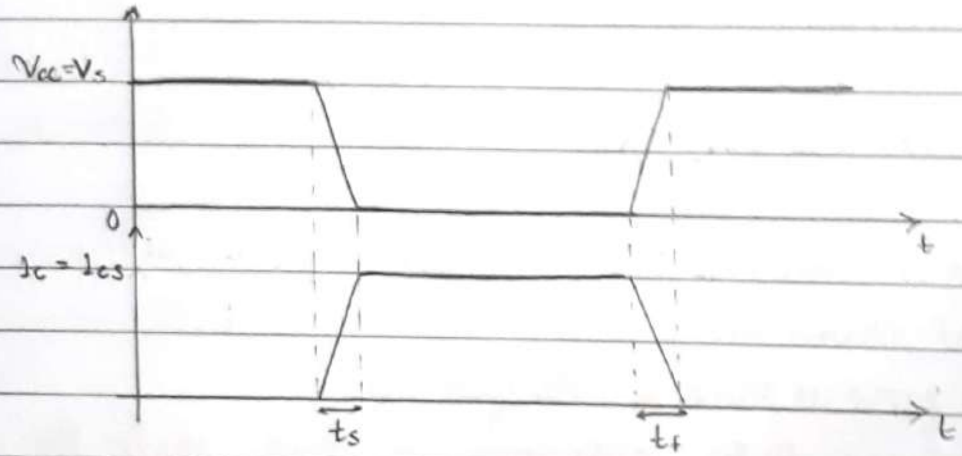
The conditions di/dt and dv/dt are set by the transistor switching characteristics and must be satisfied during turn-on and turn-off. Protection circuits are used to keep the operating di/dt and dv/dt in the allowable limits. To limit dv/dt a RC network across the transistor known as snubber circuit is used and to limit di/dt an inductor L_s is used which is known as series snubber.

During turn-on, the collector current rises and V_{ce} decreases

$$\frac{di}{dt} = \frac{I_L}{t_r} = \frac{I_{cs}}{t_r}$$

During turn-off, the collector-emitter voltage rises in relation to the fall of the collector current.

$$\frac{dv}{dt} = \frac{V_s}{t_f} = \frac{V_{cs}}{t_f}$$



$t_{ON} = t_{dON} + t_r$

$t_{OFF} = t_s + t_f$

Neglecting t_{dON} and t_s for BJT,

★ <u>Isolation of Gate or base drives:</u>

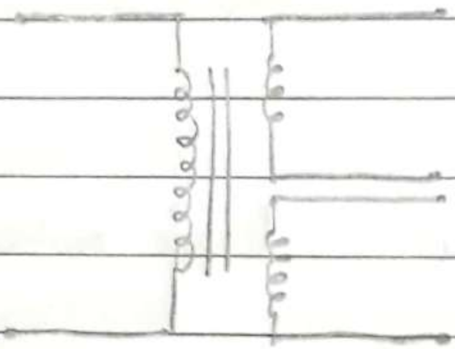
If BJT is damaged the collector-base junction gets shorted due to which high power flows into trigger circuit. Hence isolation is required.

This is because power circuits operate at high power levels (>200V) and whereas trigger circuits operate at low power levels.

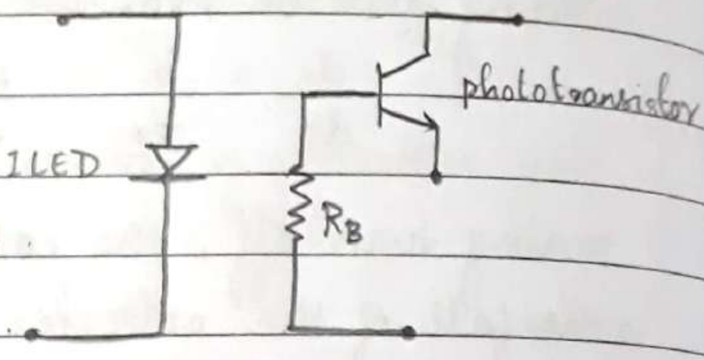
There are two ways of isolations:

1. <u>Pulse transformers</u>: They have one primary winding and one or more secondary windings. Multiple secondary windings allow simultaneous gating signals to series and parallel connected transistors.

2. <u>Optocouplers</u>: It combines an infrared light-emitting diode (ILED) and a silicon phototransistor. The input signal is applied to the ILED and the output is taken from the phototransistor.



pulse transformers

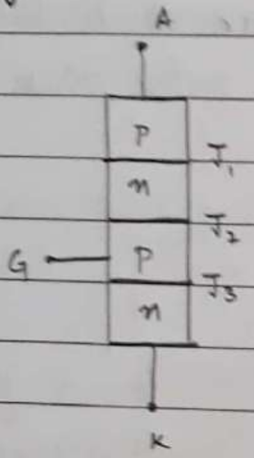


opto coupler

Unit - 2

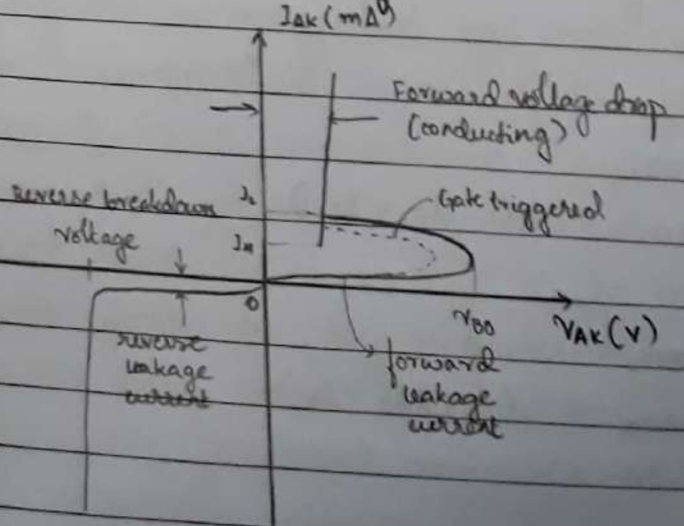
THYRISTORS:

* Thyristors: SCR



→ When V_{AK} is positive
Junctions J_1 and J_3 are forward biased and J_2 is reverse biased.
→ When V_{AK} is increased, the junction J_2 breakdowns and I_{AK} starts to flow.

Before J_2 breakdowns: a small leakage current flows from anode to cathode. Then the thyristor is said to be at forward blocking or off state. Once V_{AK} increases and J_2 breakdowns it is known as avalanche breakdown and the corresponding voltage is called forward breakover voltage V_{BO}. Now the device is at conducting state or on state.



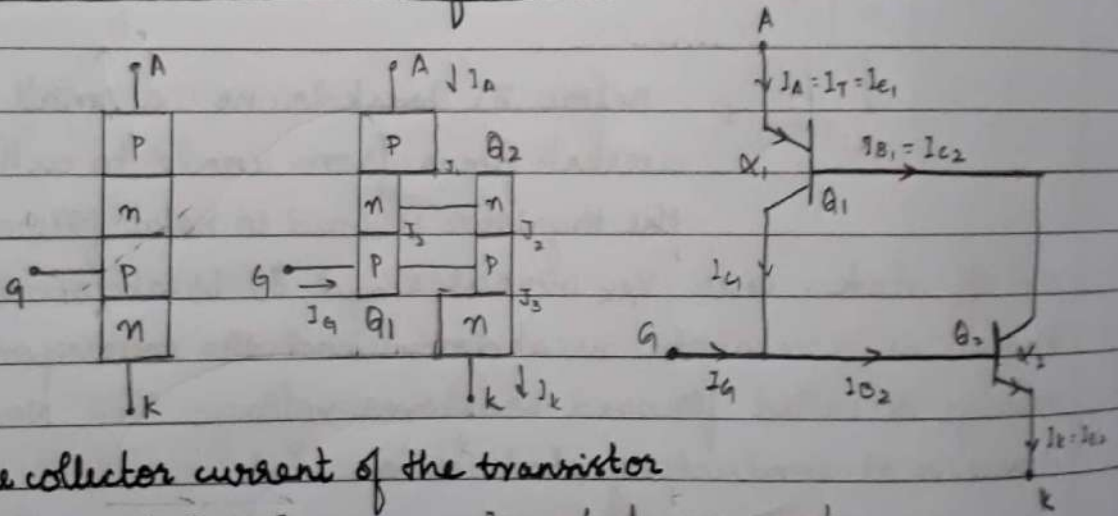
v.i characteristics.

Latching current
I_L is the minimum anode current required to maintain the thyristor in the on-state immediately after a thyristor has been turned on and the gate signal has been removed

Holding current: I_H is the minimum anode current to maintain the thyristor in on state. The holding current is less than the latching current.

- The forward anode current of a thyristor must be more than its latching current to latch into the conduction state.
- If the forward anode current of a thyristor is reduced below its holding current, the device becomes unlatched and remains in the blocking state.
- Once a thyristor conducts, it acts like a conducting diode and cannot be turned off by any gate pulse. There is no control over the device.

★ **Two Transistor model for SCR :**



The collector current of the transistor

$I_C = \alpha I_E + I_{CBO}$ $\quad$ I_{CBO} - leakage current

For transistor Q_1

$I_{C_1} = \alpha_1 I_{E_1} + I_{CBO_1}$

$I_{C_1} = \alpha_1 I_A + I_{CBO_1}$ $\quad (\because I_{E_1} = I_A)$

For transistor Q_2

$I_{C_2} = \alpha_2 I_{E_2} + I_{CBO_2}$

$I_{C_2} = \alpha_2 I_K + I_{CBO_2}$ $\quad (\because I_{E_2} = I_K)$

wkt

$I_{E_1} = I_{B_1} + I_{C_1}$

$I_A = I_{C_2} + I_{C_1}$ $\quad (\because I_{E_1} = I_A$ and $I_{B_1} = I_{C_2})$

Substituting I_{C_1} and I_{C_2}, we get

$I_A = \alpha_1 I_A + I_{CBO_1} + \alpha_2 I_K + I_{CBO_2}$ —— ①

For a gating current of I_G,

$$I_K = I_G + I_A$$

substituting in eq ①

$$I_A = \alpha_1 I_A + \alpha_2 (I_A + I_G) + I_{CBO_1} + I_{CBO_2}$$

$$I_A = I_A(\alpha_1 + \alpha_2) + \alpha_2 I_G + I_{CBO_1} + I_{CBO_2}$$

$$I_A[1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_G + I_{CBO_1} + I_{CBO_2}$$

$$I_A = \frac{\alpha_2 I_G + I_{CBO_1} + I_{CBO_2}}{[1 - (\alpha_1 + \alpha_2)]}$$

since I_{CBO_1} and I_{CBO_2} are very small leakage currents

$$\boxed{I_A = \frac{\alpha_2 I_G}{1 - (\alpha_1 + \alpha_2)}}$$

If $\alpha_1 + \alpha_2 = 1$, then $I_A = \infty$, i.e., the anode current suddenly attains a very high value approching ∞. So we say that the device latches to condition with a small gate current. This is called as Regenerative Action.

SCR is hence called as latching device.

* Thyristor Turn-ON:

A thyristor is turned on by increasing the anode current. This can be accomplished in one of the following ways:

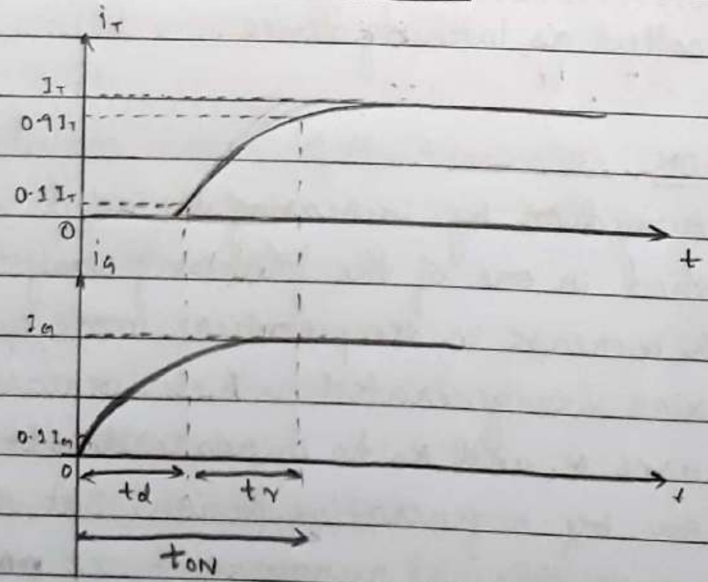
1. Thermal: With increase in temperature more and more electron-hole pairs are generated which increases the leakage currents. This causes α_1 and α_2 to increase due to which the thyristor turns on by regenerative action. But this type of turn-on may cause thermal runaway hence normally avoided.
2. Light: Only for light activated SCR's it is effective. Instead of gate, a silicon window is present through which light is made to fall on the junctions to turn-on the SCR.
3. High voltage: With $I_G = 0$ on increasing forward anode-cathode voltage greater that breakover voltage, sufficient leakage current flows to initiate regenerative turn on. This type of turn on

may be destructive as it can damage the device permanently hence avoided.

4. dv/dt : If the rate of rise of the anode to cathode voltage is high, the charging current of the capacitive junctions may be sufficient enough to turn on the device but the high charging current may damage the thyristor hence the device must be protected against high dv/dt.

5. Gate current: If a thyristor is forward biased by applying positive gate voltage between the gate and cathode terminals turns on the thyristor due to gate current. As the gate current increases forward breakover voltage decreases. Hence it is most suitable, safe, simple and cost effective methods to turn on the SCR.

★ Turn-on characteristics:



I_T - thyristor current
I_G - gate current.

— For designing the gate circuit:

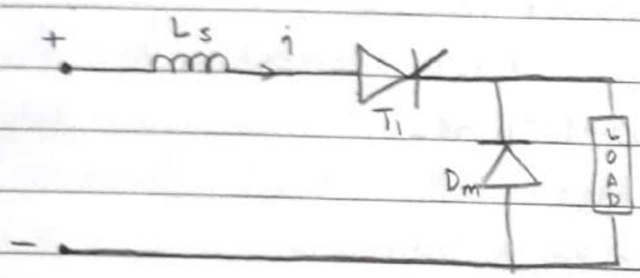
1. The gate signal should be removed after the thyristor is turned on. A continuous gating signal would increase the power loss in the gate junction.

2. During reverse bias condition of thyristor no gate signal should be applied, otherwise the thyristo may fail due

to increase in leakage current.

3. The width of the gate pulse t_g must be longer than the time required for the anode current to rise to latching current value I_L, i.e., $t_G > t_{ON}$ of the thyristor.

★ **di/dt protection:**



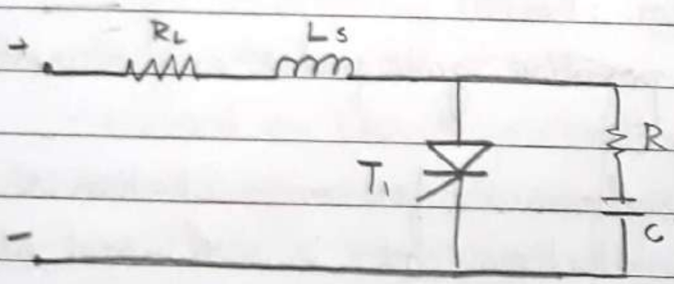
Dm - free wheeling diode

forward $di/dt = V_s / L_s$

For di/dt protection

series snubber circuit.

★ **dv/dt protection:**



For dv/dt protection

RC snubber circuit

★ **Thyristor turn-off:**

When supply is DC, computation is required. Here anode current is maintained below the holding current of SCR sufficiently for a long time.

α - delay angle of thyristor

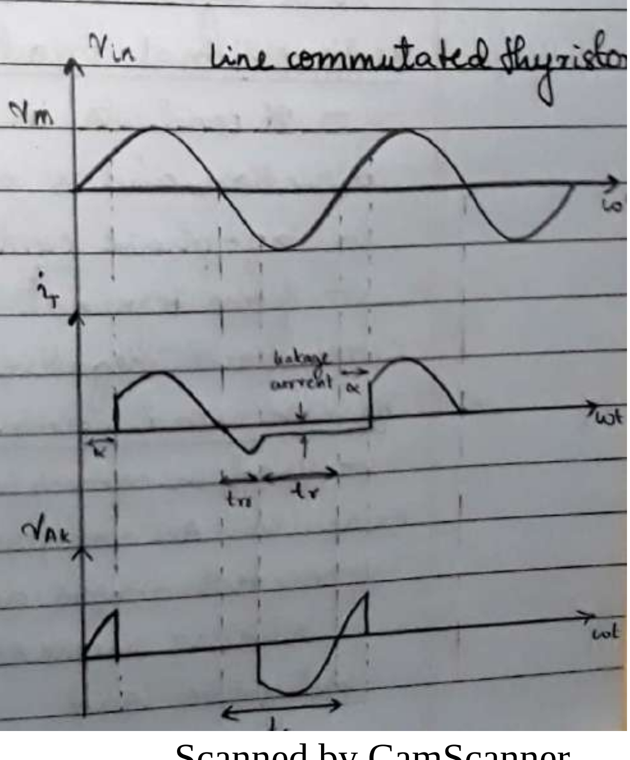
$t_{off} = t_{rr} + t_r$

where t_r - gate recovery time

t_q - turn-off time.

t_{rr} - reverse recovery time.

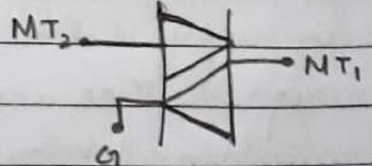
Line commutated thyristor



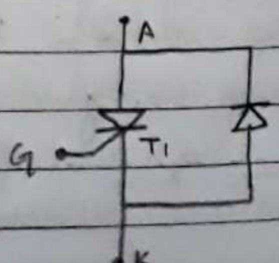
* **Types of Thyristors:**

It is classified based on physical construction and turn-on and turn-off behaviour.

1. **Phase-controlled thyristors (SCR):** converter thyristor
   - operates at line frequency : 230V/50Hz
   - turned off by natural commutation.
   - low speed switching applications
   - low frequency switching operation.
   - turn-off = 50-100μ sec
2. **Fast switching Thyristors** : Invertor thyristor
   - forced commutation is required
   - high speed switching applications
   - turn-off = 5-50μ sec
3. **Gate turn of Thyristor** : (GTO)
   - turned on by positive gate pulse and turned off by negative gate pulse.
   - As no additional circuit for commutation is required, the commutation choke is not used hence it is light and cost effective (Advantage)
4. **Bidirectional triode Thyristors:** (TRIAC's)
   - It conducts in both direction and is normally used in ac-phase control devices.



   - If one terminal is considered positive the other is considered negative as no terminal is assigned as anode or cathode
5. **Reverse-conducting thyristors:** (RCT's)
   - Used in converter and inverter circuits. An antiparallel diode is connected across an SCR to allow a reverse current flow due to inductive load.



6. Static Induction thyristors (SITH's)

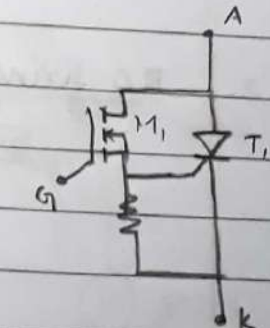
- It is turned on by applying a positive gate voltage with respect to cathode and turned off by applying a negative gate voltage with respect to cathode.
- Faster switching speed when compared to GTO
- turn off = 1-6 μ sec
- high di/dt and dv/dt capability
- Not cost effective.

7. Light Activated SCR's (LASCR's)

- turned on by direct radiation on silicon wafer with light
- high voltage and high current applications.

8. FET-controlled thyristors (FET-CTH's)

- It combines a MOSFET and a thyristor in parallel.
- High switching speed.
- High di/dt and dv/dt
- turned on like thyristor but cannot be turned off by gate control. (semicontrolled switch)

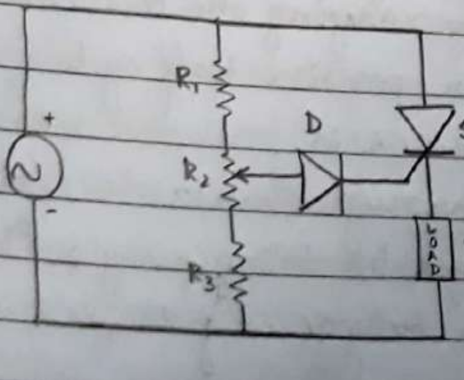


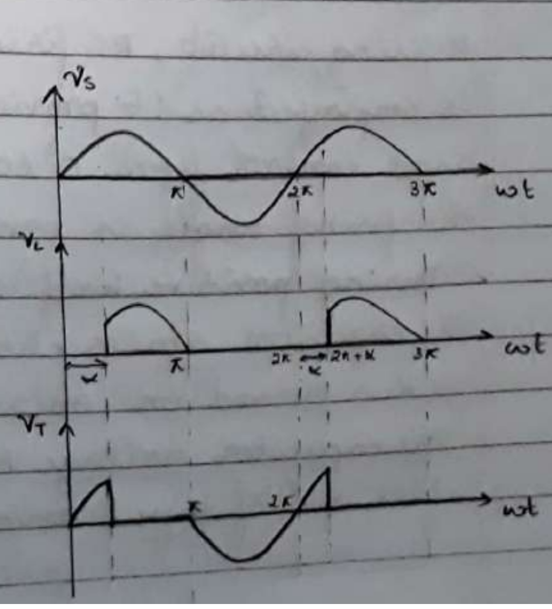
9. MOS controlled Thyristor. (MCT's)

- Fully controlled switch
- high di/dt capability.

* Thyristor Firing circuits:

1. R-firing circuit:





The resistance and diode combination circuit acts as a gate control circuitry to switch the SCR in desired condition.

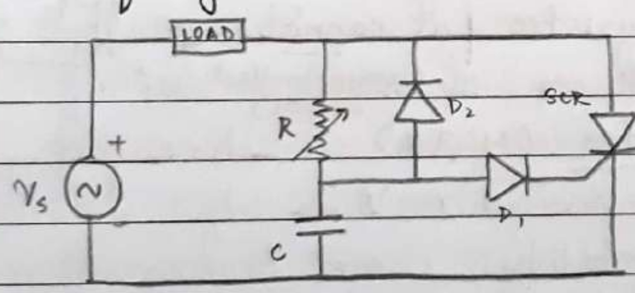
On applying positive voltage the SCR is forward biased and conducts when its gate current is more than minimum gate current required by the SCR to turn on. This can be done by varying the resistance R_2 which inturn varies the gate current.

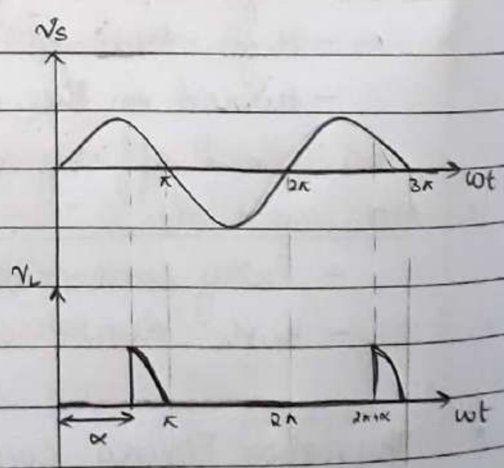
Once the SCR is turn on, load current starts to flow through the SCR.

During negative half cycle the diode protects the gate drive circuit from reverse gate voltage.

Here α can be controlled upto to maximum of $90°$, hence the gate current has to reach minimum between 0-$90°$.

2. RC firing circuit:



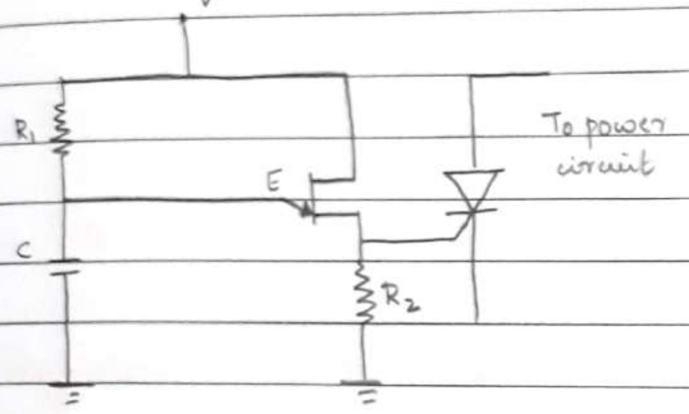


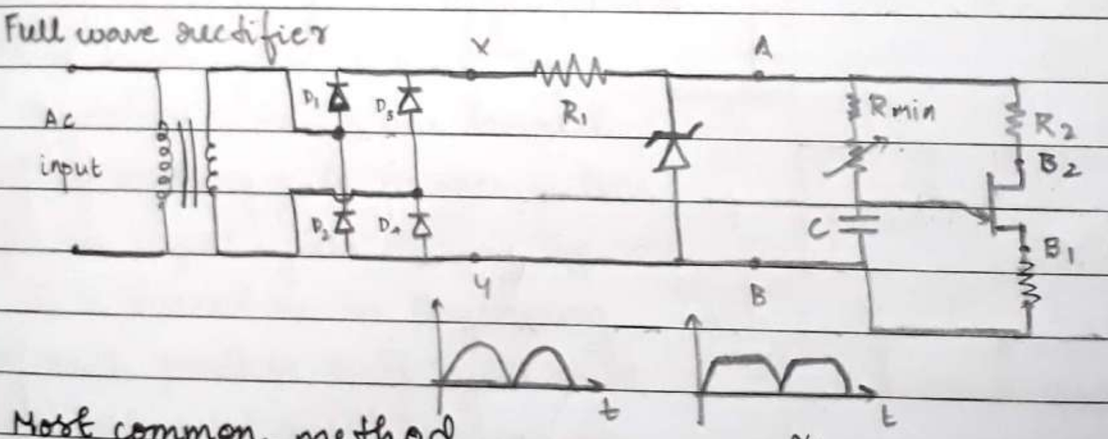
To over come the limitation of R firing circuit, RC firing circuit is employed as it provides the firing angle control from $0°$ to $180°$. By varying the variable resistance the firing angle is controlled in positive half cycle of input.

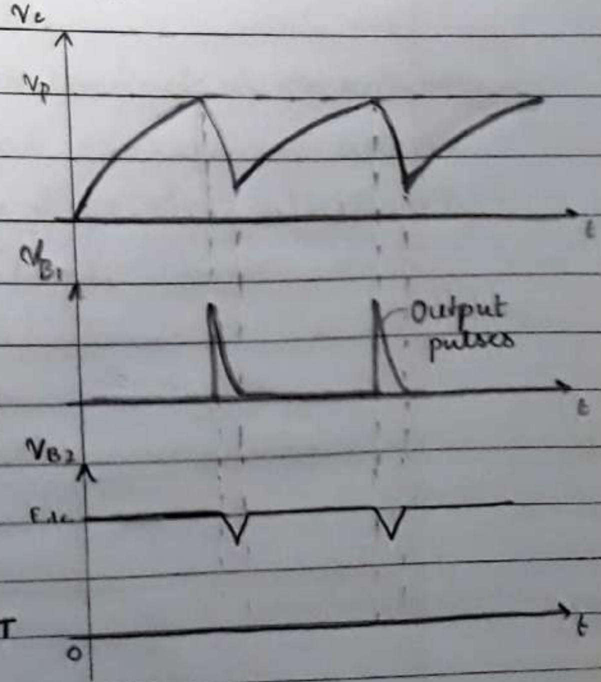
During positive half cycle the SCR is forward biased and the capacitor starts charging through variable resistance. SCR is turned on once it charges to triggering voltage value. The capacitor voltage helps for triggering the SCR even after $90°$ of input waveform.

During negative half cycle, the capacitor charges with lower plate as positive through diode D_2 upto maximum voltage. Diode D_1 prevents the negative voltage between the gate and cathode.

3. UJT firing circuit:







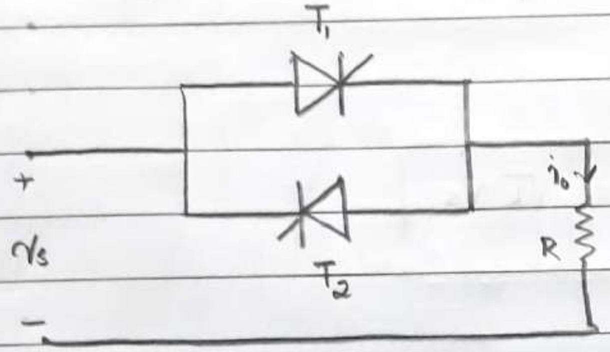
Most common method of triggering the SCR as loss is limited as it produces a train of pulses. The RC network forms the timing circuit. On varying the resistance the charging rate of the capacitor is varied hence controlling the RC time constant.

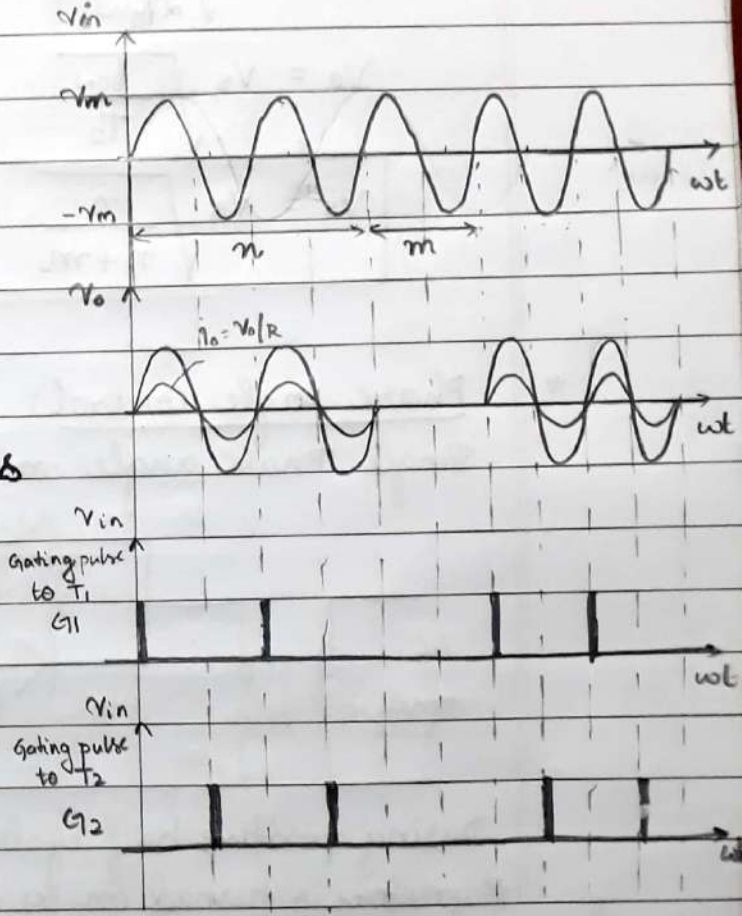
On applying voltage capacitor starts charging. Once capacitor charges to voltage equal to the peak value of UJT it starts conducting hence producing a pulse output. This process repeats and produces a train of pulse at base 1. The pulse output at the base 1 is used to turn ON the SCR at predetermined time intervals.

UNIT - 3

AC Voltage Controllers and Controlled Rectifiers.

★ **Principle of ON and OFF control:**





Thyristors T_1 and T_2 are turned on by applying gate trigger pulses for n input cycles during T_{ON}.

Thyristors T_1 and T_2 are turned off by blocking gate trigger pulses for m input cycles during T_{off}.

T_1 is turned on in beginning of each positive half cycle and T_2 is turned on in beginning of each negative half cycle. Thyristors conduct at zero crossing.

Thus we obtain a bidirectional load current in an ac voltage controller by triggering the thyristors alternately.

For a sine wave input supply voltage.

$$v_s = V_m \sin \omega t = \sqrt{2} V_s \sin \omega t$$

Output RMS voltage

$$V_0 = \sqrt{\frac{1}{\omega T_0} \int_{\omega t=0}^{\omega t_{ON}} V_m^2 \sin^2 \omega t \, d\omega t}$$

$$V_0 = \sqrt{\frac{1}{T_0 \omega} \int_{0}^{\omega t_{ON}} 2 V_s^2 \sin^2 \omega t \, d\omega t}$$

$$V_0 = \sqrt{\frac{2V_s^2}{T_0\omega}\int_0^{\omega t_{ON}}\left[\frac{1-\cos 2\omega t}{2}\right]d\omega t}$$

$$V_0 = V_s\sqrt{\frac{1}{T_0\omega}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\omega t_{ON}}}$$

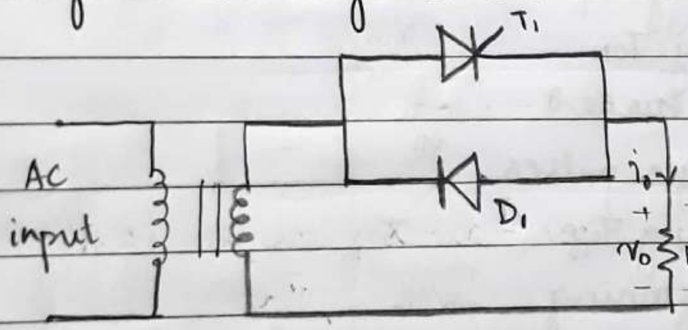
$$V_0 = V_s\sqrt{\frac{1}{T_0\omega}\left[\omega t_{ON} - 0\right]}$$

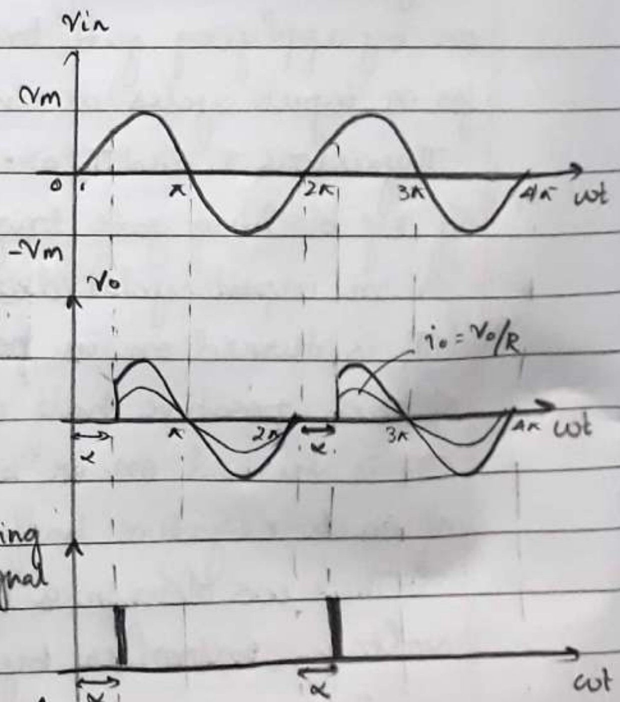
$$V_0 = V_s\sqrt{\frac{t_{ON}}{T_0}}$$

$$\boxed{V_0 = V_s\sqrt{\frac{n}{n+m}} = \sqrt{k}\,V_s}$$

★ Phase Angle control:

Single Phase angle control





During positive half cycle the thyristor is turned on by applying gate trigger pulse after the firing angle.

During negative half cycle the diode conducts as it is forward biased.

For a sine wave input voltage

$$V_s = V_m \sin\omega t = \sqrt{2}\,V_s \sin\omega t$$

Output rms voltage

$$V_0 = \sqrt{\frac{1}{2\pi}\int_\alpha^{2\pi} 2V_s^2 \sin^2\omega t \, d\omega t}$$

$$V_0 = \sqrt{\frac{2V_s^2}{2\pi}\int_\alpha^{2\pi}\left[\frac{1-\cos 2\omega t}{2}\right]d\omega t}$$

$$v_0 = v_s \sqrt{\frac{1}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{2\pi}}$$

$$v_0 = v_s \sqrt{\frac{1}{2\pi}\left[2\pi - 0 - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$\boxed{v_0 = \frac{v_s}{\sqrt{2\pi}}\sqrt{2\pi - \alpha + \frac{\sin 2\alpha}{2}}}$$

DC component

$$v_{DC} = \frac{1}{2\pi}\int_{\alpha}^{2\pi} \sqrt{2}\, V_s \sin \omega t \, d\omega t$$

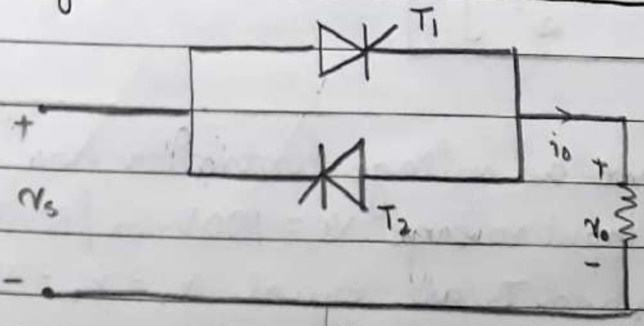
$$v_{DC} = \frac{V_s}{\sqrt{2}\,\pi}\left[-\cos \omega t\right]_{\alpha}^{2\pi}$$

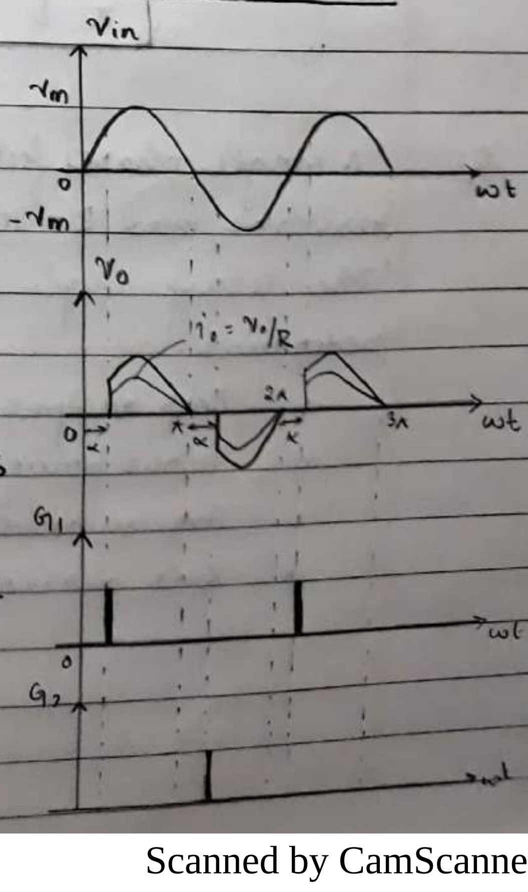
$$V_{DC} = \frac{V_s}{\sqrt{2}\,\pi}\left[-1 + \cos\alpha\right]$$

When $\alpha = 0$, then output $V_0 = V_s$

When $\alpha = \pi$, then output $V_0 = \frac{V_s}{\sqrt{2}}$

* Single Phase Bidirectional controllers with resistive load:





During positive half cycle, thyristor T_1 is forward biased and is triggered at a delay angle of α. The current flows in downward direction across the load.

During negative half cycle, thyristor T_2 is forward biased and is triggered at a delay angle of α. The current across the load flows in reverse direction.

The load voltage can be varied by varying the trigger an
Here α can be varied from 0 to π.
Hence it is also referred as full wave ac voltage controller
For a sine wave input supply voltage

$$v_s = V_m \sin\omega t = \sqrt{2}\, V_s \sin\omega t$$

Output RMS voltage.

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

$$V_0 = \sqrt{\frac{2V_s^2}{\pi} \int_{\alpha}^{\pi} \sin^2\omega t \, d\omega t}$$

$$V_0 = V_s \sqrt{\frac{2}{\pi} \int_{\alpha}^{\pi} \left(\frac{1-\cos 2\omega t}{2}\right) d\omega t}$$

$$V_0 = V_s \sqrt{\frac{1}{\pi} \left(\omega t - \frac{\sin 2\omega t}{2}\right)\Bigg|_{\alpha}^{\pi}}$$

$$V_0 = V_s \sqrt{\frac{1}{\pi} \left(\pi - 0 - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

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

Q: A single phase full wave ac voltage controller has a resistive load $R = 10\,\Omega$, input voltage $V_s = 120\,V_{rms}$ / 60Hz frequen
The delay angle of T_1 and T_2 are equal $\alpha_1 = \alpha_2 = \pi/2$.
Determine:

a. Rms output voltage : V_0
b. Input power factor
c. Avg current thyristor : I_A
d. Rms current : I_{rms}.

sol: a. rms output voltage

$$V_o = V_s \sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

$$V_o = (120)\sqrt{\frac{1}{\pi}\left(\pi - \frac{\pi}{2} + \frac{\cancel{\sin \pi}^{0}}{2}\right)}$$

$$V_o = 120\sqrt{\frac{1}{\pi}\left(\frac{\pi}{2}\right)}$$

$$V_o = \frac{120}{\sqrt{2}} = 84.85V$$

b. Input power factor.

$I_o = I_s$ assuming thyristor does not cause any loss of power.

$$I_o = \frac{V_o}{R} = \frac{84.85}{10} = 8.485A$$

$$P_o = I_o^2 R = (8.485)^2 (10) = 719.95W$$

voltmeter-Ammeter reading

$$VA = P_1 = V_s I_s = (120)(8.485)$$

$$\underline{VA = 1018.2W}$$

Input power factor

$$P_F = \frac{P_o}{VA} = \frac{719.95}{1018.2} = 0.707 \text{ (lagging)}$$

c. Average current thyristor: I_A

$$I_A = \frac{1}{2\pi R}\int_{\alpha}^{\pi} \sqrt{2}V_s \sin\omega t \, d\omega t$$

$$I_A = \frac{\sqrt{2}V_s}{2\pi R}\int_{\alpha}^{\pi} \sin\omega t \, d\omega t$$

$$I_A = \frac{\sqrt{2}(120)}{2\pi(10)}\left[-\cos\omega t\Big|_{\pi/2}^{\pi}\right.$$

$$I_A = 2.7\left[-\cos\pi + \cancel{\cos}\,\pi^{0}/2\right]$$

$$\underline{I_A = 2.7A}$$

d. rms current :

$$I_{rms} = \sqrt{\frac{1}{2\pi R}\int_{\alpha}^{\pi}(\sqrt{2}\,V_s \sin\omega t)^2 d\omega t}$$

$$I_{rms} = \sqrt{\frac{2V_s^2}{2\pi R}\int_{\alpha}^{\pi} \sin^2\omega t \; d\omega t}$$

$$I_{rms} = V_s\sqrt{\frac{1}{\pi R}\int_{\alpha}^{\pi} \frac{1-\cos 2\omega t}{2}\, d\omega t}$$

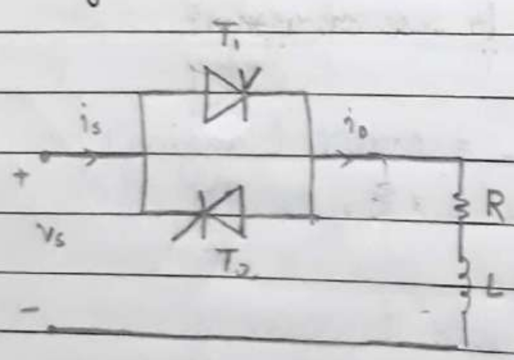
$$I_{rms} = 120\sqrt{\frac{1}{2\pi(10)}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\pi/2}^{\pi}}$$

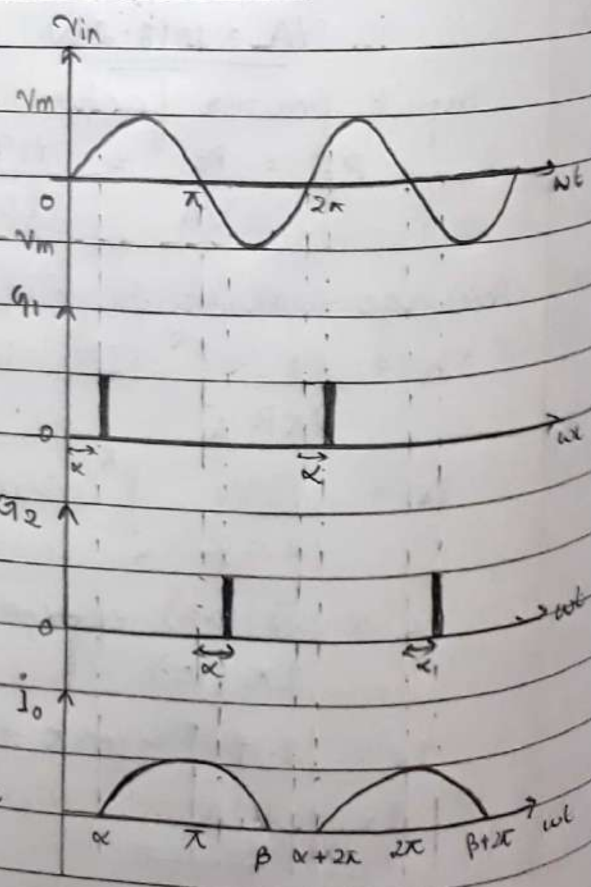
$$I_{rms} = 120\sqrt{\frac{1}{20\pi}\left[\pi - 0 - \frac{\pi}{2} + 0\right]}$$

$$I_{rms} = 120\sqrt{\frac{1}{20\cancel{\pi}}\left[\frac{\cancel{\pi}}{2}\right]}$$

$$I_{rms} = 18.97\ A$$

* Single Phase controllers with Inductive load :





During positive half cycle T_1 conducts as it is forward biased. It is trigger by gating pulse G_1 at α. Hence the current flows across the load in down-ward direction. Due to the inductance in the load, the current i_0 will not fall to zero at π. when the input becomes zero, then negative.

Hence the T_1 conducts until all the inductive energy stored in the load inductor is completely utilised. Therefore the current through the load falls to zero at $\omega t = \beta$, where β is the extinction angle. This implies that thyristor T_1 conducts from $\omega t = \alpha$ to β. Therefore conduction angle is $\delta = \beta - \alpha$.

The thyristor T_1 is made to conduct by appling gating signal at α and thyristor T_2 is made to conduct by applying gating signal at $\pi + \alpha$.

For a sine wave input voltage

$$v_s = V_m \sin\omega t = \sqrt{2} V_s \sin\omega t$$

$$\sqrt{2} v_s \sin\omega t = i_0 R + L \frac{di_0}{dt}$$

$$\frac{\sqrt{2} V_s}{L} \sin\omega t = \frac{R}{L} i_0 + \frac{di_0}{dt} \quad \text{——} (1)$$

Equation 1 is a differential equation of first order.

Thus $i_0 = i_N + i_F$ — (2) → natural component, → forced component

where $i_N = A_1 e^{-(R/L)t}$

and $i_F = \frac{\sqrt{2} V_s}{Z} \sin(\omega t - \theta)$

$$\text{where } Z = \sqrt{R^2 + \omega L^2} \text{ and } \theta = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

Substituting in eq (2) we get

$$i_0 = A_1 e^{-(R/L)t} + \frac{\sqrt{2} V_s}{Z} \sin(\omega t - \theta) \quad \text{——} (3)$$

For eq (3), A_1 can be determined from the initial conditions.

→ For $i_0 = 0$ at $\omega t = \alpha$

$$0 = A_1 e^{-(R/L)t} + \frac{\sqrt{2} V_s}{Z} \sin(\alpha - \theta)$$

$$\therefore A_1 = -\frac{\sqrt{2} V_s}{Z} \sin(\alpha - \theta)\, e^{(R/L)t}$$

for $i_0 = 0$ at $\omega t = \alpha$ $\quad t = \frac{\alpha}{\omega}$

$$\therefore A_1 = \frac{-\sqrt{2}V_s}{Z}\sin(\alpha-\theta)\, e^{(R/L)(\alpha/\omega)}$$

Substituting in eq ③, we get

$$i_0 = -\frac{\sqrt{2}V_s}{Z}\sin(\alpha-\theta)\, e^{(R/L)(\alpha/\omega)} \cdot e^{-(R/L)t} + \frac{\sqrt{2}V_s}{Z}\sin(\omega t-\theta)$$

$$i_0 = \frac{\sqrt{2}V_s}{Z}\sin(\omega t-\theta) - \frac{\sqrt{2}V_s}{Z}\sin(\alpha-\theta)\, e^{-\frac{R(\omega t)}{\omega L}}\, e^{\frac{R\alpha}{\omega L}}$$

$$\boxed{i_0 = \frac{\sqrt{2}V_s}{Z}\left[\sin(\omega t-\theta) - \sin(\alpha-\theta)\, e^{-\frac{R}{\omega L}(\omega t-\alpha)}\right]}$$

To calculate β

at β, load current $i_0 = 0$.

$$\therefore 0 = \frac{\sqrt{2}V_s}{Z}\left[\sin(\beta-\theta) - \sin(\alpha-\theta)\, e^{-\frac{R}{\omega L}(\beta-\alpha)}\right]$$

$$\therefore \boxed{\sin(\beta-\theta) = \sin(\alpha-\theta)\, e^{\frac{-R}{\omega L}(\beta-\alpha)}}$$

Hence conduction angle = $\boxed{\delta = \beta - \alpha}$

Output rms voltage

$$V_0 = \sqrt{\frac{1}{\pi}\int_\alpha^\beta 2V_s^2 \sin^2\omega t \, d\omega t}$$

$$V_0 = \sqrt{\frac{2V_s^2}{\pi}\int_\alpha^\beta \frac{1-\cos 2\omega t}{2}\, d\omega t}$$

$$V_0 = V_s\sqrt{\frac{1}{\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_\alpha^\beta}$$

$$V_0 = V_s\sqrt{\frac{1}{\pi}\left[\beta - \frac{\sin 2\beta}{2} - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

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

Short pulses are not suitable for inductive loads. When T_2 is fired at $\omega t = \pi + \alpha$, T_1 is still conducting due to load inductance hence T_2 will not be turned on. As a result T_1 will operate causing assymmetric waveform of output voltage and current.

★ <u>Controlled Rectifiers:</u>

To obtain controlled output voltages, phase control thyristors are used instead of diodes. The output voltage of thyristor rectifiers is varied by controlling the delay or firing angle of thyristors.

The phase control rectifiers can be classified into two types based on the input supply.

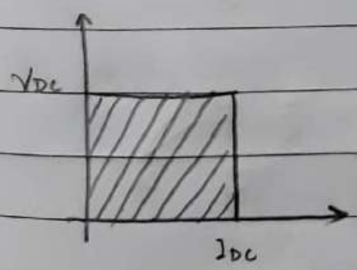
1. single phase converter
2. three phase converter.

Each type can be subdivided into

a. semiconverter
b. full converter
c. dual converter.

single phase converters

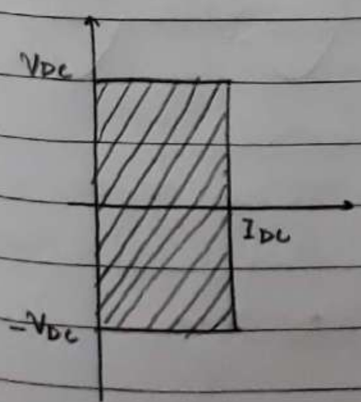
1. <u>Semiconverter</u>: operates in single quadrant.



V_{DC} : positive
I_{DC} : positive

single quadrant converter and has one polarity of its output voltage and current.

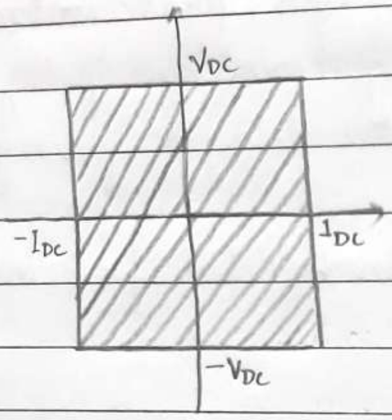
2. <u>Full converter</u>: operates in two quadrants.



V_{DC} : positive or negative
I_{DC} : positive

Two quadrant converter and the polarity of its output voltage can be either positive or negative but the output current has only one polarity.

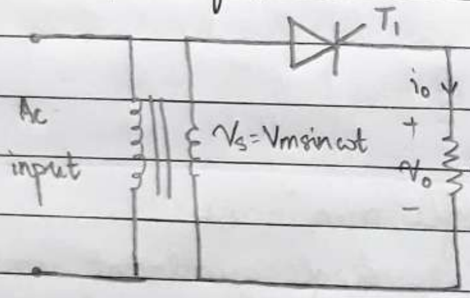
3. Dual converter: operates in four quadrants.

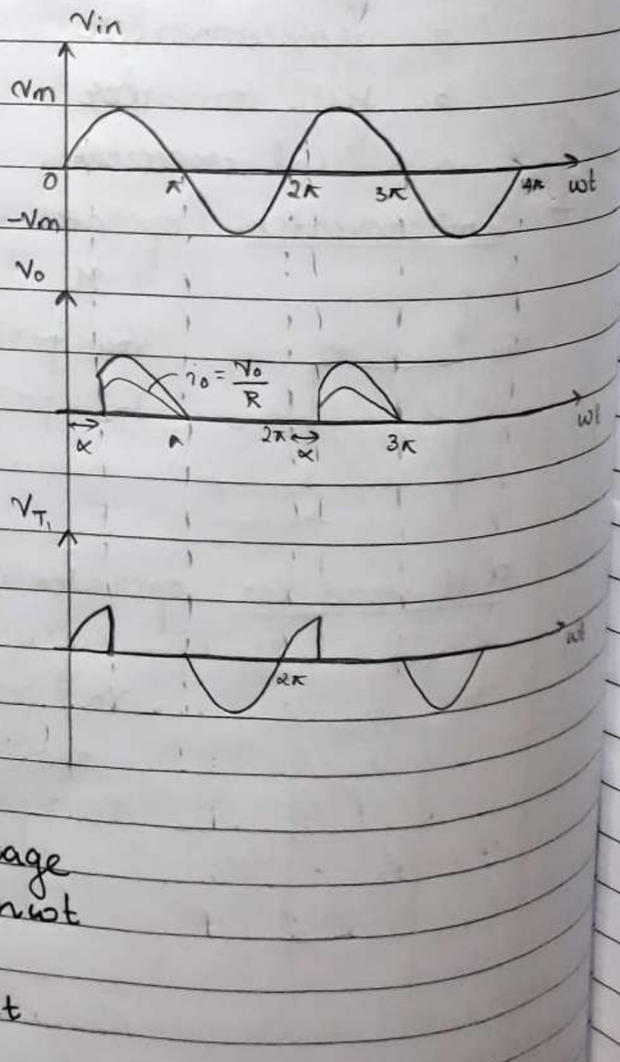


V_{DC} : positive or negative
I_{DC} : positive or negative

Four quadrant converter and the polarity of both output voltage and current can be either positive or negative.

★ Principle of phase controlled converter:





During positive half cycle thyristor T_1 is forward biased. It is triggered by appling a gating pulse at α. Hence the load current flows through the load till $\omega t = \pi$.

During negative half cycle the thyristor T_1 is reverse biased and is hence in off state.

For a sine wave input voltage

$$V_s = V_m \sin\omega t = \sqrt{2} V_s \sin\omega t$$

The dc voltage is

$$V_{DC} = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin\omega t \, dt$$

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

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

$$V_{DC} = \frac{V_m}{2\pi}\left[\cos\alpha + 1\right]$$

When $\alpha = 0$ then $V_{DC} = V_m/\pi$

When $\alpha = \pi$ then $V_{DC} = 0$

The firing angle α varies from 0 to π.
Hence as the α increases the dc voltage reduces.

Output rms voltage

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

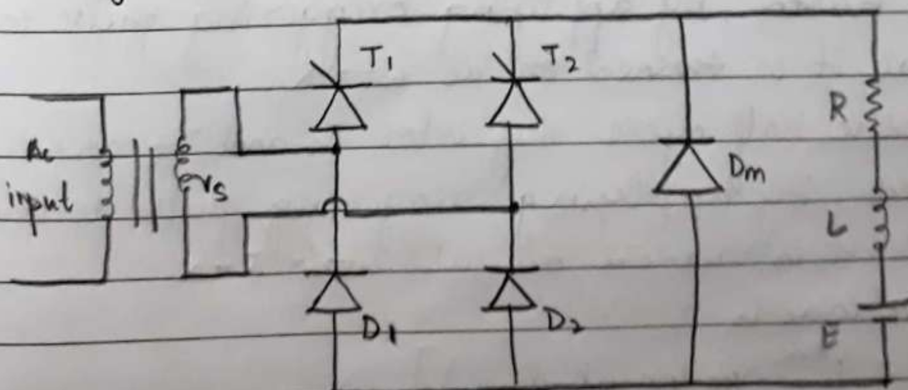
$$V_o = \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d\omega t}$$

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

$$V_o = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[\pi - 0 - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$\boxed{V_o = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}}$$

★ **Single Phase Semiconverter:**



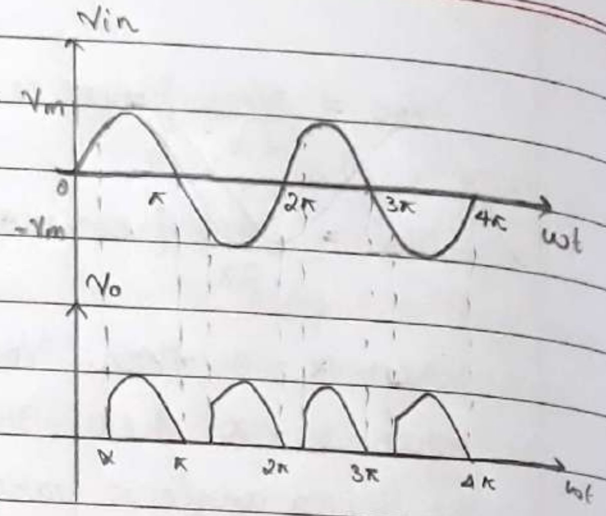
where:
- D_M : Free wheeling diode
- α_1 and α_2 are delay angles of thyristors T_1 and $T_2 \Rightarrow \alpha_1 = \alpha_2 = \alpha$.

During positive half cycle thyristor T_1 and diode D_2 are forward biased hence they are in on state.
During negative half cycle thyristor T_2 and diode D_1 are forward

biased hence they are in on state.

The dc voltage is

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



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

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

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

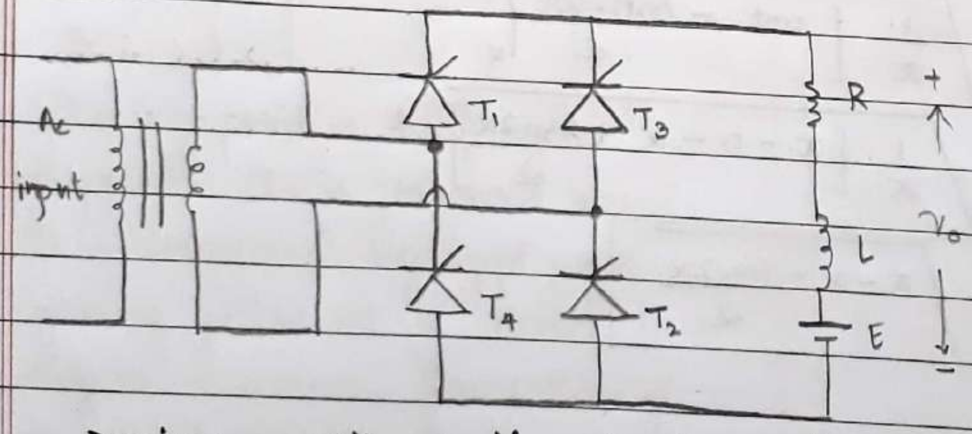
When $\alpha = 0$: $V_{DC} = 2V_m/\pi$

When $\alpha = \pi$: $V_{DC} = 0$

Here α varies from 0 to π.

As α increases the dc voltage V_{DC} decreases.

★ <u>Single Phase Full converter:</u>



During positive half cycle thyristor T_1 and T_2 are are forward biased, by applying triggering pulse to the gate terminal it is turned on. at $\omega t = \alpha$.

During negative half cycle thyristor T_4 and T_3 are forward biased, by applying triggering pulse to the gate terminal it is turned on. at $\omega t = \pi + \alpha$.

The dc voltage is

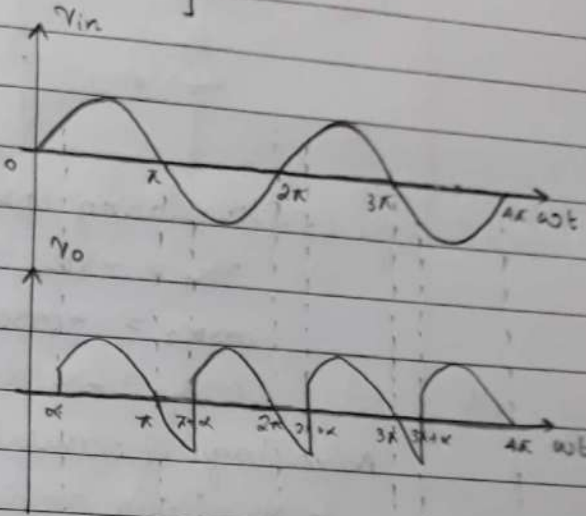
$$V_{DC} = \left[\frac{1}{2\pi}\left(2\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t\right)\right]$$

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

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

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

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



when $\alpha = 0$: $V_{DC} = 2V_m/\pi$

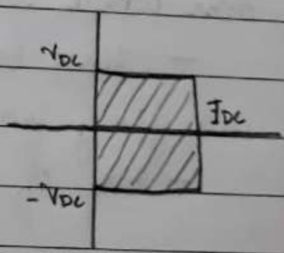
When $\alpha = \pi$: $V_{DC} = -2V_m/\pi$

Output rms voltage

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

$$V_0 = V_m\sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}\frac{1-\cos 2\omega t}{2}\, d\omega t}$$

$$V_0 = V_m\sqrt{\frac{1}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}}$$



$$V_0 = V_m\sqrt{\frac{1}{2\pi}\left[\pi+\cancel{\alpha} - \frac{\sin 2(\pi+\alpha)}{2} - \cancel{\alpha} + \frac{\sin 2\alpha}{2}\right]}$$

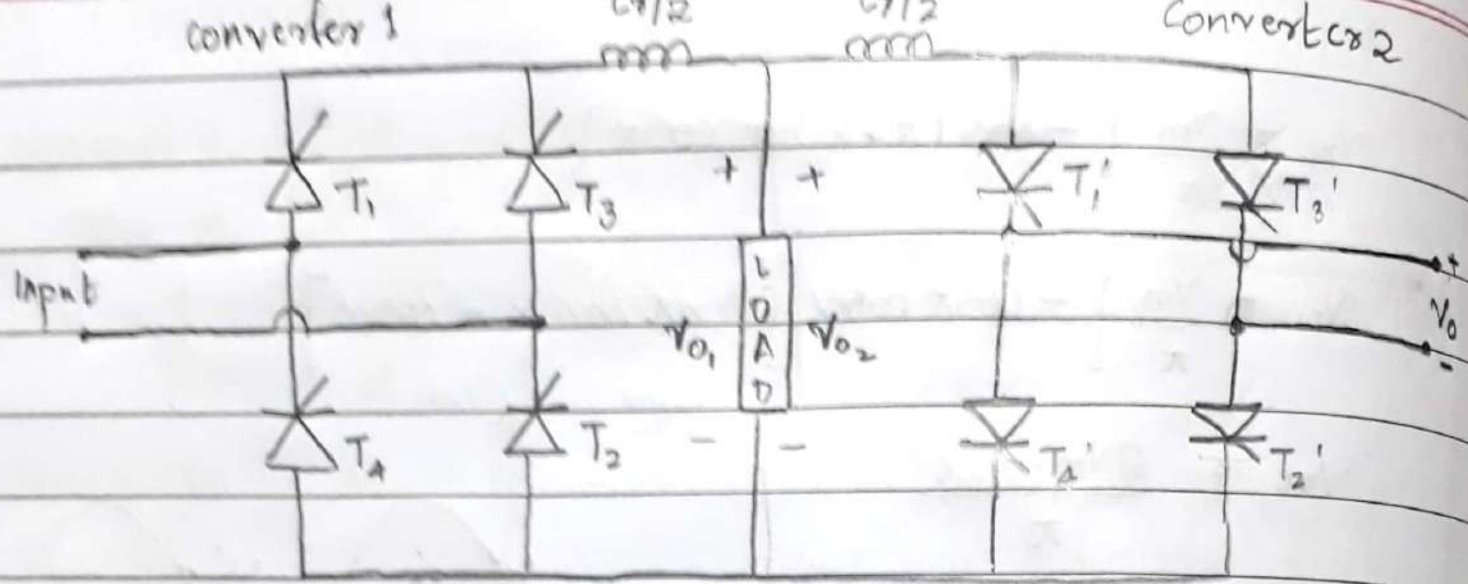
$$V_0 = V_m\sqrt{\frac{1}{2\pi}\left[\pi - \frac{\sin 2\pi\cos 2\alpha + \cos 2\pi\sin 2\alpha}{2} + \frac{\sin 2\alpha}{2}\right]}$$

$$V_0 = V_m\sqrt{\frac{1}{2\pi}\left[\pi - \cancel{\frac{\sin 2\alpha}{2}} + \cancel{\frac{\sin 2\alpha}{2}}\right]}$$

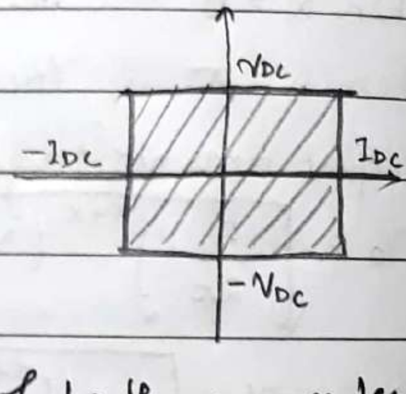
$$\boxed{V_0 = \frac{V_m}{\sqrt{2}}}$$

* Single Phase Dual Converter:

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 converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus we get AC as output.



Lr - circulating current reactor.



$V_{DC_1} = -V_{DC_2}$

$\cos\alpha_2 = -\cos\alpha_1$

$\cos\alpha_2 = \cos(\pi-\alpha_1)$

Advantage of circulating current.

- Maintains continuous conduction of both converters over whole control range.
- Since both converters are in continuous conduction changing from one quadrant to another is faster.
- Size of Lr increases at high power level.

UNIT - 4

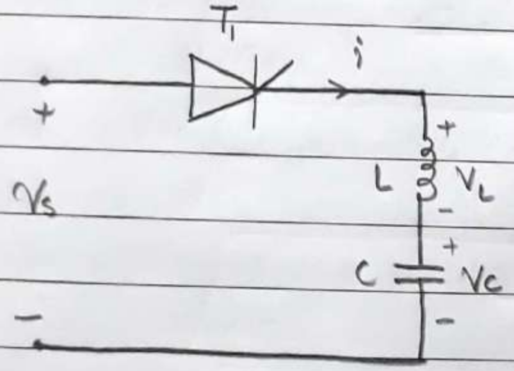
Commutation Techiques

★ <u>Thyristor commutation technique</u>

- Natural commutation : Turned off naturally
- Forced commutation : Current is forced to zero by additional circuit

★ <u>Self Commutation:</u>

Thyristor is turned off due to natural characteristics of the circuit. Hence no additional circuit is required.



During positive half cycle

T_1 is forward biased : ON

By KVL

$$V_s = V_L + V_c$$

$$V_s = L\frac{di}{dt} + \frac{1}{C}\int_0^t i\,dt + V_{c_{t=0}} \quad \text{—— (1)}$$

We assume that initially the voltage across the capacitor is zero and initially current across the inductor is zero.

$\therefore V_{c(t=0)} = 0$ and $i(t=0) = 0$. : Initial conditions.

Taking laplace transform for eq (1), we get:

$$\frac{V_s}{s} = Ls\,I(s) + \frac{I(s)}{Cs}$$

$$\frac{V_s}{s} = L\,I(s)\left[s + \frac{1}{LCs}\right]$$

$$V_s = L\,I(s)\left[s^2 + \frac{1}{LC}\right]$$

$$I(s) = \frac{V_s}{L}\left[\frac{1}{s^2 + 1/LC}\right]$$

but $\omega_m = \dfrac{1}{\sqrt{LC}}$

$$\therefore\ I(s) = \frac{V_s}{L}\left[\frac{1}{s^2+\omega_m^2}\right]$$

Multiplying ω_m on both sides.

$$\omega_m I(s) = \frac{V_s}{L}\left[\frac{\omega_m}{s^2+\omega_m^2}\right]$$

$$I(s) = \frac{V_s}{\omega_m L}\left[\frac{\omega_m}{s^2+\omega_m^2}\right]$$

Taking inverse laplace transform, we get

$$i(t) = \frac{V_s}{\omega_m L}\sin\omega_m t$$

$$i(t) = \frac{V_s}{\frac{1}{\sqrt{LC}}L}\sin\omega_m t$$

$$\therefore \boxed{i(t) = V_s\sqrt{\frac{C}{L}}\sin\omega_m t}$$

$$V_c(t) = \frac{1}{C}\int_0^t i(t)\,dt$$

$$V_c(t) = \frac{1}{C}\int_0^t V_s\sqrt{\frac{C}{L}}\sin\omega_m t\,dt$$

$$V_c(t) = \frac{V_s}{\cancel{\sqrt{LC}}}\left[\frac{-\cos\omega_m t}{\cancel{\omega_m}}\right]_0^t \qquad \because \omega_m = \frac{1}{\sqrt{LC}}$$

$$V_c(t) = V_s\left[-\cos\omega_m t + \cos 0\right]$$

$$\boxed{V_c(t) = V_s\left[1-\cos\omega_m t\right]}$$

at $t = t_0 = \pi\sqrt{LC}$

$$i(t) = V_s\sqrt{\frac{C}{L}}\sin\cancel{\omega_m}(\pi\cancel{\sqrt{LC}})$$

$i(t) = 0$

$\pi\sqrt{LC}$: commutation time

$\therefore T_1$ is switched off. by natural commutation due to

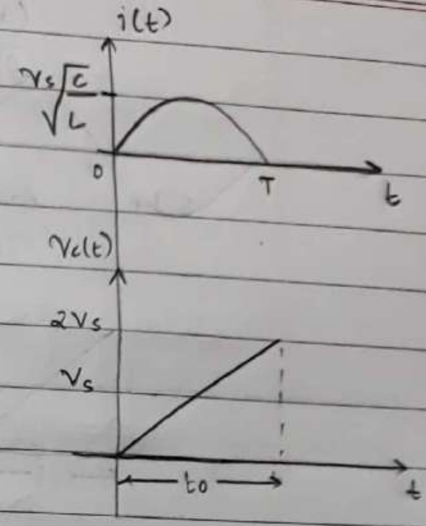
Page

at $t = t_0 = \pi\sqrt{LC}$

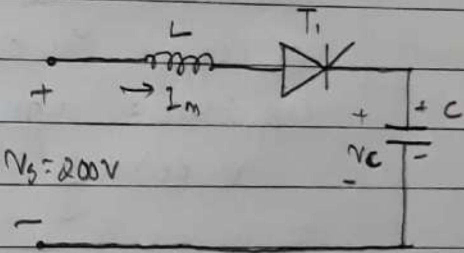
$$V_c(t) = V_s\left[1 - \cos \omega_m (\pi\sqrt{LC})\right]$$

$$V_c(t) = V_s\left[1 - (-1)\right]$$

$$\therefore \underline{\underline{V_c(t) = 2V_s}}$$



Q1: For a thyristor shown, it is switched on at $t=0$. Determine the conduction time of T_1 and capacitor voltage after T_1 is turned off. The circuit parameters are $L = 10\mu H$, $C = 50\mu F$, $V_s = 200V$. The inductor carries an initial current of $I_m = 250$ A.



Sol: By applying KVL

$$V_s = L\frac{di}{dt} + \frac{1}{C}\int i\,dt + V_c(t=0)$$

Initial conditions

$$V_c(t=0) = V_s = 200V$$

$$i(t=0) = I_m = 250\text{ A}$$

taking laplace transform

$$\cancel{\frac{V_s}{s}} = L\left[s I(s) - I(t=0)\right] + \frac{1}{Cs} I(s) + \cancel{\frac{V_s}{s}}$$

$$0 = L\left[s I(s) - I_m\right] + \frac{1}{Cs} I(s)$$

$$L I_m = L s I(s) + \frac{I(s)}{Cs}$$

$$I_m = s I(s) + \frac{I(s)}{LCs}$$

$$s I_m = s^2 I(s) + \frac{I(s)}{LC}$$

$$s I_m = I(s)\left[s^2 + \frac{1}{LC}\right]$$

$$s I_m = I(s)\left[s^2 + \omega_m^2\right]$$

$$I(s) = I_m\left[\frac{s}{s^2+\omega_m^2}\right]$$

taking inverse laplace transform

$$i(t) = I_m \cos \omega_m t$$

capacitor voltage

$$v_c(t) = \frac{1}{C}\int_0^t i(t)\,dt + v_c(t=0)$$

$$v_c(t) = \frac{1}{C}\int_0^t I_m \cos\omega_m t\,dt + V_s$$

$$v_c(t) = \frac{I_m}{C}\left[\frac{\sin\omega_m t}{\omega_m}\right]_0^t + V_s$$

$$v_c(t) = \frac{I_m}{C}\,\frac{\sin\omega_m t}{1/\sqrt{LC}} + V_s$$

$$v_c(t) = I_m\sqrt{\frac{L}{C}}\sin\omega_m t + V_s$$

$$i(t) = I_m \cos\omega_m t$$

$$\text{at } t = t_0 = \frac{\pi\sqrt{LC}}{2}$$

$$i(t) = I_m \cos \cancel{\omega_m}\left(\frac{\pi \cancel{\sqrt{LC}}}{2}\right)$$

$$i(t) = 0$$

$$\therefore t_0 = \frac{\pi\sqrt{LC}}{2} = \frac{\pi\sqrt{10\mu(50\mu)}}{2} = 35.124\,\mu sec$$

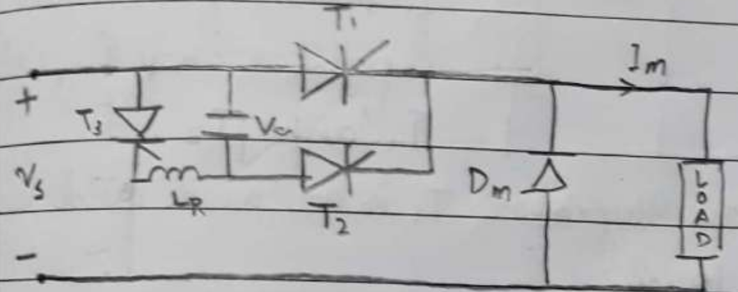
$\therefore v_c(t) = I_m \sqrt{\frac{L}{C}} \sin \omega_m \left(\frac{\pi \sqrt{LC}}{2} \right) + V_s$

$v_c(t) = 250 \sqrt{\frac{10\mu}{50\mu}} \; (1) + 200$

$v_c(t) = 311.8\,V$

Auxillary Commutation

* **Impulse Commutation**: (Voltage commutation / classical commutation)



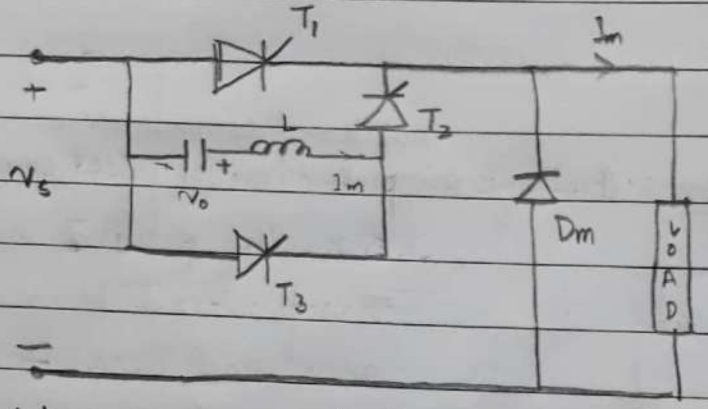
During positive half cycle T_1 is forward biased, hence ON now load current I_m flows across the load.

The commutation circuit starts with an assumption that capacitor is initially charged to a voltage (negative). The thyristor T_1 is conducting and carrying the load current and when the auxillary thyristor T_2 is fired, the main thyristor T_1 is reverse biased due to the negatively charged capacitor. Now T_2 will carry a load current which inturn discharges the capacitor and then charges to positive voltage.

Therefore T_2 will be turned off on its own once the capacitor is fully charged to a positive voltage. The charge reversal of capacitor is done by third thyristor T_3 which is placed in resonant loop. Once T_3 is fired and circuit will resonate at particular frequency and capacitor will be charged negatively. Discharging of capacitor depends on the load current.

* **Resonant Pulse commutation:**

charged capacitor is used to pass a reverse current through the thyristor to turn it off this is called as current commutation.



D_m : free wheeling diode

The resonant circuit is formed by inductor, capacitor and thyristors T_1 and T_2.

Let us assume initially the thyristor T_1 is on and load current I_m is flowing across the load.

Thyristor T_2 is a commutation thyristor. On turning on T_2 by capacitive voltage leads to turning off of T_1.

wkt

$$i(t) = V_s \sqrt{\frac{C}{L}} \sin\omega_m t$$

but since initially T_1 is conducting $V_s = V_0$

$$\therefore i(t) = V_0 \sqrt{\frac{C}{L}} \sin\omega_m t$$

$$i(t) = I_p \sin\omega_m t$$

T_1 is forced to zero at time $t = t_1$

under steady state condition $i(t = t_1) = I_m$

$$\therefore I_m = V_0 \sqrt{\frac{C}{L}} \sin\omega_m t_1$$ t_1: commutation time.

$$I_m = V_0 \sqrt{\frac{C}{L}} \sin \frac{1}{\sqrt{LC}} t_1$$

$$\sin \frac{1}{\sqrt{LC}} t_1 = \frac{I_m}{V_0} \sqrt{\frac{L}{C}}$$

$$\frac{t_1}{\sqrt{LC}} = \sin^{-1}\left[\frac{I_m}{V_0}\sqrt{\frac{L}{C}}\right]$$

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$$\boxed{t_1 = \sqrt{LC}\,\sin^{-1}\left[\frac{I_m}{V_0}\sqrt{\frac{L}{C}}\right]}$$

wkt

$$V_c(t) = \frac{1}{C}\int_0^t i(t)\,dt$$

but $V_0(t=t_1) = -V_1 = -V_0 \cos \omega_m t$

Hence the capacitor voltage varies from $-V_1$ to 0 and from 0 to V_s. Therefore it is over charged this is because of Energy stored in the inductor due to I_m is transfered to the capacitor.

T_3 is self commutated due to the presence of the capacitor and inductor.

$$V_0 = V_s + \Delta V$$

$$V_0 = V_s + \left(I_m\sqrt{\frac{L}{C}}\right)$$

V_c : $-V_1$ to 0 then 0 to V_s

$$V_1 = \frac{1}{C}\int_0^{t_{off}} I_m\,dt$$

$$V_1 = \frac{I_m}{C}\,t_{off}$$

$$\therefore \boxed{t_{off} = \frac{V_1 C}{I_m}}$$

Q: For a resonant pulse commutation $C = 30\mu F$, $L = 4\mu H$. Initial capacitor voltage $V_0 = 200V$. Determine the turn off time if load current $I_m = 250A$.

Sol:

Given: $C = 30\mu F$ to find : t_{off}

$L = 4\mu H$

$V_0 = 200V$

$I_m = 250A$

$$t_1 = \sqrt{LC}\ \sin^{-1}\left[\frac{I_m}{V_0}\sqrt{\frac{L}{C}}\right]$$

$$t_1 = \sqrt{30\mu \times 4\mu}\ \sin^{-1}\left[\frac{250}{200}\sqrt{\frac{4\mu}{30\mu}}\right]$$

$$t_1 = 10.95\times10^{-6}\ \sin^{-1}\left[0.4564\right]$$

$$t_1 = 10.95\times10^{-6}\ (0.4739)$$

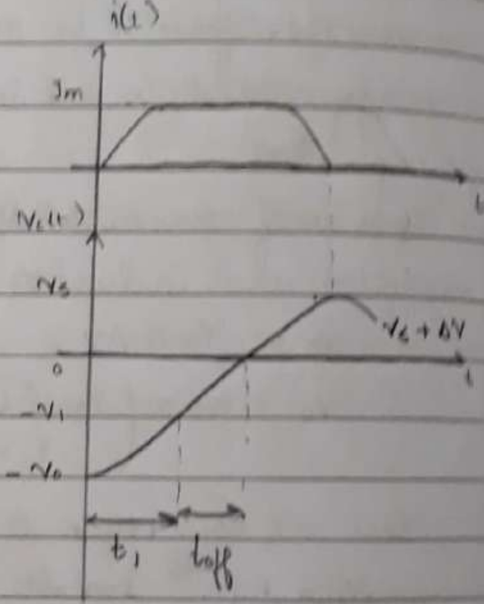
$$\underline{t_1 = 5.19\mu\,sec}$$

$$-V_1 = -V_0 \cos \omega_n t_1$$

$$-V_1 = -200\cos\left(\frac{1}{\sqrt{LC}}t_1\right)$$

$$V_1 = 200\cos\left[\frac{1}{\sqrt{4\mu\times30\mu}}(5.19\mu)\right]$$

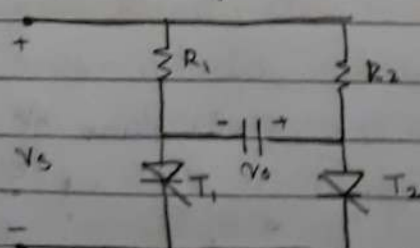
$$V_1 = -178.05V$$



$$t_{off} = \frac{V_1 C}{I_m}$$

$$t_{off} = \frac{(-176.05)(30\mu)}{250} \qquad \therefore \underline{t_{off} = 21.36\mu\,sec}$$

★ <u>complementary commutation</u> :



Initially both T_1 and T_2 are off. When T_1 is triggered the current flows across the capacitor charging it to V_0 in the polarity shown in the circuit.

When T_2 is triggered and a negative input is applied across T_1 due to reverse voltage T_1 turns off immediately. Now the capacitor starts charging with a reverse polarity. Again if T_1 is triggered the discharging current of the capacitor turns off T_2.

UNIT - 5

DC Choppers

* Choppers convert fixed DC voltage to variable DC voltage.

Applications:

- It is used in traction motor control in electric automobiles.
- DC voltage regulators.

Choppers are basically switch, which can be implemented by:

1. Bipolar Junction Transistor.
2. Power MOSFET
3. Gate Turn off Thyristors (GTO's)
4. Forced commutated Thyristor.

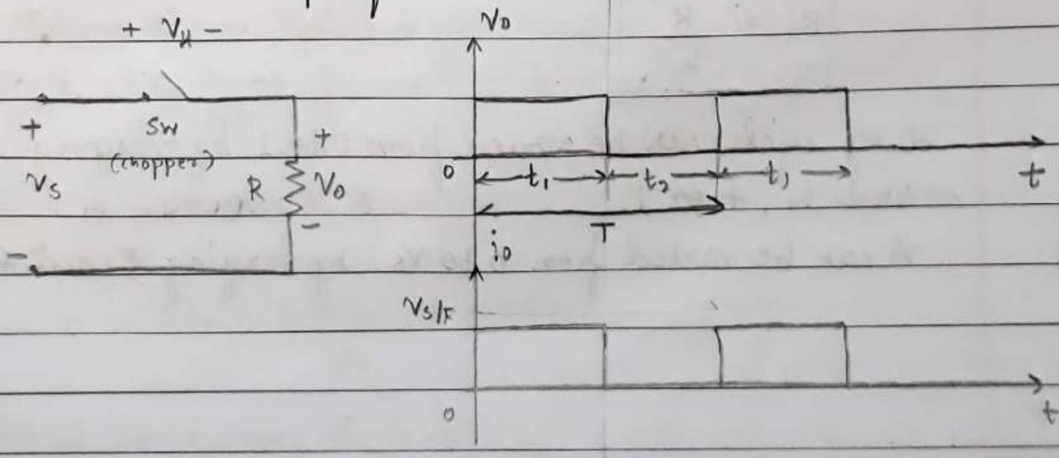
Thyristors which does not require any additional commutation circuits are only used.

* Principle of step-Down Operation:

When the switch SW is closed for time t_1, then input voltage appears across the load.

When the switch SW is open for time t_2, then the voltage across the load as it is an open circuit.

There can be voltage drops ranging from 0.5 V to 2V depending on the device. This voltage drop across the device is neglected until and unless specified.



Output voltage.

$$V_{av} = \frac{1}{T}\int_0^{t_1} V_s \, dt$$

$$\boxed{V_{av} = \frac{t_1}{T} V_s = t_1 f V_s = k V_s}$$

k - duty cycle

$k = t_1/T$

T - chopping period

f - chopping frequency.

Load current

$$\boxed{I_{av} = \frac{V_{av}}{R} = \frac{kV_s}{R}}$$

rms output voltage

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^{t_1} V_s^2 \, dt}$$

$$\boxed{V_{rms} = V_s\sqrt{\frac{t_1}{T}} = \sqrt{k}\,V_s}$$

Assuming lossless chopper

Input power = output power

$$P_i = \frac{1}{T}\int_0^{t_1} V_s \, i \, dt$$

$$P_i = \frac{1}{T}\int_0^{t_1} \frac{V_s^2}{R} \, dt$$

$$\boxed{P_i = \frac{V^2}{R}\frac{t_1}{T} = k\frac{V_s^2}{R}}$$

Input resistance seen by source

$$R_i = \frac{V_s}{I_{av}} = \frac{V_s}{kV_s/R}$$

$$\boxed{R_i = \frac{R}{k}}$$

duty cycle can be varied from 0 to 1 by varying ontime t_1, f or T.

V_0 can be varied from 0 to V_s. by varying t_1 and f or T.

★ control Stratagies:

1. constant Frequency Operation

Chopping frequency f is kept constant and on time t1 is varied: Pulse width modulation (PWM) control.

2. Variable Frequency Operation:

On time t_1 / Off time t_2 is kept constant and chopping frequency f is varied: Frequency Modulation control.

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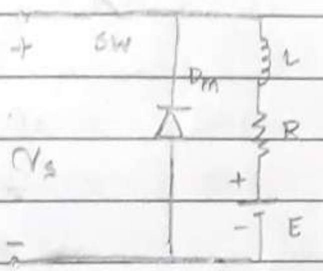
★ Step Down Chopper with R-L load:



mode 1: switch is closed.

current flows from supply to load.

Dm - free wheeling diode

By applying KVL

$$V_s = L\frac{di_1}{dt} + i_1 R + E$$

Initial condition: $i_1(t=0) = I_1$

taking laplace transform on both sides.

$$\frac{V_s}{s} = L\,s\,I(s) - L I_1 + R\,I(s) + \frac{E}{s}$$

$$\frac{V_s - E}{s} = L\,s\,I(s) - L I_1 + R\,I(s)$$

Solving for $I(s)$ let $\beta = R/L$

$$I(s) = \frac{V_s - E}{R}\left(\frac{1}{s} - \frac{1}{s+\beta}\right) + \frac{I_1}{s+\beta}$$

Taking inverse laplace transform.

$$i_1(t) = \frac{V_s - E}{R}\left[1 - e^{-\beta t}\right] + I_1 e^{-Rt/L} \quad \text{—— (1)}$$

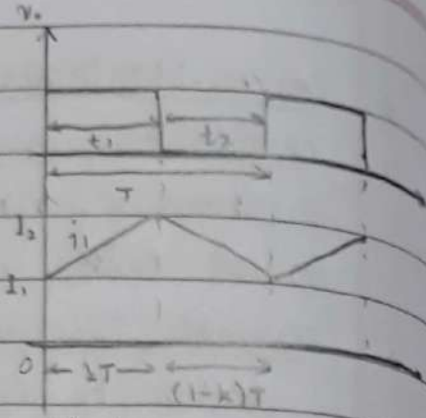
mode 2: Switch is open.

By applying KVL.

$$0 = R i_2 + L\frac{di_2}{dt} + E$$

initial conditions $i_2(t=0) = I_2$

$$i_2(t) = I_2 e^{-Rt/L} - \frac{E}{R}\left[1 - e^{-Rt/L}\right] \quad \text{——} (2)$$



at the end of mode 2: $i_2(t) = I_3$

under steady state: $I_3 = I_1$ —— (3)

$i_1(t = t_2) = I_2$ —— (4)

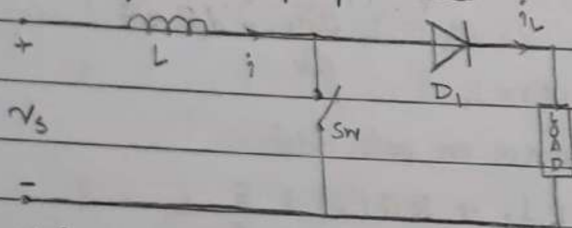
From eq (1) and eq (2)

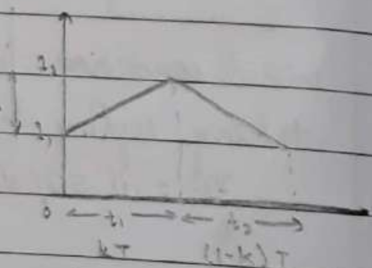
$$I_2 = \frac{V_s - E}{R}\left(1 - e^{-R/L \cdot kT}\right) + I_1 e^{-R/L \cdot kT}$$

$$I_3 = I_1 = I_2 e^{-R/L(1-k)T} - \frac{E}{R}\left(1 - e^{-R/L(1-k)T}\right)$$

$$\Delta I = I_2 - I_1$$

★ <u>Principle of step-up operation:</u>





<u>switch is closed for time t_1.</u>

Inductor current rises and energy is stored in it. The current flows through switch and not across the load.

<u>Switch is open for time t_2.</u>

The energy stored in the inductor is transfered to the load.

when the chopper is turned on

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

Peak to peak ripple current: ΔI

$$\Delta I = \frac{V_s}{L} t_1$$

Instantenious voltage

$$V_0 = V_s + L\frac{\Delta I}{t}$$

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substituding for ΔI

$$V_0 = V_s + \frac{L}{t_2}\left(\frac{V_s}{L}\right)t_1$$

$$V_0 = V_s\left[1 + \frac{t_1}{t_2}\right]$$

wkt $t_1 = kT$ and $t_2 = (1-k)T$ where k - duty cycle.

$$\therefore V_0 = V_s\left[1 + \frac{kT}{(1-k)T}\right]$$

$$V_0 = V_s\left[\frac{1-k+k}{1-k}\right]$$

$$\boxed{V_0 = \frac{V_s}{1-k}}$$

When $k = 0$ then $V_0 = V_s$

When $k = 1$ then $V_0 \to \infty$ (practically not possible)

V_0 becomes very large. Hence it is sensitive to duty cycle.

Hence $V_0 = V_s$ or $V_0 > V_s$ always.

* Performance Parameters:

→ Duty cycle: k

$k = \frac{t_{ON}}{T}$; k should be controlled between k_{min} ~~to~~ k_{max} as power semiconductor devices require minimum time to turn on or turn off, thereby limiting the maximum output voltage. Hence $k_{max} \neq 1$.

→ Chopping frequency:

$\Delta I_m = \frac{V_s}{4fL}$; where f: chopping frequency

ΔI_m : load ripple current.

since load ripple current is inversely proportional to chopping frequency. If 'f' is low, current increases hence damaging the load. Hence 'f' should be as high as possible to reduce load ripple current and to minimize the size of any additional inductor in the circuit.

Q1: A DC chopper has a resistive load of $R = 10\Omega$ and input voltage is $V_s = 20V$ when the chopper switch remains on, voltage drop is $V_{ch} = 2V$ and chopping frequency of 1kHz. If the duty cycle is 50%, then determine:

i. Average output voltage
ii. RMS output voltage
iii. chopping efficiency
iv. the effective input resistance R_i of the chopper

sol: i. $V_{dc} = kV_s$

$$V_{dc} = k(V_s - V_{ch})$$
$$= 0.5(220-2)$$
$$= 0.5(218)$$
$$= \underline{\underline{109V}}$$

ii. $V_o = \sqrt{k}(V_s - V_{ch})$

$$V_o = \sqrt{0.5}(220-2)$$
$$= \underline{\underline{154V}}$$

iii. chopping efficiency

$$\eta = \frac{P_o}{P_i}$$

$$P_o = \frac{1}{T}\int_0^{kT} v_o i \, dt$$
$$= \frac{1}{T}\int_0^{kT} \frac{v_o^2}{R} dt$$
$$= \frac{1}{T}\int_0^{kT} \frac{(V_s - V_{ch})^2}{R} dt$$
$$= \frac{1}{\cancel{T}} \frac{(V_s - V_{ch})^2}{R}[k\cancel{T}]$$
$$= \frac{0.5(220-2)^2}{10}$$
$$= 2376.2W$$

$$P_i = \frac{1}{T}\int_0^{kT} v_s i \, dt$$
$$= \frac{1}{T}\int_0^{kT} v_s \frac{v_o}{R} dt$$
$$= \frac{1}{\cancel{T}} \frac{v_s v_o}{R}[k\cancel{T}]$$
$$= \frac{k v_s (V_s - V_{ch})}{R}$$
$$= \frac{0.5(220)(220-2)}{10}$$
$$= 2398.0W$$

$$\eta = \frac{P_o}{P_i} = \frac{2376.2}{2398.0} = 0.9909 = 99.09\%$$

iv. $$R_i = \frac{V_s}{I_s} = \frac{V_s}{I_{dc}} = \frac{V_s}{V_{dc}/R} = \frac{220\times10}{109} = 20.18\,\Omega$$

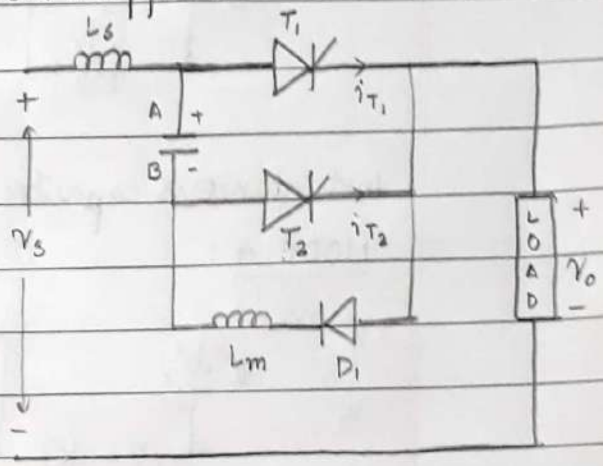
* Thyristor Chopper

= Impulse commutated chopper (classical chopper)

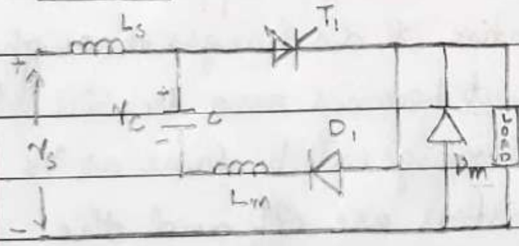
Initially the capacitor is charged with the polarity shown in the fig. by triggering the thyristor T_2.

As the capacitor starts discharging thyristor T_2 will be turned off.

The chopper operation is divided into five modes.



— MODE 1 :



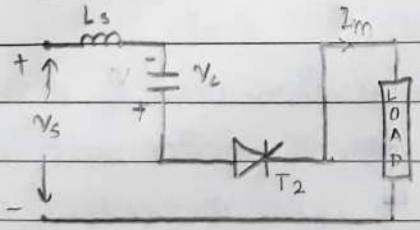
At $t=0$ thyristor T_1 is fired. The supply voltage comes across the load and the load current I_L flows through T_1 and load. The capacitor reverses its voltage and discharges.

Resonant recovery circuit consists of D_1, L_m, C and L_s.

$i_c(t) = V_c\sqrt{\frac{C}{L_m}}\sin\omega t \Rightarrow I_P = V_c\sqrt{\frac{C}{L_m}}$

$V_c(t) = V_c\cos\omega t$; at $t = \pi\sqrt{L_mC}$ capacitor voltage is reversed.

— MODE 2 :



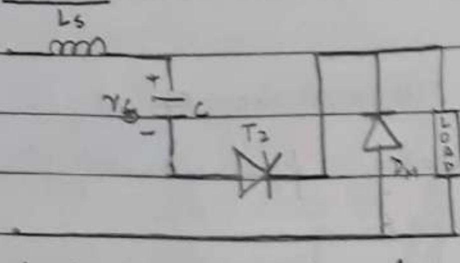
T_2 is fired to commute T_1. When T_2 is on the capacitor reverse biases T_1 and turns it off. The capacitor discharges from $-V$ to 0 through load. This discharging time is known as 'circuit turn-off time'.

$$V_c = \frac{1}{C}\int_0^{t_{off}} I_m\,dt = \frac{I_m t_{off}}{C} \quad \therefore \left[\, t_{off} = \frac{V_c C}{I_m} \,\right]$$

Then the capacitor recharges back to V_s (with plate a as positive)
This time is called the 'recharging time'.

$$t_c = \frac{V_c C}{I_m} \; ; \; \text{total time} = t_{off} + t_c \text{ (commutation time)}$$

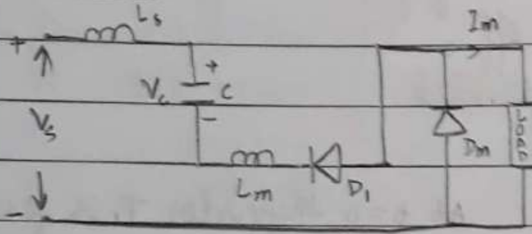
- MODE 3:



D_m starts conducting and the load current decays. The energy stored in L_s is transfered to C, hence charging it higher than V_s. Thus T_2 turns off naturaly.

Instantaneous capacitor voltage: $V_c(t) = V_s + I_m\sqrt{\frac{L_s}{C}}\sin\omega t = V_s + \Delta V$

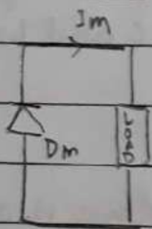
- MODE 4:



capacitor has been overcharged i.e. greater than V_s. Resonant oscillations cause capacitor to discharge in opposite direction

Hence capacitor current is negative. It discharges through L_s, V_s, D_m, D_1 and L_m. Once the current becomes zero D_1 will stop conducting and the capacitor voltage will be same as V_s.

- MODE 5:



Both the thyristors are off and the load current flows through D_m.

$$V_0 = \frac{1}{T}\left[V_s kT + t_c \tfrac{1}{2}(V_c + V_s)\right]$$

When k is minimum (i.e., k=0)

$$V_{0(k=0)} = 0.5 f\, t_c (V_c + V_s)$$

Q1: An AC voltage controller has a resistive load of $10\,\Omega$. The input voltage $V_s = 120V / 60\,Hz$. The thyristor switches on for $n = 25$ cycles and off for $m = 75$ cycles. Determine:

i. rms output voltage V_o.
ii. The input power factor.
iii. The average and rms current of thyristor.

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Sol: i. The rms output voltage: V_o

$$V_o = V_s\sqrt{k}$$

$$V_o = V_s\sqrt{\frac{n}{n+m}} = 120\sqrt{\frac{25}{25+75}}$$

$$\underline{V_o = 60V}$$

rms current $I_o = \frac{V_o}{R} = \frac{60}{10} = 6A$ //

ii. The input power factor

$$P_o = I_o^2 R = (6)^2(10) = \underline{360W}$$

Input voltage-ammeter reading

$$VA = V_s I_s = 120(6) = 720W$$

(Assuming $I_s = I_o$: no loss)

Power Factor

$$PF = \frac{P_o}{VA} = \frac{360}{720} = \underline{0.5} \text{ (lagging current)}$$

iii. The average and rms current of thyristor.

$$I_m = \frac{V_m}{R} = \frac{\sqrt{2}V_s}{R} = \frac{\sqrt{2}(120)}{10} = \underline{16.97A}$$

Average current

$$I_a = \frac{n}{n+m}\left(\frac{1}{2\pi}\right)\int_0^{\pi} I_m \sin\omega t \, d\omega t$$

$$I_a = \frac{1}{2\pi}\left(\frac{25}{25+75}\right) I_m \left[-\cos\omega t\right]_0^{\pi}$$

$$I_a = \frac{1}{8\pi}(16.97)[+1+1]$$

$$\underline{I_a = 1.35A}$$

rms current =

$$I_{rms} = \sqrt{\frac{1}{2\pi}\left(\frac{n}{n+m}\right)\int_0^{\pi} I_m^2 \sin^2\omega t \, d\omega t}$$

$$I_{rms} = \sqrt{\frac{1}{8\pi}(16.97)^2\int_0^{\pi}\frac{1-\cos2\omega t}{2} d\omega t}$$

$$I_{rms} = \sqrt{5.73\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\pi}}$$

$$I_{rms} = \sqrt{5.73\left[\pi - 0 - 0 - 0\right]}$$

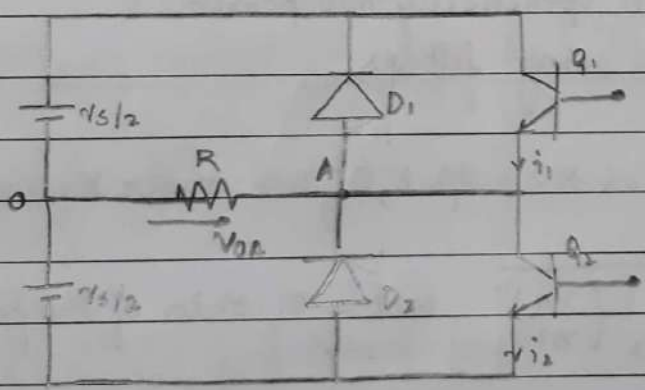
$$I_{rms} = 4.24A$$

UNIT - 06

Inverters

* Inverters convert DC voltage to AC voltage. (symmetrical output) of desired magnitude and frequency
  Gain of the inverter is varied by pulse width modulation.
  Output of practical inverters are non-sinusoidal and contains harmonics.
  For low or medium (power) applications, square wave are acceptable but for high ~~power~~ (frequency) applications low distorted sinosoidal waves are preffered.
  Inverters can be Single / Three phase Half bridge / Full bridge inverter.

* Principle of operation:



Half Bridge Inverter

At a time only one transistor is provided with base signal. Hence Q_1 is ON for time $T_0/2$ then Q_2 should be off. as the circuit is designed such that Q_1 and Q_2 are not turned on at the same time.

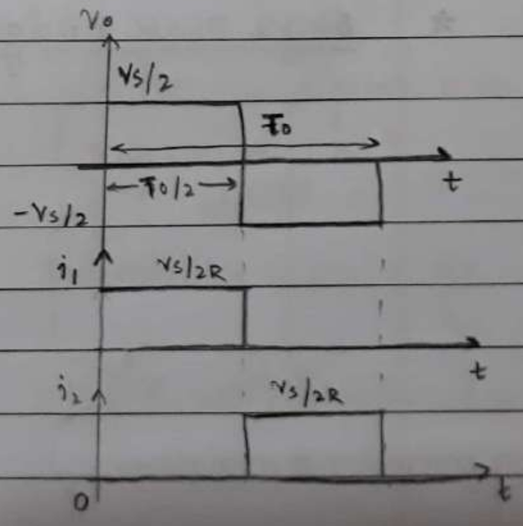
rms output voltage.

$$V_0 = \sqrt{\frac{2}{T_0}\int_0^{T_0/2}\left(\frac{V_s}{2}\right)^2 dt}$$

$$V_0 = \frac{V_s}{2}\sqrt{\frac{2}{T_0}\, t\Big|_0^{T_0/2}}$$

$$V_0 = \frac{V_s}{2}\sqrt{\frac{\cancel{2}}{T_0}\cdot\frac{T_0}{\cancel{2}}}$$

$$\boxed{V_0 = \frac{V_s}{2}}$$



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Limitation:

- A center tapped DC source is required
- Due to non linear behaviour of the transistors the output is distored due to the presence of unwanted signals

★ **Performance Parameters:**

- Output of practical inverters contain harmonics
- Quality of output is evaluated in terms of performance parameters.

1. Harmonic factor of n^{th} harmonic

$$HF_n = \frac{V_n}{V_1} = \frac{\text{rms value of } n^{th} \text{ component}}{\text{rms value of fundamental component}}$$

2. Total Harmonic distortion (THD)

$$THD = \frac{1}{V_1}\sqrt{\sum_{n=2,4,6}^{\infty} V_n^2}$$ It should be as small as possible.

Ideally THD = 0. (practically not possible)

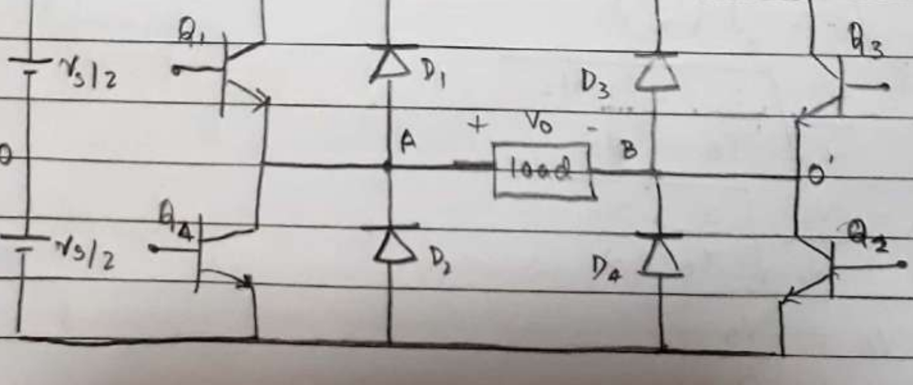
It can be reduced using filters.

3. Distortion Factor:

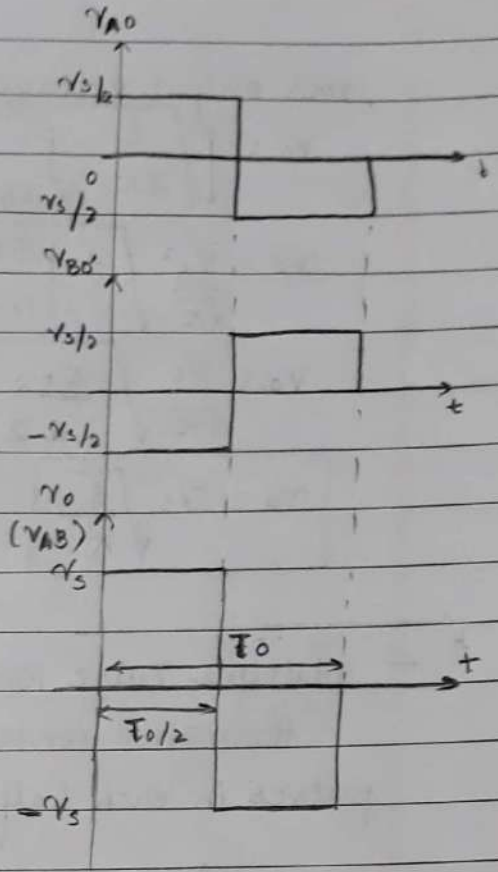
If filter is used at the output, higher order harmonics are attenuated.

$$D_F = \frac{1}{V_1}\sqrt{\sum_{n=2,4,6}^{\infty}\left(\frac{V_n}{n^2}\right)^2}$$ where n: order of the filter

★ **Single Phase Bridge Inverters:**



At a time only two transistors are on and the other two are off. When Q_1 and Q_2 is on then Q_3 and Q_4 is off similarly when Q_3 and Q_4 is on then Q_1 and Q_2 is off.



rms output voltage.

$$V_0 = \sqrt{\frac{2}{T_0}\int_0^{T_0/2} V_s^2\, dt}$$

$$V_0 = V_s\sqrt{\frac{2}{T_0}\cdot t\Big|_0^{T_0/2}}$$

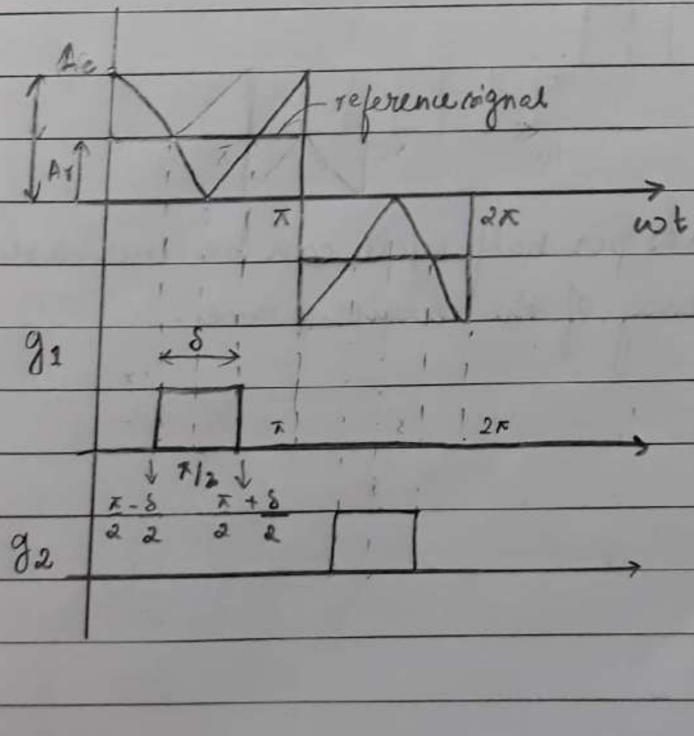
$$V_0 = V_s\sqrt{\frac{2}{T_0}\cdot\frac{T_0}{2}}$$

$$\boxed{V_0 = V_s}$$

Here no center tapped DC source is required.

* Voltage Control of Single Phase Inverters:

– Single Pulse Width Modulation:



carrier signal : triangular waveform

Reference signal: Rectangular waveform.

A_r can be varied from 0 to maximum (A_c).

Modulation Index $= \dfrac{A_r}{A_c}$

When $A_c = A_r$; modulation index = 1.

rms output voltage

$$v_0 = \sqrt{\frac{2}{2\pi}\int_{(\pi-\delta)/2}^{(\pi+\delta)/2} V_s^2\, dt}$$

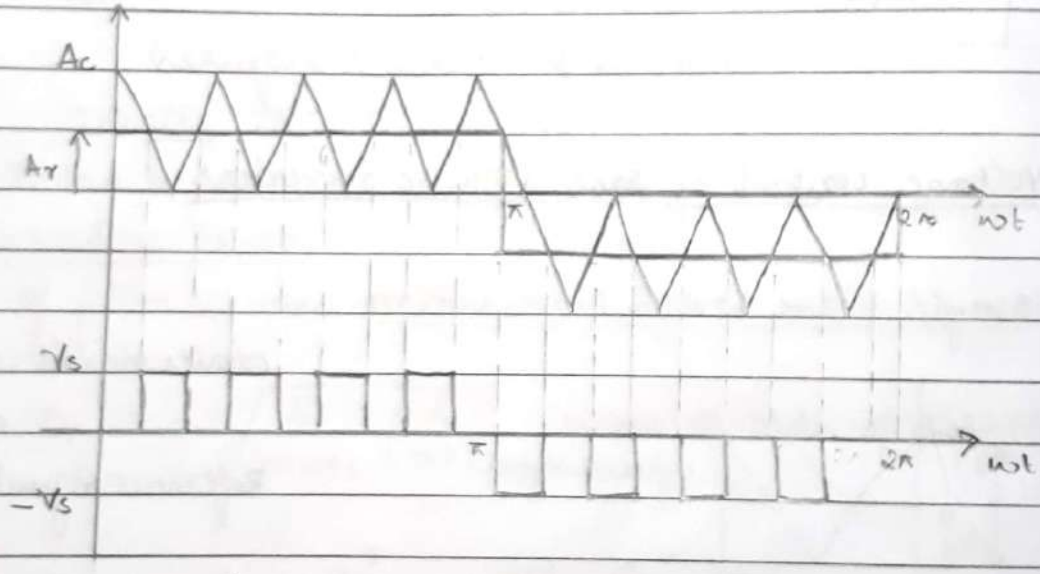
$$v_0 = \frac{V_s}{\sqrt{\pi}}\sqrt{t\Big|_{(\pi-\delta)/2}^{(\pi+\delta)/2}}$$

$$v_0 = \frac{V_s}{\sqrt{\pi}}\sqrt{\cancel{\frac{\pi}{2}}+\frac{\delta}{2}-\cancel{\frac{\pi}{2}}+\frac{\delta}{2}}$$

$$\boxed{v_0 = V_s\sqrt{\frac{\delta}{\pi}}}$$

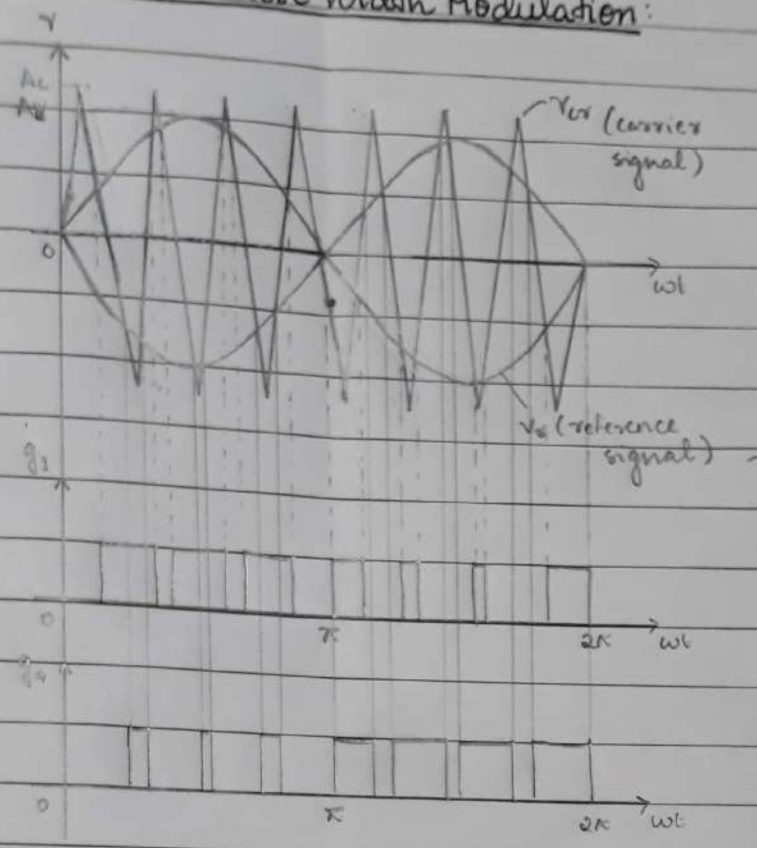
- Multiple Pulse Width Modulation:

Harmonic content is reduced by using several pulses in each half cycle.



The number of pulses per half cycle can be increased by increasing the frequency of the carrier wave.

- Sinusoidal Pulse Width Modulation:



- Modified Sinusoidal Pulse Width Modulation: