Thyristor DATE - 31/07/19 (1)

Thyristor family → triac, diac, silicon controlled switch, programmable unijunction Transistor (PUT), GTO, RCT etc.

└ one of the oldest member → Silicon controlled Rectifier
↳ so called because silicon is used for its construction and its operation as a rectifier and can be controlled

Thyristor → pnpn device
↳ THYRatron + tranSISTOR

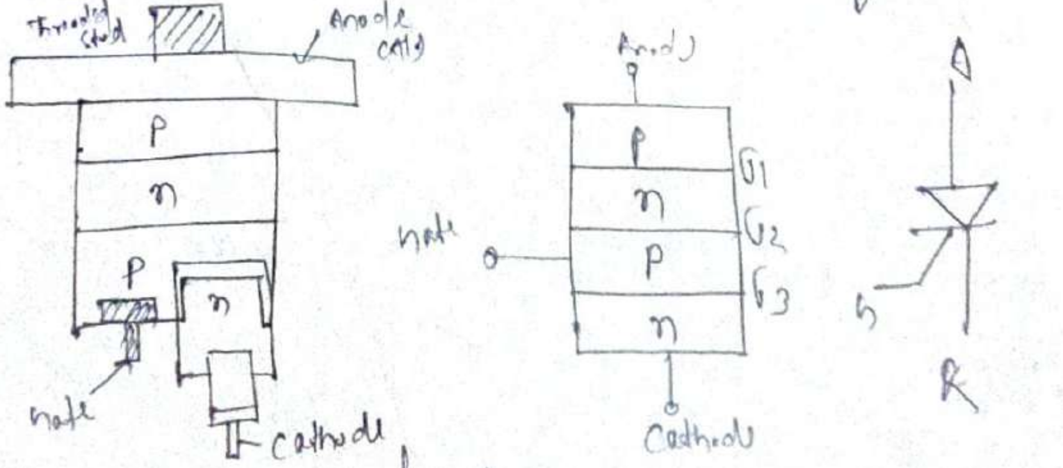
That means thyristor is a solid state device like transistor and has characteristic similar to that of a thyratron tube.

Thyristor

(i) It constitute three p-n junction
(ii) It has two stable states, an ON state & an OFF state and can change its state from one to other.

→ Thyristor is a four layer, 3 junction p-n-p-n semiconductor switching device.

→ It has 3 terminals; anode, cathode & gate




→ The threaded portion is for the purpose of tightening the thyristor to the frame or heat sink with the help of a nut.

→ Gate terminal is usually kept near cathode terminal. (2)

outer p region → Anode

outer n region → cathode

inner p region → Gate

## Rating

SCR of voltage Rating 10kV and an rms current rating of 3000A or 3kA with corresponding power handling capacity of 30MW are available

→ Such a high power thyristor can be switched on by a low voltage supply of about 1A & 10W and this gives gives an idea of the immense power amplification capability ($3 \times 10^6$) of this device

→ Because of these useful features, SCR is almost universally employed these days for all high power controlled device

→ Like diode, an SCR is an unidirectional device that blocks the current from cathode to Anode. Unlike diode, a thyristor also blocks current from anode to cathode untill it is triggered into conduction by a proper gate signal b/w gate & cathode

## Static IV characteristic of Thyristor

An elementary ckt diagram for obtaining static IV characteristic of a thyristor is shown below

The anode and cathode (3) are connected to Main source through a load. The gate and cathode are ~~connected to Main source~~ fed from a source Es which provides +ve gate current from gate to cathode

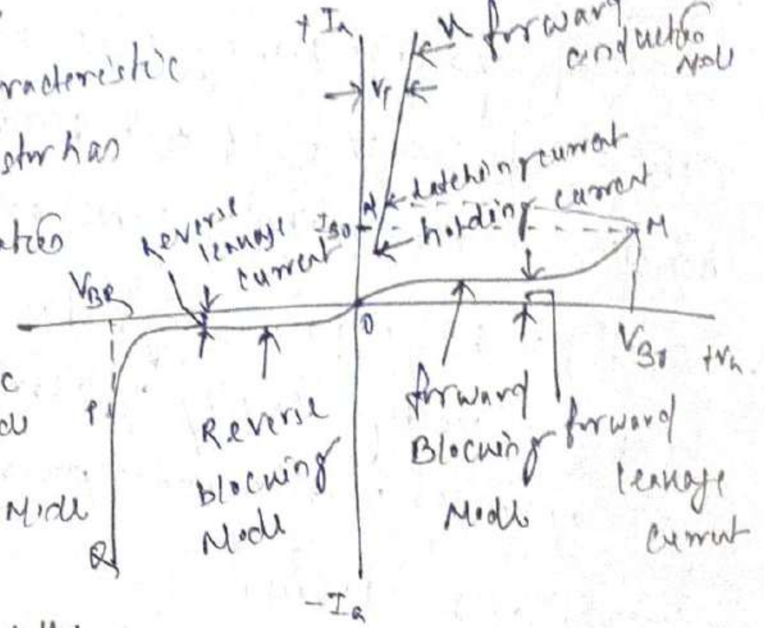
## Static V-I characteristic

→ Typical SCR I-V characteristic reveals that a thyristor has 3 basic Mode of operation namely.

(i) Reverse blocking Mode

(ii) forward blocking Mode (off)

(iii) forward conduction Mode (on)




## Reverse blocking Mode:

When cathode is made +ve w.r.t anode with switch open, thyristor is reverse biased.

so $J_1, J_3$ → Reverse biased
$J_2$ → forward biased.

→ This device behaves as if two diodes are connected in series with reverse voltage applied across them.

→ A small leakage current of the order of few milliampere flows.

→ This is reverse blocking Mode, called off state of thyristor

→ If the reverse voltage is increased, then at a critical breakdown level called reverse breakdown voltage $V_{BR}$, an avalanche occurs at $J_1$ & $J_3$ and the reverse current increases rapidly.

→ A large current associated with $V_{BR}$ gives rise to more losses in the SCR which leads to damage of SCR.

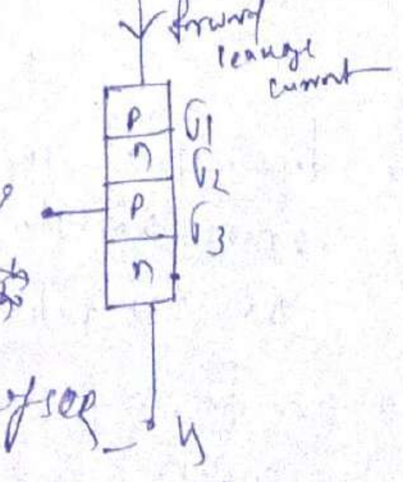
→ So SCR in the reverse blocking mode may be therefore treated as open switch.

→ Note that IV characteristic after avalanche breakdown during reverse blocking mode is applicable only when load resistance is zero.

Forward blocking Mode:

→ When anode is positive w.r.t cathode with gate cut open thyristor is said to be forward biased

→ $J_1$ & $J_3$ → forward biased
$J_2$ → reverse biased




→ In this mode small current called forward leakage current flows. OFF represent forward blocking mode of SCR.

→ As forward leakage current is small, SCR offer a high impedance; therefore a thyristor can be treated as an open switch even in the forward blocking mode

## forward conduction mode

(5)

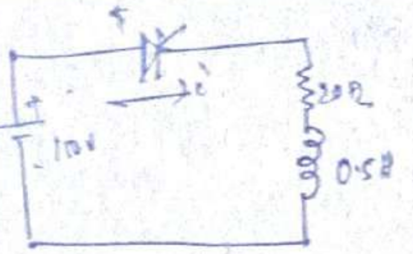
When anode to cathode forward voltage is increased with gate cut open, reverse bias junction $J_2$ will have avalanche breakdown at a voltage called forward breakover voltage $V_{BO}$.

- After this breakdown, thyristor gets turned on with point M at once shifting to N and then to a point anywhere b/w N & K.
- Here NK represents forward conduction mode
- A thyristor can be brought from forward blocking mode to forward conduction mode by turning it on by applying (i) a +ve gate pulse b/w gate & cathode or (ii) a forward breakover voltage accross anode and cathode

- forward conduction mode NK shows that voltage drop across thyristor is of the order of 1 to 2V depending upon the SCR rating
- In forward conduction mode, thyristor is treated as closed switch.

DATE 5/08/19

(a) The latching current of thyristor ckt in fig [2.1] is 50mA. The duration of firing pulse is 50μsec. Will the thyristor get fired?




$i = \frac{V}{R}(1 - e^{-t/\tau})$ (current in RL ckt)

$\tau = L/R = \frac{0.5}{20} = \frac{5}{20} = 0.025 sec$

$i(t) = \frac{100}{20}(1 - e^{-t/0.025})$

$50 mA = 5 (1 - e^{-t/0.025})$

$10 mA = (1 - e^{-t/0.025})$

$e^{-t/0.025} = 1 - 0.010$

$-t/0.025 = \ln(0.99)$

$+t/0.025 = +0.01$

$t = 0.01 \times 0.025$

$= 250 \mu sec$

so SCR will not on.

Q.2 The latching current in the ckt shown below is 4 mA obtain the minimum width of the gating pulse required to properly turn on the SCR.




2 $v = L\, di/dt$

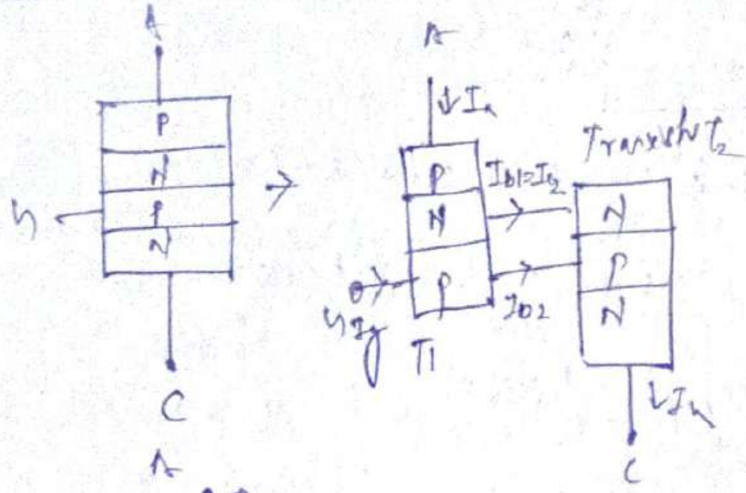
$L\, di = v\, dt$

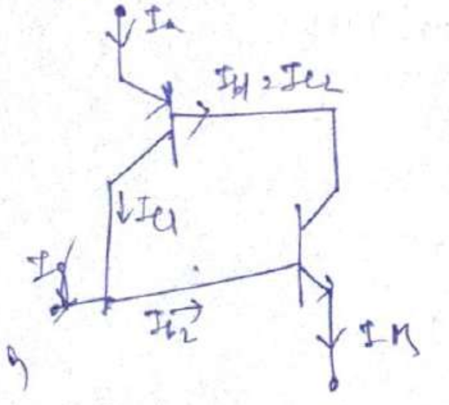
$\int di = \int \frac{v}{L} dt$

$i = \frac{Vt}{L}$

$4 mA = \frac{100}{0.1} \times t \Rightarrow t = \frac{0.004 \times 0.1}{100} = 4 \mu sec$

Two transistor Model of SCR 




It is observed from the figure that the collector current of transistor T1 becomes the base current of $T_2$.

$I_{b1} = I_{c2}$ $Q_1$ = PNP transistor = emitter current = collector current + Base current

$I_k = I_a + I_g$

$I_{c1} = \alpha I_a + I_{CBO_1}$

where $\alpha$ = common base current gain of $Q_1$

$I_{CBO1}$ = common base leakage current of $Q_1$

similarly for $Q_2$, the collector current $I_{c2}$ is given by

$I_{c2} = \alpha_2 I_k + I_{CBO_2}$

$\alpha_2$ = common base current gain of $Q_2$

$I_{CBO_2}$ = common base leakage current of $Q_2$.

& $I_k$ = emitter current of $Q_2$

$I_k = I_{c1} + I_{c2}$ (8)

$\therefore I_k = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2}$

When gate current is applied then $I_k = I_a + I_g$.

substituting the value of $I_k$ in above

$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$

$$I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

Assuming the leakage current of transistor $T_1$ & $T_2$ to be negligible small, we have

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

if $(\alpha_1 + \alpha_2) = 1 \Rightarrow$ the value of anode current is i.e anode current suddenly attains a very high value approaching infinity i.e the device suddenly latches into conduction on state from the nonconduction state

→ This characteristic of device is known as regenerative action.

Turn on Methods of a thyristor

① Forward voltage triggering

→ When anode to cathode forward voltage is increased with gate cut open, the reverse biased junction $J_2$ will have an avalanche breakdown at a voltage called forward breakover voltage $V_{BO}$. At this voltage a thyristor changes from off state to on state.

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## (b) Temperature triggering

Like any other semiconductor, the width of depletion layer of thyristor decreases on increasing the junction temperature.

→ Thus in a thyristor when the voltage applied b/w the anode and cathode is very near to breakdown voltage, the device can be triggered by increasing its junction temp.

→ By increasing the temperature to a certain value, a situation comes when the reverse biased junction collapses making the device conduct. This is also known as thermal triggering.

## (c) Light triggering (Radiation triggering)

→ In this method, as the name suggests, the energy is imparted by radiation. Thyristor is bombarded by energy particle such as neutrons or photons.

→ With the help of external energy, electron-hole pair are generated in the device, thus increasing the no. of charge carriers. This leads to instantaneous flow of current within the device and the triggering of the device.

## (d) dv/dt triggering

→ With forward voltage across anode and cathode of a device the junction $J_1$, & $J_3$ are forward biased where as junction $J_2$ becomes reverse biased.

→ This reverse biased junction $J_2$ has the characteristic of a capacitor due to charge existing across the junction.

→ If a forward voltage is suddenly applied, a charging current will flow tending to turn the device on.

If the voltage impressed across device is 'V' and the charge is 'Q' and the capacitance is $C_j$.

then $i_c = \frac{dQ}{dt} = \frac{d}{dt}(C_j V) = C_j \frac{dv}{dt} + V \frac{dC_j}{dt}$ (where $\frac{dC_j}{dt} = 0$)

$$\Rightarrow \boxed{i_c = C_j \frac{dv}{dt}}$$

Therefore, if rate of change of voltage across the device is large, the device may turn on even though the voltage appearing across the device is small.

(5) Gate triggering

→ This is most commonly used method for triggering SCRs.

→ By applying a +ve signal at the gate terminal of the device, it can be triggered much before the specified breakover voltage.

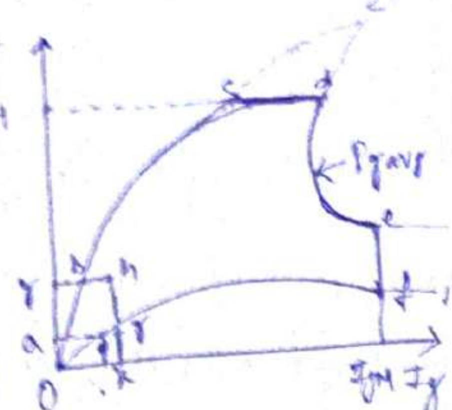
→ The conduction period of the SCR can be controlled by varying the gate signal with in the specified values of maximum & minimum gate current.

→ For gate triggering, a signal is applied between gate & cathode of the device. Three types of signals can be used for this purpose which are either DC signal, pulse signal or AC signal.

DATE: 7/08/19 (11)

Thyristor Gate characteristic:

→ The forward gate characteristic of thyristor is a graph between gate voltage and gate current.



→ The gate trigger circuitry must be suitably designed to take care of unavoidable scatter of characteristic.

→ curve-1 represents the lowest voltage values that must be applied to turn on the SCR.

→ curve-2 gives the highest possible voltage values that can be safely applied to gate circuit.

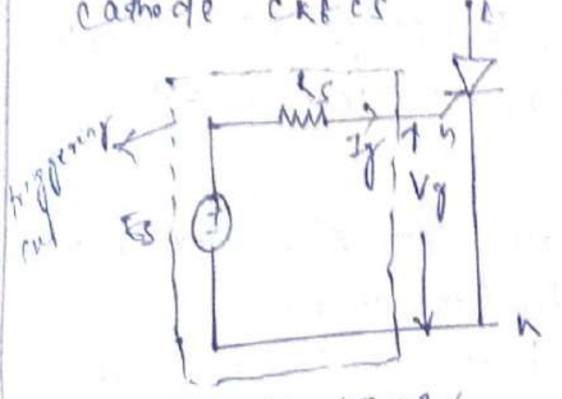
→ Each thyristor has maximum limit of $V_{gm}$ for gate voltage and $I_{gm}$ for gate current. There is also rated (avg) gate power dissipation $P_{gavg}$ specified for each thyristor. These limits should not be exceeded in order to avoid permanent damage of $G$.

→ There are also minimum limits for $V_g$ & $I_g$ for reliable turn on; these are represented by oy and ox respectively.

→ A non-triggered gate voltage is also prescribed by the manufacturer of SCRs. This is indicated by oa.

→ If firing ckt generates +ve gate signal prior to the desired instant of triggering of SCR, it should be ensured that this unwanted signal is less than the nontriggered gate voltage oa. At the same time, all noise signals should be less than voltage oa.

The firing ckt which is used to feed power to gate cathode ckt is (12)



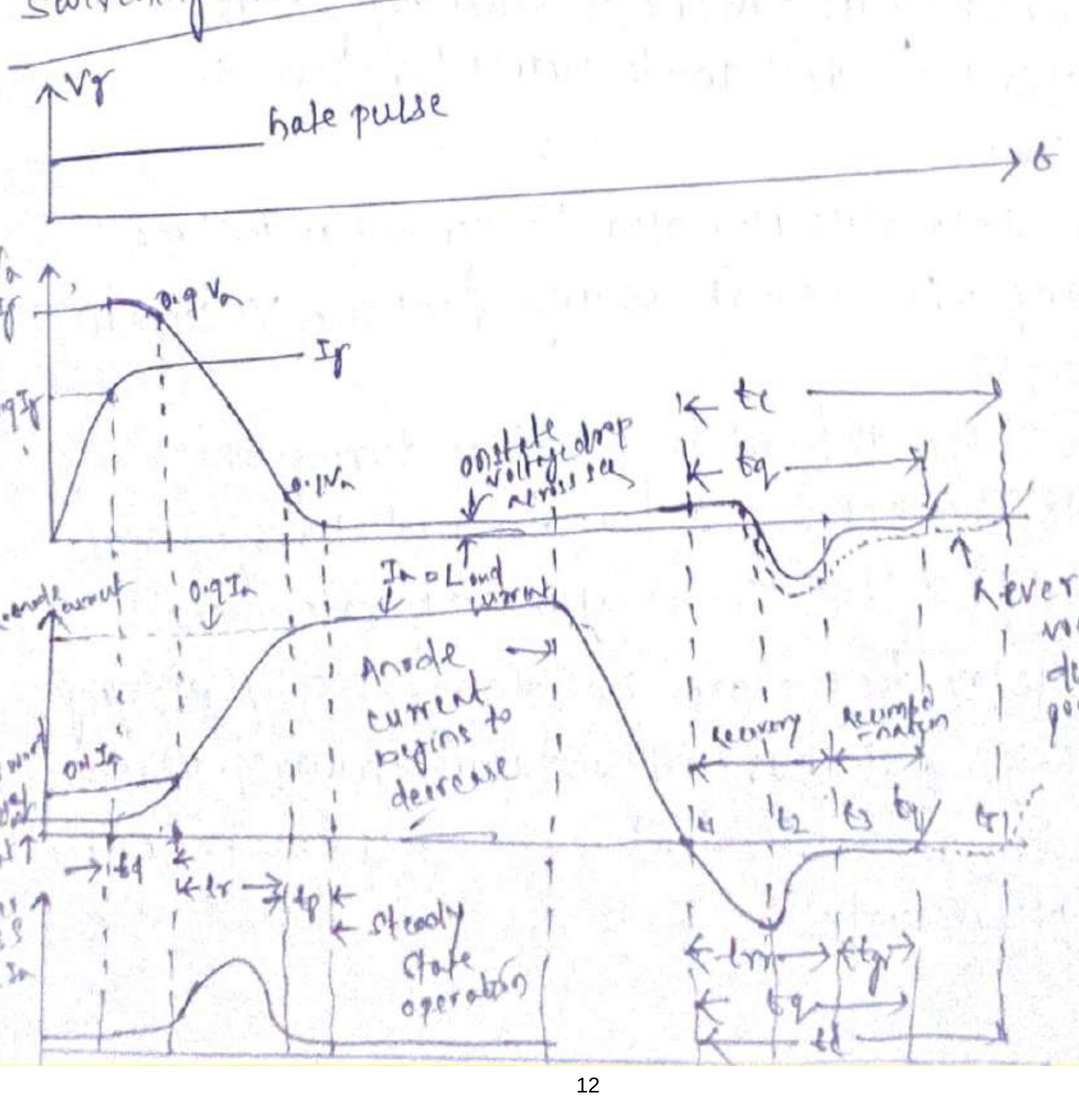

where $E_s$ = gate source voltage
$V_g$ = gate cathode voltage
$I_g$ = gate current
$R_s$ = gate source Resistance

$E_s = V_g + I_g R_s$

## Switching characteristics of thyristor:

- The time variations of the voltage across the thyristor and the current through it during turn on & turn off process give the dynamic or switching characteristic of thyristor.

## Switching characteristic



switching characteristic during turn on!

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→ A forward biased thyristor is usually turned on by applying a +ve gate voltage between gate & cathode. There is however a transition time forward off state to forward on state.

→ This transition time called thyristor turn on time. & is defined as the time during which it changes from forward blocking state to final on state.

→ Total turn on time can be devided into three intervals (I) Delay time $t_d$
(II) Rise time $t_r$
(III) spread time $t_p$

(I) Delay time

→ The delay time is measured from the instant at which gate current reaches $0.9 I_g$ to the instant at which anode current reaches to $0.1 I_a$.

→ The delay time may also be defined as the time during which anode voltage falls from $V_a$ (initial) to $0.9 V_a$.

→ It's also defined as the time during which anode current rises from forward leakage current to $0.1 I_a$ where $I_a$ = final value of anode current.

→ The delay time can be decreased by applying a high gate current and more forward voltage between anode & cathode. The delay time is fraction of microsecond.

(ii) Rise time (tr)

→ The rise time tr is the time taken by anode current to rise from 0.1Ia to 0.9Ia.

→ In rise time ~~anode voltage~~ forward blocking off state voltage fall from 0.9 to 0.1 of its initial value.

→ The rise time is inversely proportional to magnitude of gate current and its build up rate. Thus tr can be reduced if high and steep current pulses are applied to gate

→ The main factor determining tr is the nature of anode circuit.
eg for RL ckt tr is high while for RC circuit tr is low.

→ During rise time turn on losses in the thyristor are highest due to high anode voltage and large anode current

(iii) Spread time (tp)

→ It is the time taken by the anode current to rise from 0.9Ia to Ia & the forward blocking voltage fall from 0.1 of its initial value to the on state voltage drop (1 to 1.5V).

→ During this time conduction spreads over entire cross section of the cathode of SCR.

→ The spreading time depends upon the area of cathode & on gate structure of SCR.

Ton = Td + Tr + Tp

→ The magnitude of gate current is usually 3 to 5 times minimum gate current required to trigger an SCR.

→ When gate current is several times higher than minimum gate current required, then the thyristor is said to be hard fired or overdriven.

→ Hard firing or overdriven thyristor reduces its turn on time and enhances its di/dt capabilities.

Switching characteristic during turn off:

→ Thyristor turn off means that it has changed from on state to off state and is capable of blocking the forward voltage. This dynamic process of the SCR from conduction state to forward blocking state is called commutation process or turn off state.

→ The turn off time time $t_q$ of a thyristor is defined as the time b/w the instant the anode current becomes zero and the instant SCR regains forward blocking capability.

→ During turn off time, all the excess carriers from the four layers of SCR ~~regions~~ must be removed. This removal of excess carriers consists of sweeping out of holes from outer p layer and $e^-$ from outer n-layer. The carriers around $J_2$ can be removed only by recombination.

turn off time = Reverse Recovery time + gate Recovery time
($t_q$) ($t_{rr}$) ($t_{gr}$)

→ Thyristor with slow turn off time (50-100 μsec) are called converter grade SCR and those with fast turn off time (3-50 μsec) called inverter grade SCRs.

→ Converter grade SCRs are cheaper and are used for slow turn off process as in phase controlled rectifier, ac voltage controller, cyclo-converter etc.

→ Inverter grade SCRs are costlier and are used in inverters choppers and force commutated converters.

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Turn off Methods of Thyristor

→ Turn off a thyristor means bringing the device from forward conduction state to forward blocking state

→ for sucessful turn off (i) its anode current falls below the holding current (ii) & a reverse voltage is applied to thyristor for a sufficient time to enable it to recover to blocking state

→ Simply commutation means process of turning off a thyristor.

→ Commutation is basically two types
(i) Natural commutation (Line commutation)
(ii) forced commutation.

① Natural commutation (Line commutation) (17)

→ If the nature of the supply supports the commutation process then it is known as Natural commutation

exp (I) Rectifier (AC to DC)
(II) AC voltage controller (AC to AC)
(III) Step down cyclo converter (AC to AC)

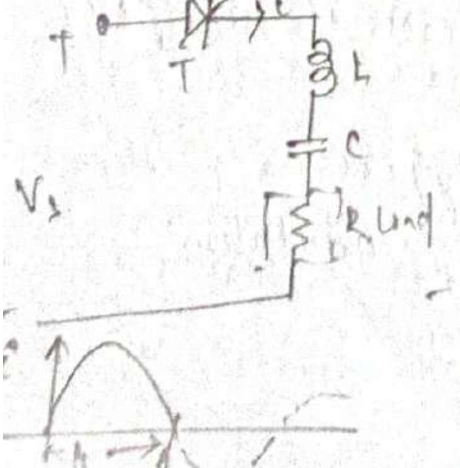
② forced commutation:

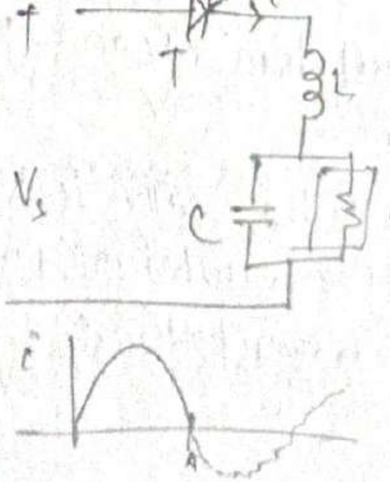
→ DC supply will not support the commutation process therefore we must use a forced commutation circuit to turnoff SCR, if load commutation is not possible.

exp (I) Chopper (DC to DC)
(II) Inverter (DC to AC)
(III) Stepup cycloconverter (AC to AC)

① CLASS-A commutation / Load commutation / Resonant commutation

→ for achieving load commutation of a thyristor the commutating component L & C are connected as shown



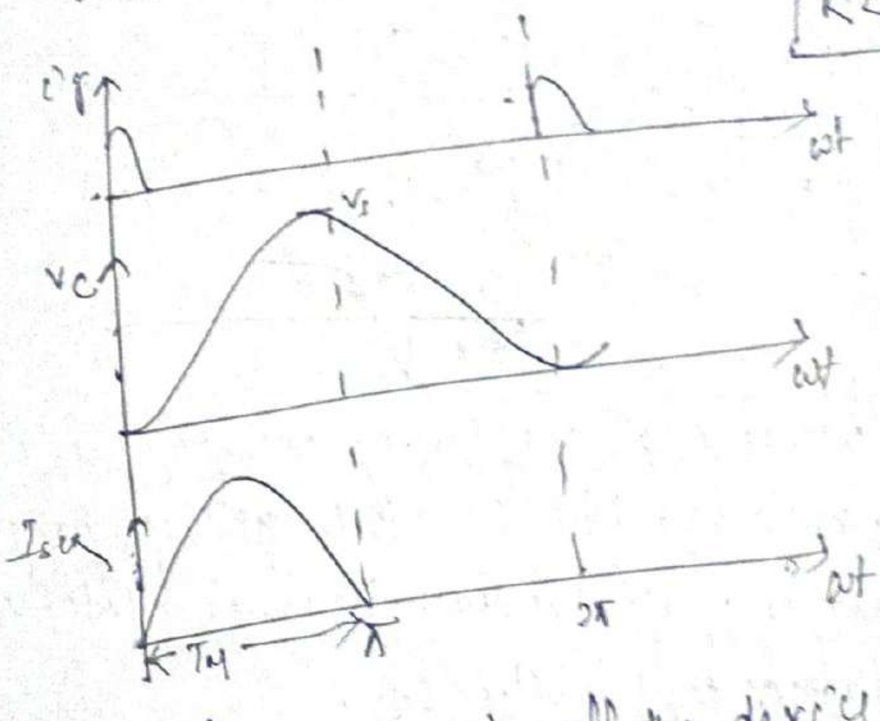
→ For high value of R, load R is connected across C.

→ The essential requirement for both the ckt is that over all circuit must be on underdamped.

When these ckts are energised from dc source current i first rises to maximum value and then begin to fall. When current decays to zero and tends to reverse thyristor T is turned off on its own at instant A.

condition for underdamped

$$R^2 < \frac{4L}{C}$$




The time for switching off the device is determined by the resonant frequency or ringing frequency which in turn depends on the value of the commutating components L & C and total load resistance.

for series RLC ckt Ringing frequency (ωr)

$$\omega_r = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

conduction time of thyristor $\omega_r t = \pi$

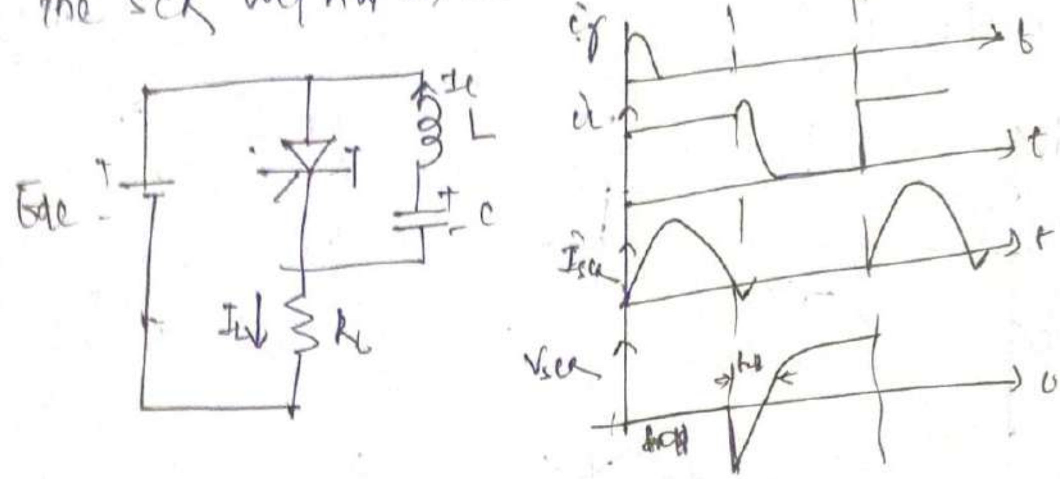
$$t = \pi/\omega_r \text{ sec}$$

## Application

→ This type of commutation circuits are most suitable for high frequency operation i.e above 1000 Hz.
Eg: used in series inverter.

## CLASS-B or Resonant pulse commutation

→ In this method, the LC resonating circuit is across the SCR and not in series with the load.




→ Initially as soon as the supply voltage Edc is applied, the capacitor C starts getting charged with its upper plate +ve and the lower plate -ve. & it charges upto voltage Edc.

→ When thyristor T is triggered, the circuit current flow in two direction:
(1) The load current $I_L$ flows through Edc − T − $R_L$ − Edc.
(2) commutating current $I_c$

→ The moment thyristor T is turned on, capacitor C starts discharging through the path $C_+$ − L − T − $C_-$

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- When the capacitor becomes completely discharged it starts getting charged with reverse polarity.
- Due to reverse polarity, a commutating current $I_c$ starts flowing which opposes the load current $I_L$.
- When $I_c > I_L$, then thyristor is turned off & capacitor C again starts getting charged to its original polarity through L & load. Thus when it is fully charged thyristor will be on again.
- Hence it is clear that the thyristor after getting on for sometime automatically gets off and after remaining in off state for sometime it again gets turned on.

Design considerations

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = 0$$

$$L\frac{d^2i}{dt^2} + \frac{1}{C} i(t) = 0$$

Taking Laplace transform

$$\left(s^2L + \frac{1}{C}\right) I(s) = 0$$

$$i(t) = E_{dc}\sqrt{C/L}\ \sin\omega_0 t$$

where $\omega_0 = \sqrt{1/LC}$

Peak commutating current $I_{c(peak)} = E_{dc}\sqrt{C/L}$

$$T_{off} = \pi/2\sqrt{LC}$$

voltage & current Rating of thyristor (21)

Assignment →

protection of thyristor

① over current protection:

We must connect either fuse (or) CB in series with SCR for over current protection

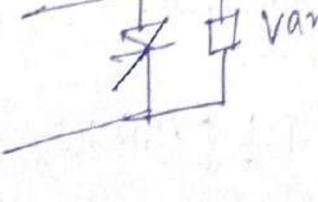
② over voltage protection

→ We must connect a varyster across the SCR for over voltage protection.

→ Varyster is a non-Linear Resistance

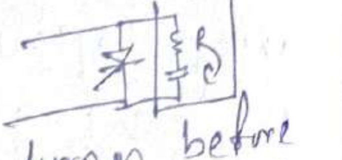
→ All Metal oxide resister behave as non-Linear resister

Exp ZnO




③ $\frac{dv}{dt}$ protection

$i_c = C_s \frac{dv}{dt}\uparrow$




→ At very high dv/dt SCR May turn on before the gate pulse is given. This is an accidental turn on.

→ This unwanted turn on is also known as false turn on.

→ so we must connect a snubber ckt across the SCR for dv/dt protection

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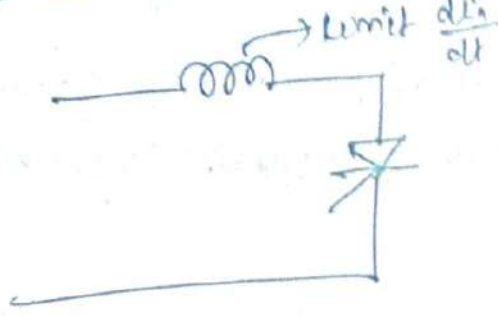
(4) $\frac{di_a}{dt}$ protection

We must connect an inductor in series with SCR for $\frac{di_a}{dt}$ protection. Otherwise it will result in Local hotspots hence damage the device.




(5) Gate protection: ( $I_{gmin} \leq I_g \leq I_{gmax}$ )

→ overcurrent protection:

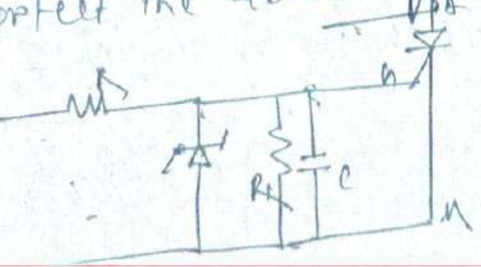
→ We must connect a resistor in series with the gate to limit the gate current with in the Max^m value.

→ Over voltage protection

→ We must connect a zener diode across gate cathode terminals for over voltage protection in the gate

protection against Noise signal

We must connect a parallel RC across gate cathode terminal. to protect the device against noise signal.



Date. 14/08/19

Firing circuits of thyristor (23)

As we know gate voltage control is the most common method for turning on the SCR.

→ The gate control circuit is also called firing or triggering ckt. These gating circuits are usually low power electronic ckt.

→ The basic requirement for successful firing of a thyristor are that the current supplied to the gate should

(1) be of adequate amplitude & sufficiently short rise time.

(2) be of adequate duration.

(3) Occur at a time when the main circuit conditions are favourable to conduction.

Gate current Amplitude:

→ The firing current $I_{gmin}$ expresses the minimum gate current required to fire all thyristor of a given type at a standard temperature however for satisfactory turn on & to reduce the turn on time, to increase di/dt rating or to reduce the turn on switching loss we normally require a firing current of about 1.4 $I_{gmin}$.

Hence amplitude & rise time must be considered together in designing a firing ckt in accordance with any stipulated di/dt capability & switching performance.

So for a successful firing we need high amplitude with a commensurately short rise time.

## Gate pulse duration

→ Under favourable conditions a thyristor may be triggered successfully by a gate pulse of duration approximately equal to turn on time of SCR. However a considerably longer pulse duration is desirable for one or more of the following reasons:

(a) A relatively long period may be required for the anode current to rise to the latching current level.

(b) Oscillations, reflections or other disturbance may conspire to turn off the thyristor shortly after it is first triggered.

(c) There may be uncertainity as to whether the anode circuit condition are favorable to conduction when the firing pulse is activated.

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→ Two alternatives to use if a gate pulse long enough to cover the region of uncertainty of firing are

(a) a control system in which the timing of the gate pulse is synchronized with the gate thyristor voltage or current zero rather than with supply voltage

(b) an extended train of short pulses.

extended gate firing pulse with high initial amplitude

## Gate Trigger circuit

→ A firing circuit should fulfill the following two functions

(i) If the power circuit has more than one SCR the firing ckt should produce gating pulse for each SCR at the desired instant for proper operation of the power ckt

(ii) The control signal generated by a firing circuit may not be able to turn on an SCR. It is therefore common to feed the voltage pulses to a driver ckt and then to gate cathode ckt. The driver ckt consists of a pulse amplifier & pulse Transformer

(27)

→ Resistance R should have such a value that Maximum voltage drop across it doesn't exceed Maximum possible gate voltage $V_{gm}$. This can happen only when R is under this cond?

$$\frac{V_m}{R_1+R} \times R \leq V_{gm}$$

$$\Rightarrow R \leq \frac{V_{gm} \times R_1}{V_m - V_{gm}}$$

→ As resistance $R_1, R_2$ are large, gate trigger ckt draws a small current. Diode 'D' allows the flow of current during positive halfcycle only i.e gate voltage $V_g$ is half wave dc pulse.
The amplitude of dc pulse can be controlled by varying $R_2$.

→ The potentiometer setting $R_2$ determines the gate voltage amplitude. When $R_2$ is large, current $i$ is small and the voltage across R i.e $V_g = i.R$ is also small as shown in fig(1). As $V_{gp}$ (peak of gate voltage $V_g$) is less than $V_{gt}$ (gate trigger voltage), SCR will not turn on. Therefore, load voltage $V_0 = 0$, $i_0 = 0$ and supply voltage $V_s$ appear as $V_T$ across SCR.
As trigger circuit consists of Resistance only, $V_g$ is therefore in phase with Voltage $V_s$.

→ In 2nd fig $R_2$ is adjusted such that $V_{gp} = V_{gt}$. This gives the value of firing angle = 90°.

→ In 3rd fig. $V_{gp} > V_{gt}$. As soon as $V_g$ becomes equal to $V_{gt}$ for the first time SCR is turned on. So resistance triggering can't give firing angle beyond 90°.

→ A relationship between $V_{gp}$ & $V_{gt}$ may be expressed as follows

$V_{gp} \sin\alpha = V_{gt}$

$\Rightarrow \alpha = \sin^{-1}\left[\frac{V_{gt}}{V_{gp}}\right]$

Since $V_{gp} = \frac{V_m R}{R_1 + R_2 + R}$

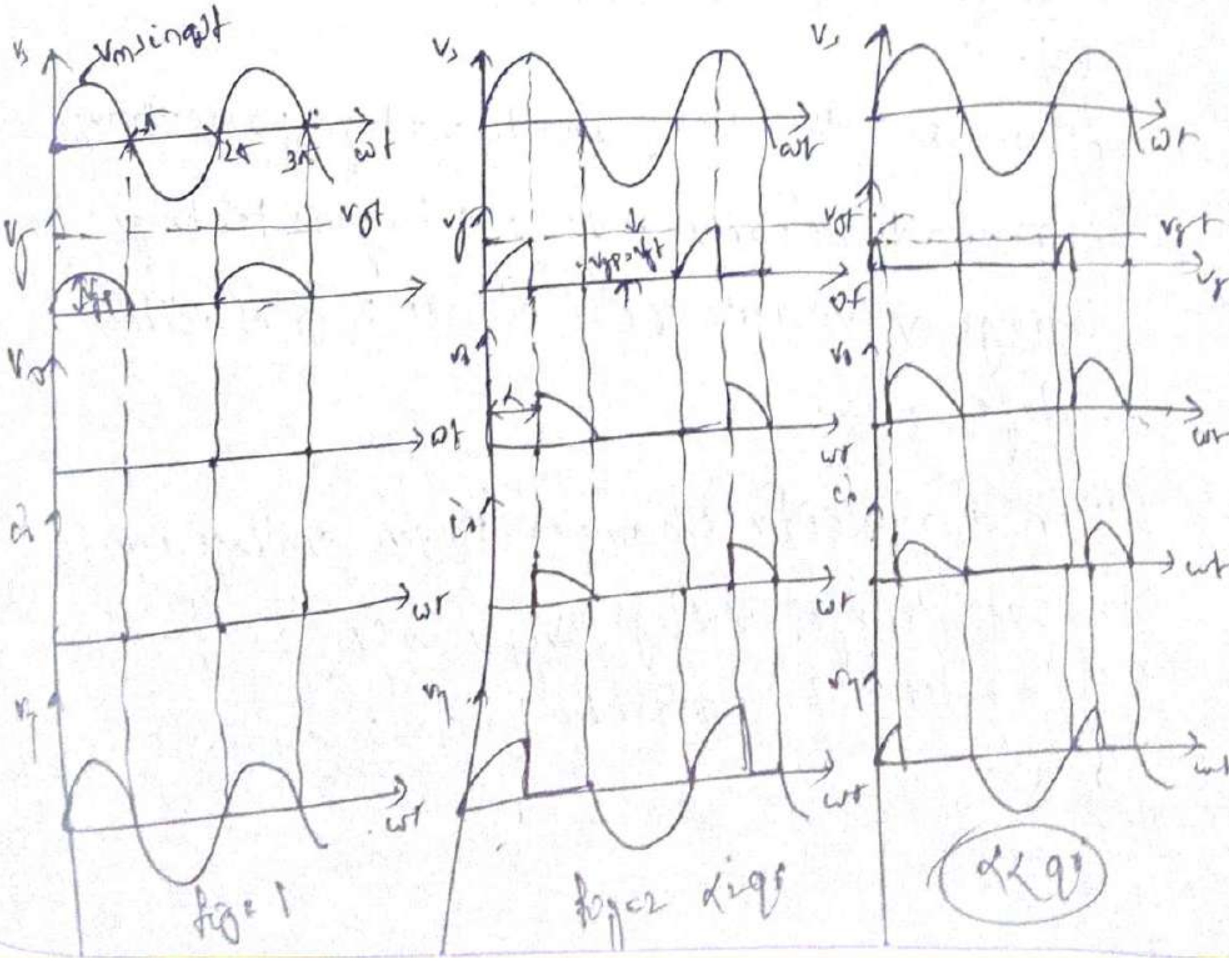
$\Rightarrow \alpha = \sin^{-1}\left[\frac{V_{gt}(R_1+R_2+R)}{V_m R}\right]$

As $V_{gt}$, $R_1$, R & $V_m$ are fixed,

$\Rightarrow \alpha \propto \sin^{-1}(R_2)$

or $\boxed{\alpha \propto R_2}$

→ As the firing angle controls from 0° to 90° the half wave power o/p can be controlled from 100% (when α=0) down to 50% (when α=90°)

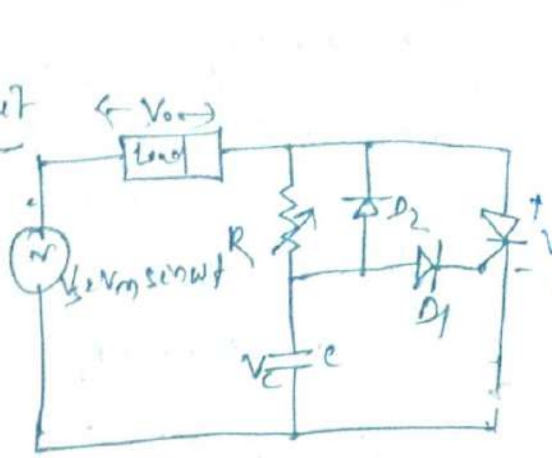


(29) DATE: 17/08/19

RC firing ckt:

(1) half wave trigger circuit

By varying the value of R, firing angle can be controlled from 0-180°




→ On the -ve half cycle, capacitor C charges through $D_2$ with lower plate +ve to the peak supply $V_m$ at ωt = -90°.

→ After ωt = -90°, source voltage $V_s$ decreases from $-V_m$ at -90° to zero at ωt=0°. During this period, capacitor voltage $V_c$ may fall from $-V_m$ at ωt=-90° to some lower value -Oa at ωt = 0°.

→ Now as the SCR anode voltage passes through zero and becomes +ve, C begins to charge through variable resistance R from initial voltage -Oa.

→ When capacitor charges to +ve voltage equal to gate trigger voltage $V_{gt}$, SCR is fired and after this capacitor holds a small +ve voltage.

→

$V_s \geq R I_{gt} + V_c$

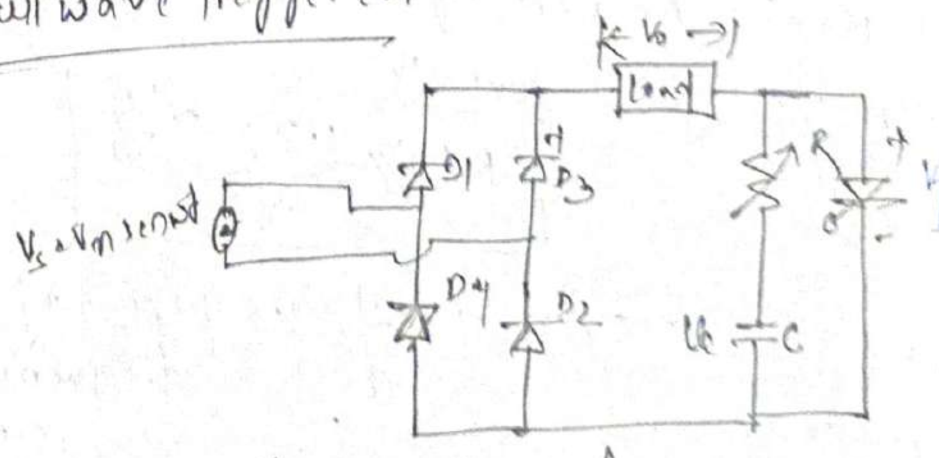
$V_s \geq R I_{gt} + V_{gt} + V_d$

$$R \leq \frac{V_s - V_{gt} - V_d}{I_{gt}}$$

where $V_s$ = source voltage at which thyristor turn on.

→ In the above figure if R is More the time taken for c to charge from $-V_m$ to $(V_{gt} + V_d)$ is More, firing angle is More and therefore average O/P voltage is low. If R is less, firing angle is low and therefore average o/p voltage is More.

(ii) RC full wave trigger ckt




→ In this case initial voltage from which the capacitor 'c' charges it almost zero.

→ The value of RC is calculated by emperical formula

$$RC \geq 50\, T/2 = \frac{157}{\omega}$$

$$R << \frac{V_s - V_{gt}}{I_{gt}}$$

(32)

## Unijunction Transistor

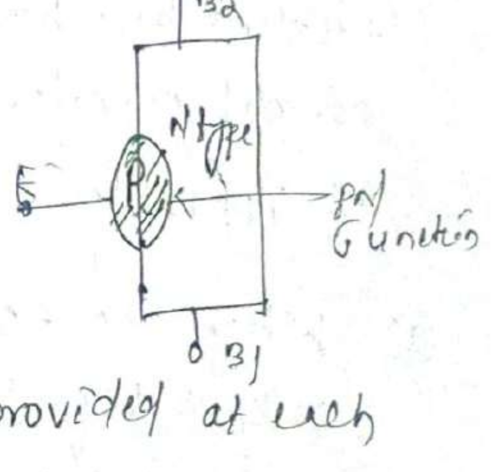
DATE: 19/08/19

→ The unijunction transistor is a three terminal single junction device.

→ UJT is always operated as a switch and finds most frequent applications in oscillator, timing circuits & SCR/Triac trigger circuits.

## Basic operation

→ An UJT is made up of an n-type silicon base to which p type emitter is embedded closer to $B_2$.




→ The n-type base is lightly doped whereas p type is heavily doped.

→ The two ohmic contact provided at each end are called base one ($B_1$) & base two ($B_2$). So unijunction transistor has 3 terminal namely Emitter (E), Base-one ($B_1$) & Base (2) ($B_2$).

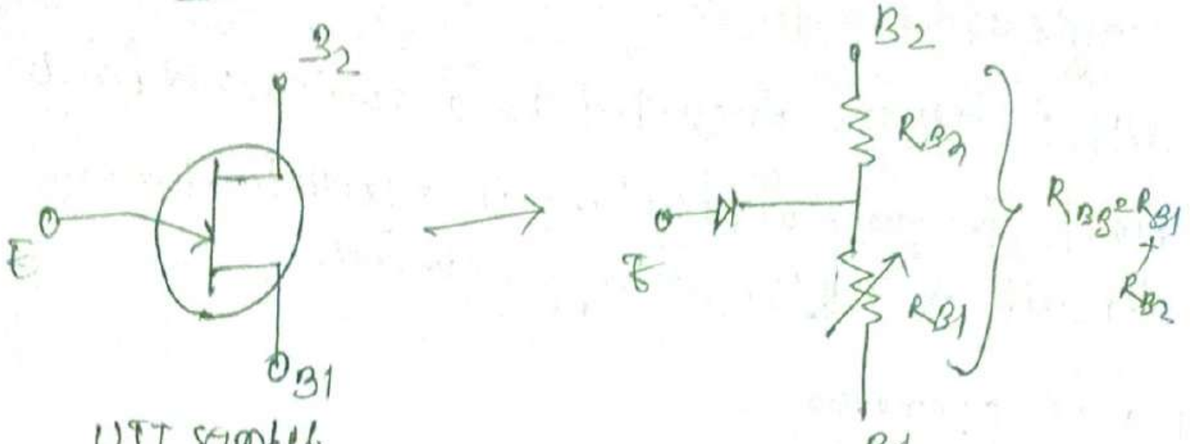
→ Between $B_1$ & $B_2$ an interbase resistance is present ($R_{BB}$)

→ This interbase resistance is broken into two resistances (i) the resistance from $B_1$ to E → $R_{B_1}$
(ii) the resistance from $B_2$ to E → $R_{B_2}$.

→ Since Emitter is closest to $B_2$ so $R_{B1} > R_{B2}$.

(33)

UJT Symbol & equivalent circuit




UJT Symbol

→ The diode represents the pn junction b/w emitter & base bar. & $R_{B1}$ is variable during normal operation

UJT Operation

(a) When the emitter diode is reverse biased only a very small emitter current flows. Under this condition $R_{B1}$ is at normal high value. This is the UJT off state

(b) When the emitter diode becomes forward biased, $R_{B1}$ drops to a very low value so that the total resistance b/w E & $B_1$ is very low, allowing emitter current to flow readily. This is the on state

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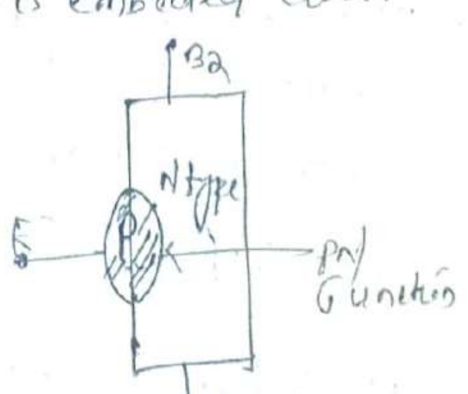


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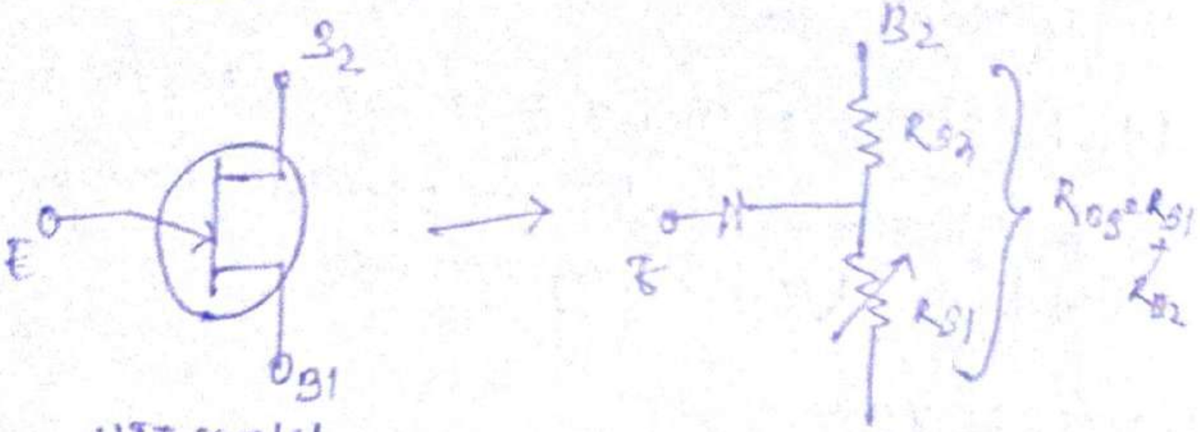


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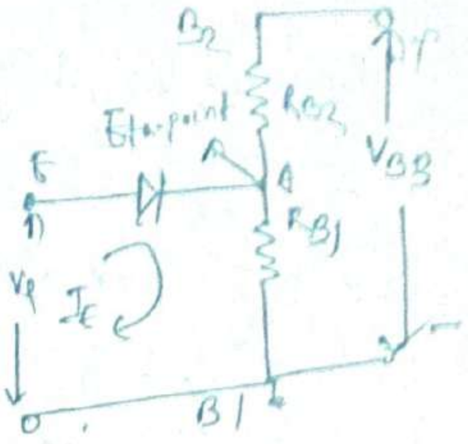
Circuit operation

When voltage $V_{BB}$ is applied across the two base terminal the potential of point A with respect to B1 is given by -




$$V_{AB1} = V_{BB} \times \frac{R_{B1}}{R_{B1}+R_{B2}}$$

$$\boxed{V_{AB1} = \eta V_{BB}}$$

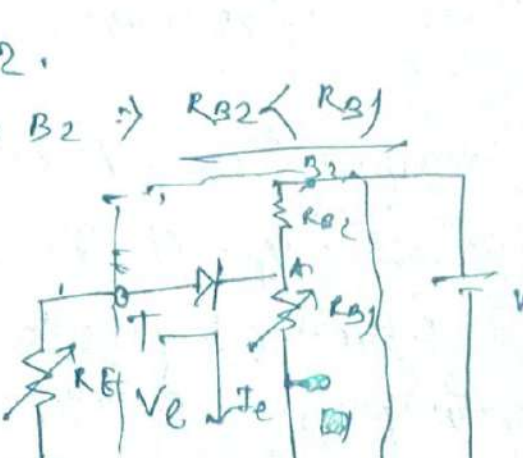
where $\eta = \frac{R_{B1}}{R_{B1}+R_{B2}}$ is called intrinsic standoff ratio.

$$0.51 < \eta < 0.82$$

The interbase resistance $R_{BB} = R_{B1}+R_{B2}$ is of the order (5-10)kΩ.

Since E is closer to B2 ⇒ $R_{B2} < R_{B1}$

→ The magnitude of Ve can be varried by regulating external resistance $R_E$.




→ As long as $V_e < \eta V_{BB}$, the E-B1 is reverse biased & the emitter current is -ve as shown by the curve PS. The region PS of very low current is treated as off switch. (equivalent ckt)

→ ~~$R_{B1}$ is very high~~

→ The resistance between E - $B_1$ Junction is therefore very high.

→ At S, $I_e = 0$, drop across $R_E = 0$ therefore $V_e$ = source voltage i.e. OS = $V_e = V_{EE}$

→ So when $V_e = \eta V_{BB} + V_D$, point B is reached and E-B1 Junction gets forward biased to allow forward current through the diode

→ point B is called <u>peak point</u> and at this point voltage is $V_p$ & current is $I_p$ which is known as peak point voltage & peak point current respectively.

→ By varying $R_E$, $V_e$ is increased till $V_e$ approaches $V_p$. At this peak point $V_e = \eta V_{BB} + V_D = V_p$ the P-emitter begins to inject holes from the heavily doped emitter E into the lower base region $B_1$. As n type Base is lightly doped the holes rarely get any chance to recombine.

→ The lower base $B_1$ is therefore filled up with additional current carriers (holes). As a result resistance $R_{B1}$ of E-$B_1$ Junction decreases.

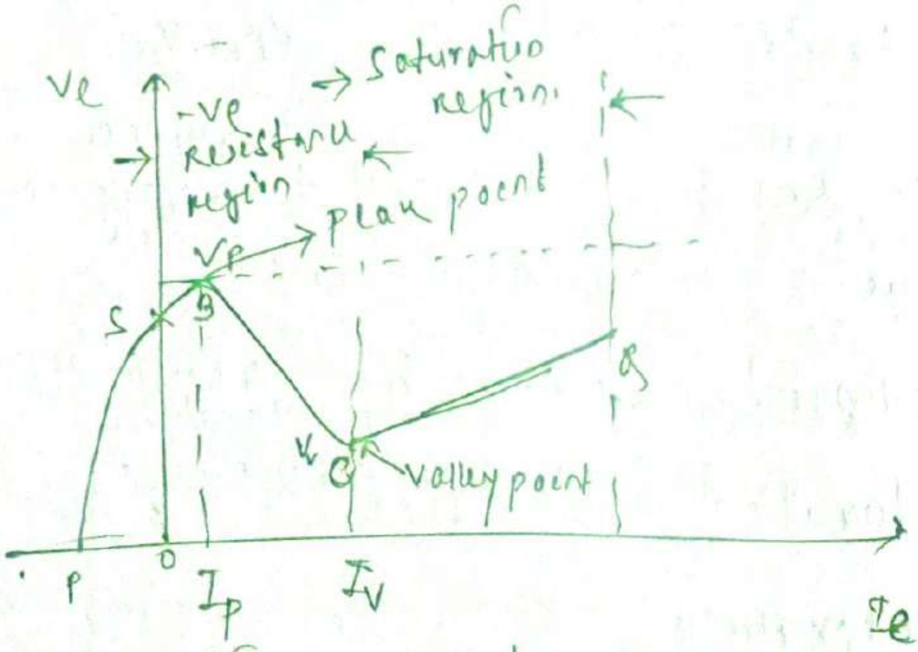
- The fall in $R_{B1}$ causes potential of point A to drop
- This drop in $V_A$ in turn causes $V_e = V_A + V_D$ to fall. As $V_{EE}$ is constant, fall in $V_e$ gives rise to more emitter current $I_e = \frac{V_{EE} - V_e}{R_E}$.
- This increased $I_e$ injects more holes into region $B_1$, thereby further reducing the resistance $R_{B1}$ and so on. This effect known as regenerative or snow-balling effect which continues till $R_{B1}$ has dropped to a small value (a to a r e).
- The emitter current limited by external resistance $R_E$ is then given by $I_E = \frac{V_{EE} - V_D}{R_{B1} + R_E}$
- When $R_{B1}$ has dropped to a very small value indicated by point 'c'.
- At point 'c' entire base region $B_1$ is saturated and resistance $R_{B1}$ can't decrease further more.
- The point 'c' is called the valley point & $V_V$ & $I_V$ are the corresponding valley voltage & valley current.
- After UJT is on or after valley point is reached an increase in $V_e$ is accompanied by increase in

$I_e$ ; this is indicated by curve CQ.

→ At point Q, Ve is little more than its valley point voltage $V_v$.

→ Between B & C, emitter voltage Ve falls as $I_e$ increases; UJT therefore exhibits negative resistance between these two points.

→ At the valley point, the current is given by $V_v/R_{B1}$. Valley point current, also called holding current, keeps UJT on. When $I_e$ falls below $I_V$ UJT is off.

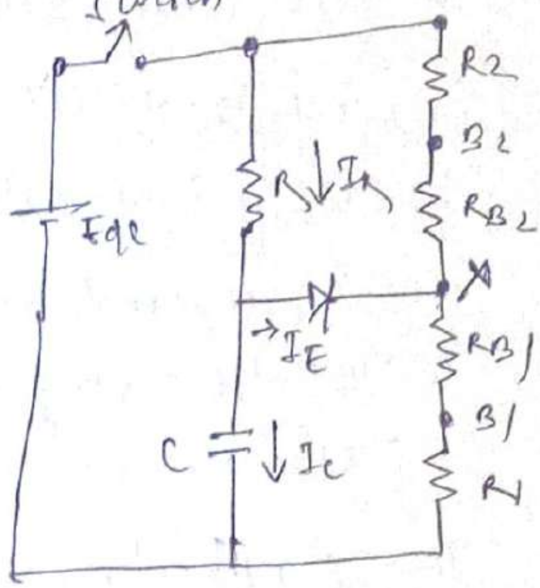



UJT Relaxation oscillator

The most common UJT circuit in use today is the relaxation oscillator which is shown in the figure. Also this type of circuit is basic to other timing (or) trigger circuit

(38)

→ Let us consider a situation in which capacitor is at zero volt & the switch is suddenly closed at t=0, applying Edc to the circuit.




Since $V_E = V_C = 0$, the UJT emitter diode is reverse biased and UJT is off.

$$V_x = E_{dc} \times \frac{(R_{B1}+R_1)}{R_{B1}+R_{B2}+R_1+R_2}$$

Normally $R_1$ & $R_2$ is much smaller than $R_{B1}$ & $R_{B2}$

so $V_x \simeq \eta E_{dc}$.

→ In this condition the only emitter current flowing will be small reverse leakage $I_{E0}$. So Emitter is open. Now capacitor will begin to charge towards the input voltage Edc through R.

→ The capacitor voltage increases with a time constant of RC. It will continue to increase till voltage of emitter reaches to peak point voltage $V_p$.

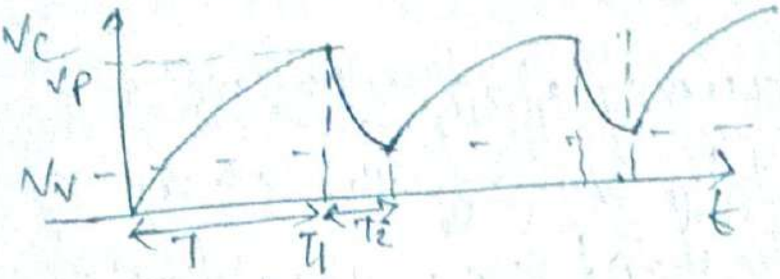
(39)

→ At this time, emitter diode becomes forward biased and UJT turns on with RB1 dropping to very low value. Since the diode is now forward biased, the capacitor will discharge through low resistance path containing the diode, RB, R4.

→ The capacitor discharge time is normally short compared to its charging time constant.

→ The discharging capacitor provides the emitter current needed to keep the UJT 'on'; it will remain on until $I_E$ drops below the valley current $I_V$ at which time the UJT will turn off. This occurs at time T2 when the capacitor voltage dropped to valley voltage $V_V$. At this time, $R_{B1}$ returns to its off value, the diode is again reverse biased & $I_E \approx 0$.

→ The capacitor will begin charging towards $E_{dc}$ once again and the previous chain of events will repeat itself indefinitely so long as power is applied to the circuit. The result is a periodic saw tooth wave-form.




The length of one period T1 is essentially the time it takes for the capacitor to charge to Vp since the discharging time T2 is usually very short. Thus $T \simeq T_1$

$$T = RC \ln\left[\frac{E_{dc}}{E_{dc} - V_p}\right]$$

In most cases $V_p \simeq \eta E_{dc} + V_D$

$$T \simeq RC \ln\left[\frac{E_{dc}}{E_{dc} - (\eta E_{dc} + V_D)}\right]$$

$$T = RC \ln\left[\frac{E_{dc}}{E_{dc}(1-\eta) + V_D}\right]$$

Normally $V_D \simeq 0$

$$\Rightarrow T \simeq RC \ln\left[\frac{E_{dc}}{(1-\eta) E_{dc}}\right]$$

$$\boxed{T \simeq RC \ln\left(\frac{1}{1-\eta}\right)}$$

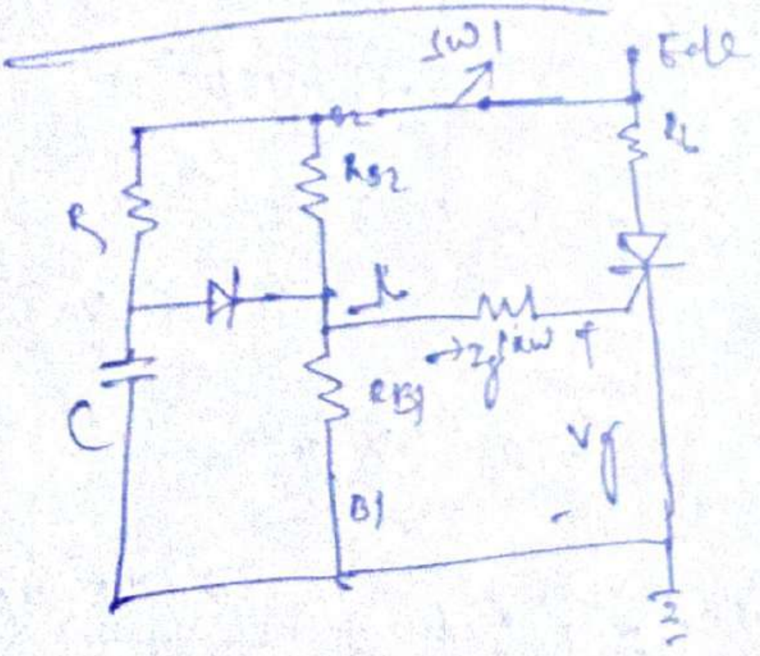
Point

→ The frequency of oscillation can be controlled by varying the charging time constant RC. Then fore the limits on R are

$$R_{min} = \frac{E_{dc} - V_V}{I_V}$$

$$R_{max} = \frac{E_{dc} - V_P}{I_P}$$

The UJT as an SCR trigger



DATE: 21/08/19

## pulse transformer in Triggering circuits

→ pulse transformer are used quite often in firing circuits for SCRs and GTOs. This transformers have usually two secondaries. The turn ratio from primary to secondaries is 2:1:1 or 1:1:1

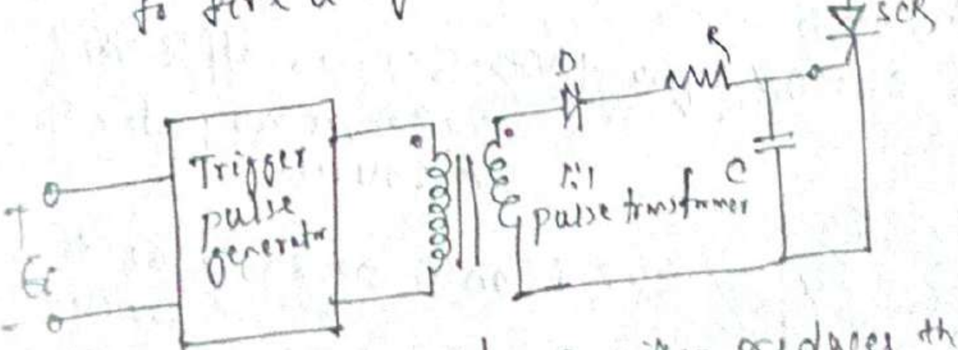
→ These transformers are designed to have low winding resistance, low leakage reactance & low inter winding capacitance.

## Advantage of using pulse transformer in triggering ckt

(i) The isolation of low voltage gate circuit from high voltage anode circuit

(ii) the triggering of two or more devices from the same trigger source.

→ The below figure shows a complete output circuit to fire a thyristor correctly.

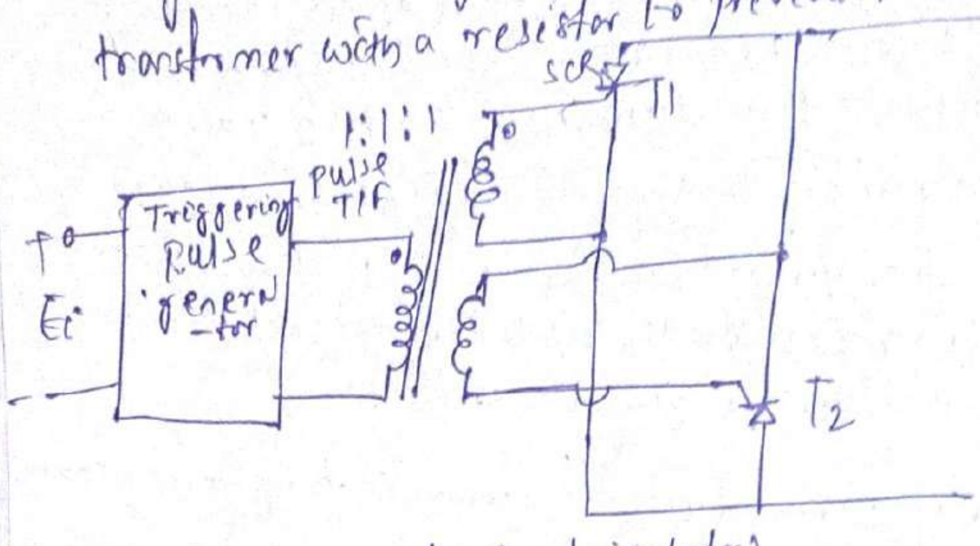



→ The series resistor R either reduces the SCR holding current or balances the gate current in a 3 winding transformer connected to two SCRs.

→ The series diode D prevents reverse gate current in case of reversal of the pulse transformer output voltage.

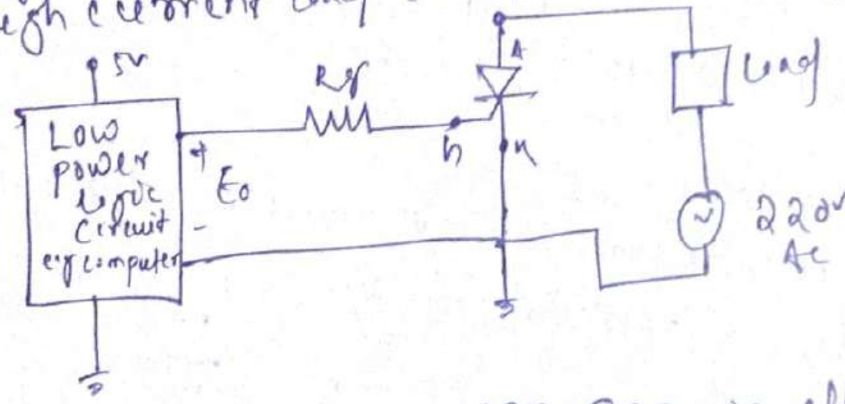
(43)

→ In some cases where high noise level is present it may be necessary to load the secondary of the transformer with a resistor to prevent false triggering.




## Optical isolator (optoisolator)

→ A common situation where a low voltage, low current logic circuit controlling a high voltage and high current load is shown in below fig




when $E_0 = 0V$ (ground) (or) SCR is off & the load receives no power from the ac source

when $E_0 = 5V$ ⇒ SCR is on & the 230V ac is switched to load

→ Generally it is not desirable to have a direct electrical connection between low power control circuit and the high-power load it controls, as done in the circuit

Dis advantage of transistor (54)

1) noise being coupled from high current circuit to low power logic circuit (especially over wiring ground (i.e))

2) There is a possibility of high voltage from the load circuitry feeding back into the logic circuit as a result of component failure

-> Another Means for doing this is to use an electromechanical relay.

-> In this case the logic circuit drives the low current relay coil and the relay Magnetically controls the switch contacts that connect power to load

disadvantage of electromechanical relay

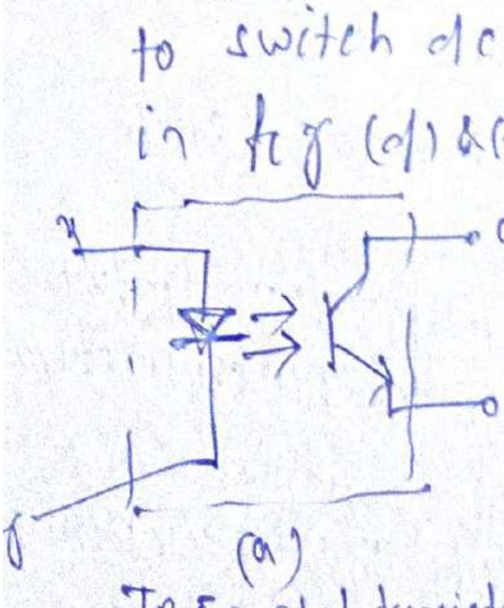
-> They are fairly expensive
-> Relays are bulkier than solid state devices
-> They create Magnetic fields and inductive spikes which can be trouble some source of electrical noise
-> Relays have shorter life than semiconductor device
-> The contacts create sparking upon opening.

→ These above disadvantages are largely overcome by the devices called optical isolator, which use light energy to couple the control signal to the load.

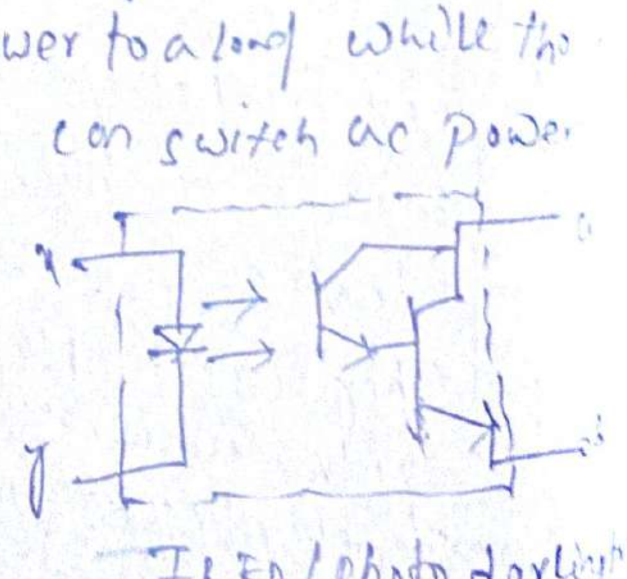
→ Optical isolator consists of a light source (usually an infrared emitting diode IRED) a light sensitive device (e.g. phototransistor) and a switching device.

→ The input circuit is simply an IRED which emits IR radiation when it is sufficiently forward biased. This radiation is focused on a light sensitive device so that it switches on when sufficient current flows through IRED.

→ The optoisolator in fig (a), (b), & (c) are used to switch dc power to a load while those in fig (d) & (e) can switch ac power.

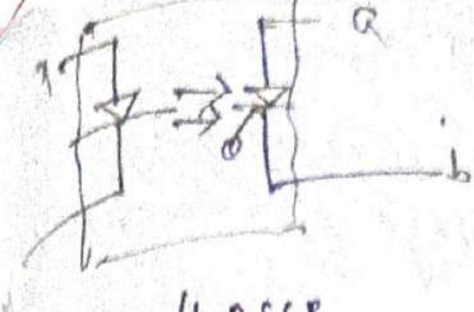



(a)
IRED phototransistor



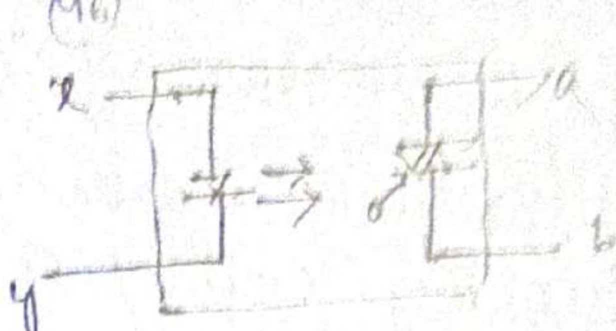

IRED / photo darlington
(b)

(46)

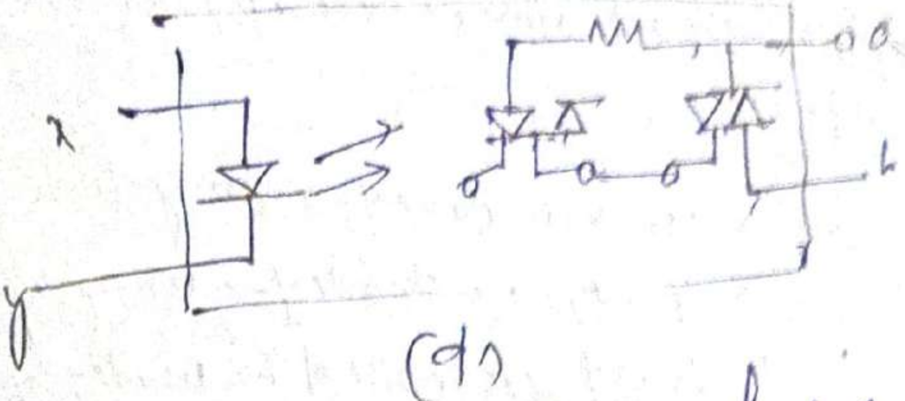



IRED/LDSCR

(C)



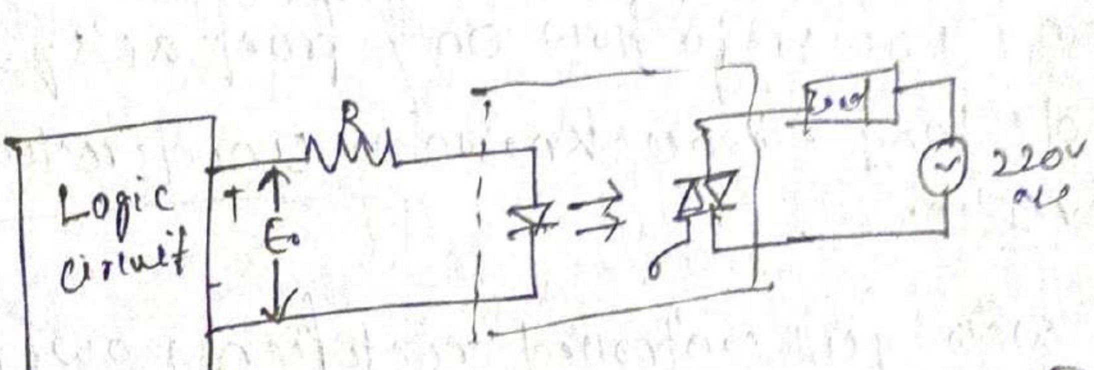

(d) IRED / light activated TRIAC




(d)

IRED / Triac / Triac for high current ac

Electrical isolation provided by an optoisolator




When $E_0$ = 0V IRED is nonconducting ⇒ TRIAC is off
So load receives no ac voltage

When $E_0$ = 5V IRED conducts ⇒ Triac = on
So load receives ac voltage

## Introduction Phase Controlled Converter (47) DATE 22/01/17

→ Rectification is a process of converting an alternating current (or) voltage into a direct current & voltage.

→ This conversion can be done using switching devices like Diode, thyristor, power transistor, power MOS etc.

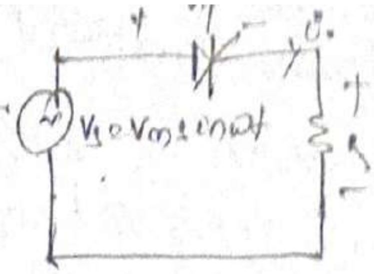
Rectifier → uncontrolled → using diode
→ fully controlled → using thyristor
→ half controlled → Diode + thyristor
⇓
half controlled rectifier is cheaper than fully controlled rectifier

→ Uncontrolled & half controlled rectifiers will permit power to flow only from ac system to dc load & hence known as unidirectional converter.

→ But with full controlled rectifier, power can be transferred from dc side to ac system also. This is why it is known as bidirectional converter.

Control Techniques (phase control)

→ The simplest form of rectifier circuit consists of a single thyristor feeding dc power to a resistive load R.




An SCR can conduct only when anode voltage is +ve and a gating signal is applied. Thyristor blocks the flow of load current $i_o$ until it is triggered.

→ suppose at some ~~firing~~ delay angle $\alpha$, a +ve gate signal is applied between gate & cathode which turns on the SCR. Immediately full supply voltage is applied to load as $V_o$.

→ firing angle of a thyristor is measured from the instant it would start conducting if it were replaced by a diode

→ so firing angle is defined as the angle between the instant the thyristor would conduct if it were a diode and the instant it is triggered

OR

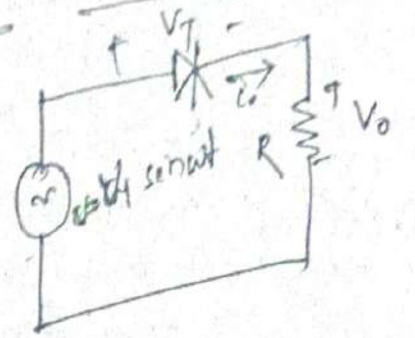
firing angle can also be defined as the instant that gives the largest average o/p voltage to the instant it is triggered.

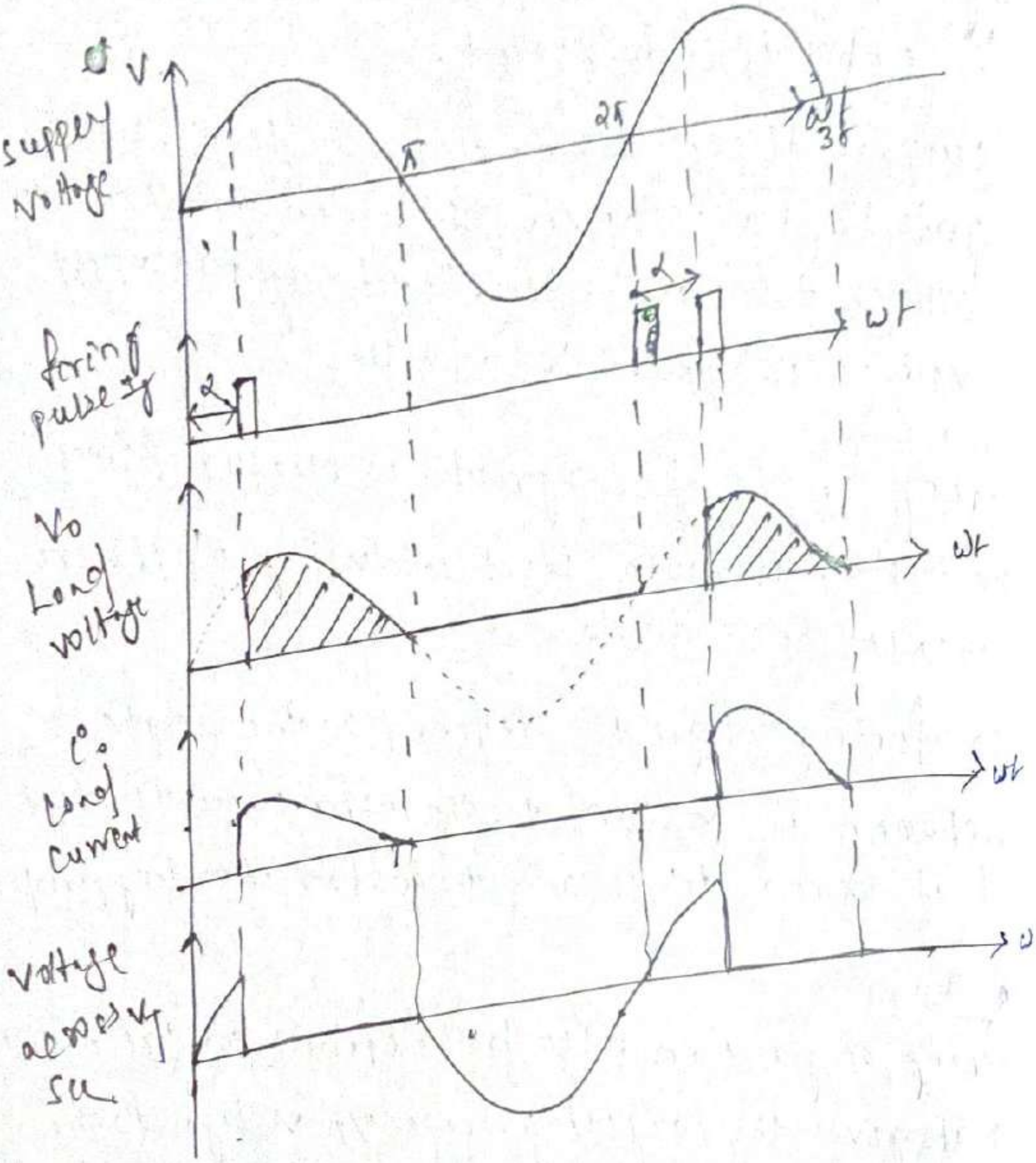
(or)

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

(49)

① Single phase half wave controlled Rectifier with R-load




Average output voltage:

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

$$= \frac{V_M}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_M}{2\pi}\left(-\left[-1-\cos\alpha\right]\right)$$

$$V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)$$ (4)

$$V_0\Big|_{Max\ \alpha=0} = \frac{V_m}{\pi}$$

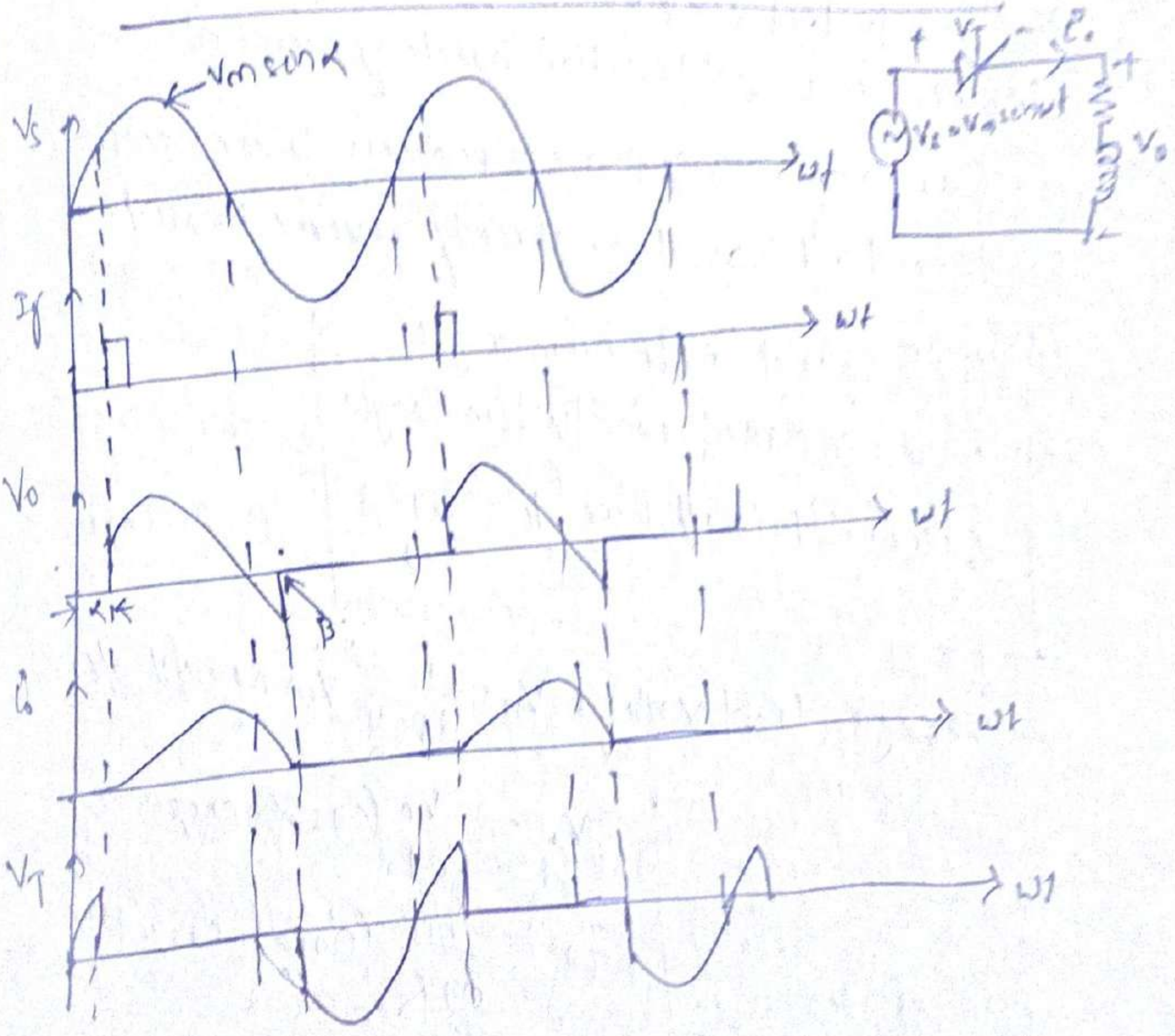
conduction angle $\gamma = \pi-\alpha$

$\omega t_c = \pi$
$t_c = \pi/\omega$

Average load current

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

(2) Single phase half wave controlled Rectifier with RL Load



(51)

→ At $\omega t = \alpha$, thyristor is turned on by gating signal. The load voltage $v_0$ at once becomes equal to source voltage $V_s$. But the inductance L forces the load or output current $i_0$ to rise gradually. After some time $i_0$ reaches maximum value and then begins to decrease.

→ At $\omega t = \pi$, $v_0$ is zero but $i_0$ is not zero because of load inductance 'L'.

→ After $\omega t > \pi$, SCR is subjected to reverse anode voltage but it will not be turned off as load current $i_0$ is not less than holding current.

→ At some angle $\beta > \pi$, $i_0$ reduces to zero and SCR is turned off as it is already reverse biased.

| |
|---|
| $\beta$ is called extinction angle |
| $\beta - \alpha = \gamma$ called conduction angle |
| Circuit turn off time $t_c = \dfrac{2\pi - \beta}{\omega}$ |

Average load voltage $V_0 = \dfrac{1}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t \, d(\omega t)$

$$V_0 = \frac{V_m}{2\pi} (\cos\alpha - \cos\beta)$$

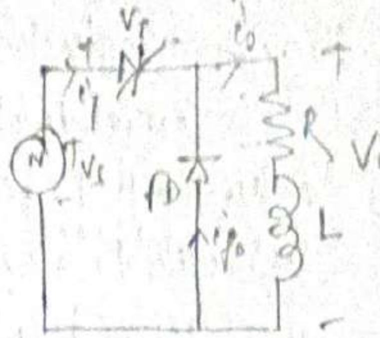
$$I_0 = \frac{V_m}{2\pi R} (\cos\alpha - \cos\beta)$$

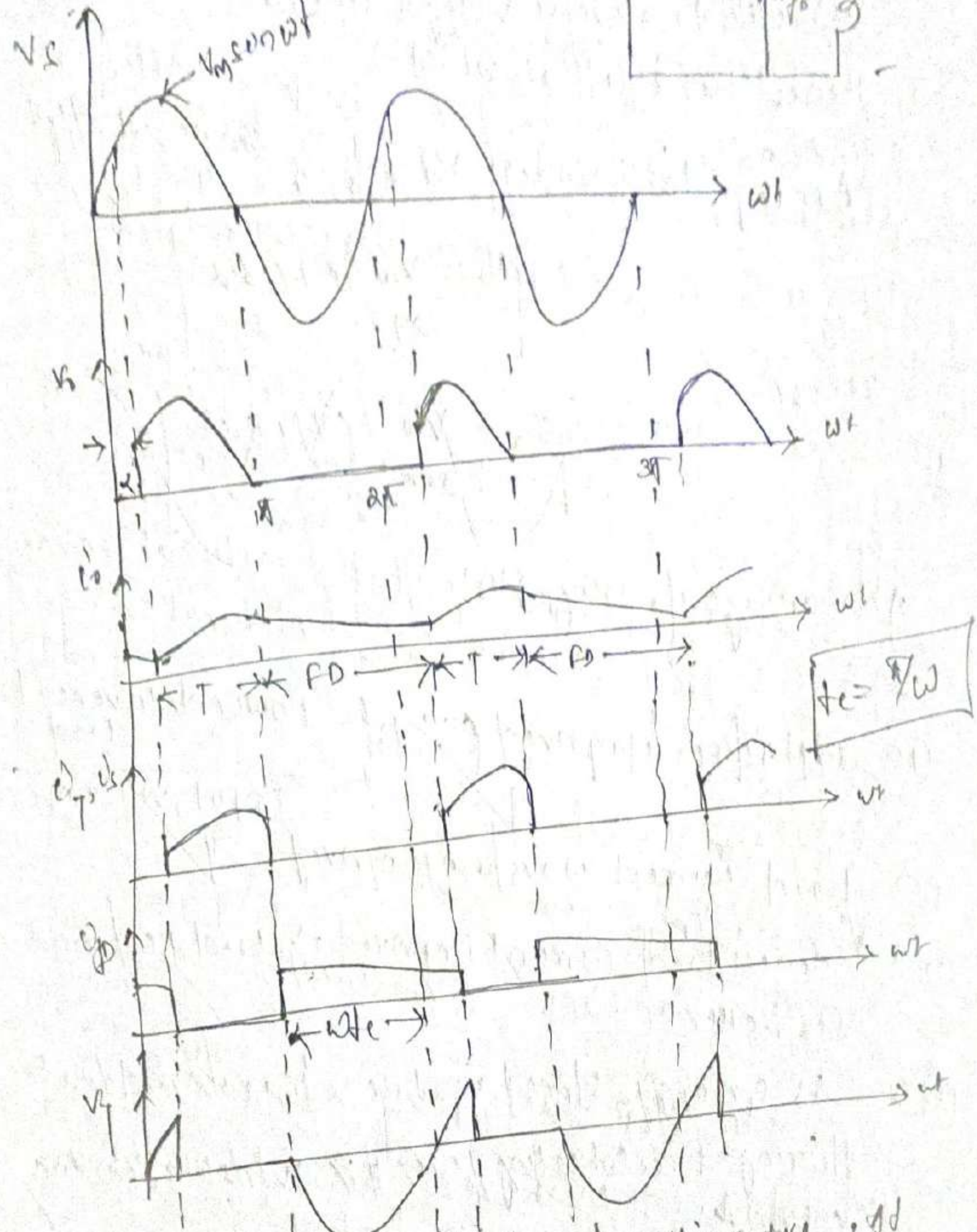
(52) DATE 25/01/17

## Single phase half wave circuit with RL Load & FD:

FD:→ freewheeling diode

Also called bypass or commutating diode




At ωt=0, source voltage becoming +ve. At some delay angle α, forward biased SCR is triggered and source voltage $V_s$ appeared across load as $V_0$.

→ At ωt = π, source voltage $v_s$ is zero and [illegible] it tends to reverse. Just after this [illegible] free wheeling diode (FD) becomes forward biased [illegible]. As a result load current [illegible] is gradually transferred from SCR to FD [illegible] it tends to reverse. At the same time [illegible] subjected to reverse voltage and zero current and [illegible] hence turned off at ωt = π.

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

$$V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)$$

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

Advantage of using FD:

(i) i/p pf is improved ($\because$ p.f. = $\frac{\text{power delivered to load}}{\text{Input volt amp}}$)

(ii) Load current waveform improved

(iii) since load current improved ⇒ load performance is better.

(iv) as energy stored in L is transferred to load during freewheeling period ⇒ overall efficiency improves.

Disadvantage of halfwave converter

from halfwave converter, the supply current is taken from source is unidirectional and is in the form of dc pulse.

(54)

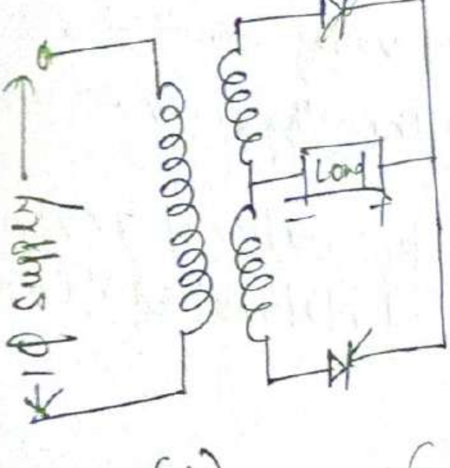
→ Single phase half wave converter thus introduces a dc component into the supply line. This is undesirable as it leads to saturation of the supply transformer and other difficulties (harmonics etc.)

→ These shortcomings can be overcome to some extent by use of single phase full wave circuits

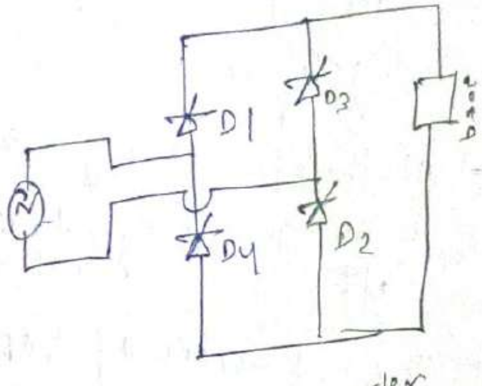
Single phase full wave converter:

(i) Midpoint converter

(ii) Bridge converter

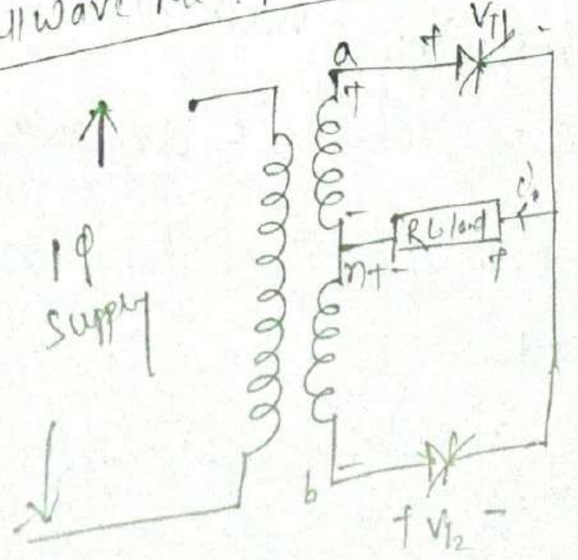



(1)
Midpoint connection




Bridge converter

Single phase full wave Midpoint converter (CT connection)

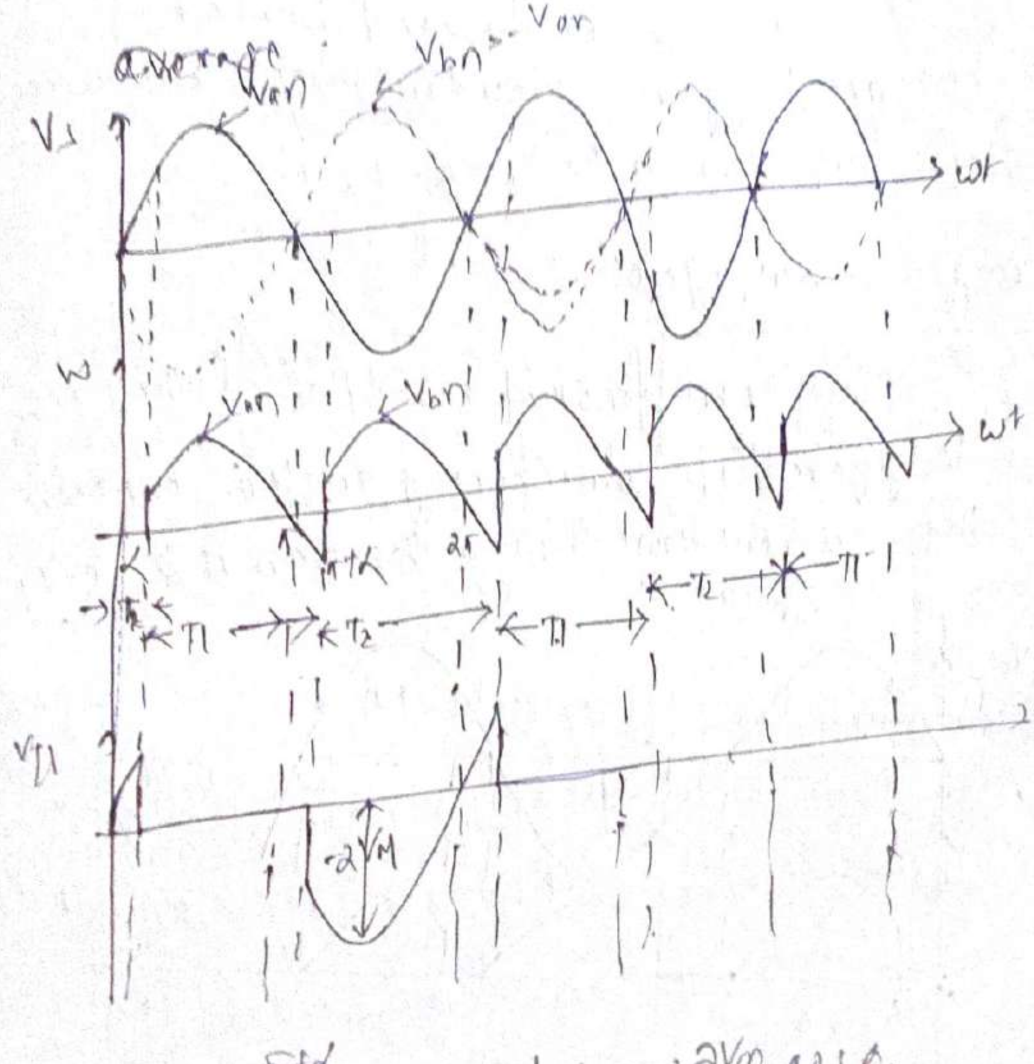


(56)

→ At $\omega t = \pi + \alpha$, $T_2$ is triggered, $T_1$ is reverse biased by voltage of magnitude $2V_m \sin\alpha$ & current is transferred from $T_1$ to $T_2$, $T_1$ is therefore turned off.

→ At $\omega t = \alpha$, $T_2$ is turned off and it remains reverse biased from $\omega t = \alpha$ to $\omega t = \pi$.

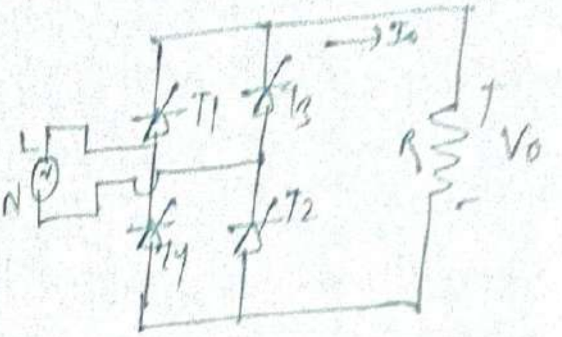
So circuit turn off time = $t_c = \frac{\pi - \alpha}{\omega}$




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

(57) DATE: [illegible]

Single phase full converter (B-2 connection) (with Resistive load)

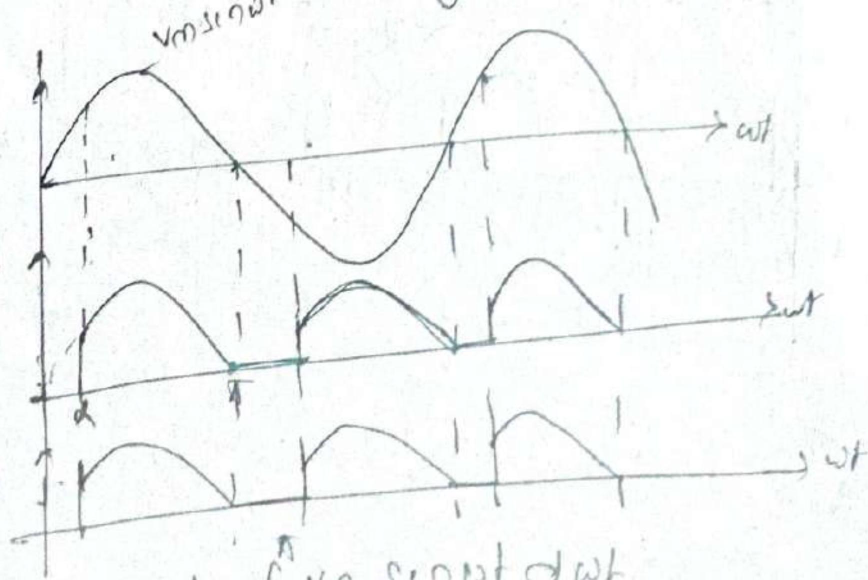



**During +ve half cycle**

$T_1$ & $T_2$ are forward biased & if both are triggered simultaniously, then current flows through L - $T_1$ - R - $T_2$ - N.

**During -ve half cycle**

$T_3$ & $T_4$ are forword biased & if they are triggered at same firing angle α then current flows through the path N - $T_3$ - R - $T_4$ - L.



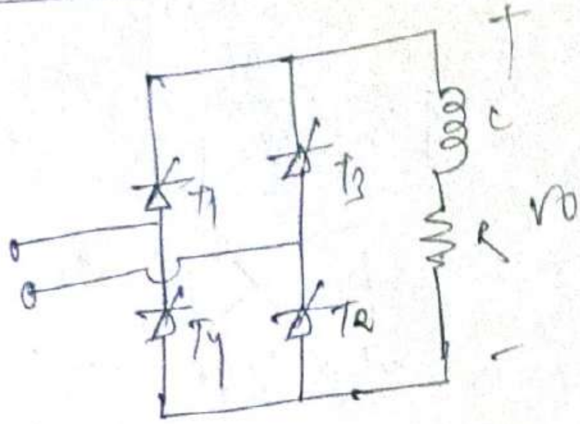

$$V_o = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

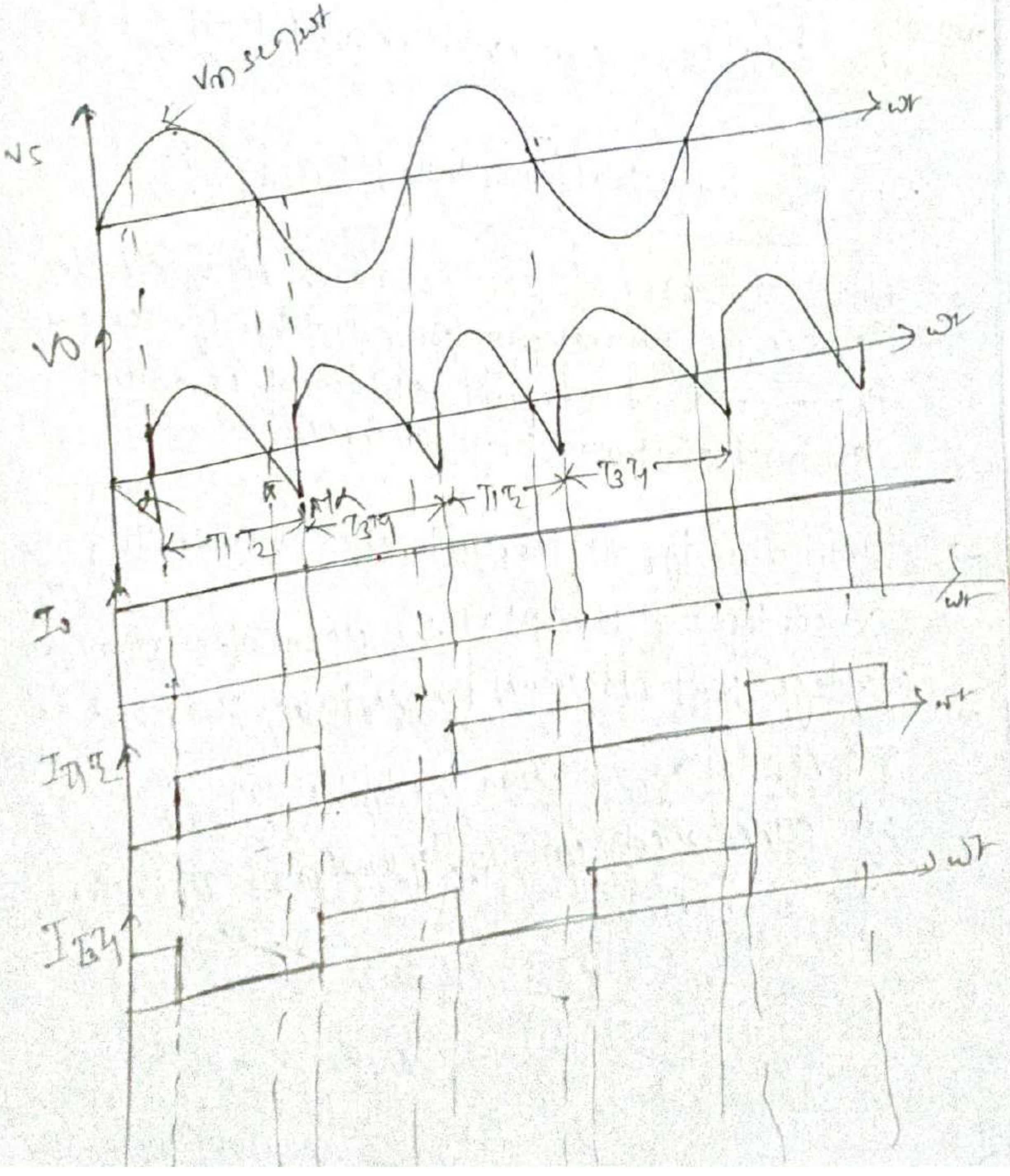
$$V_o = \frac{V_m}{\pi} \times \left(-\cos\omega t\right)_{\alpha}^{\pi} = \frac{V_m}{\pi}(1+\cos\alpha)$$

(58)

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

fully controlled Bridge circuit with R-L load



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

$$\boxed{V_0 = \frac{2V_m}{\pi}\cos\alpha}$$

$$\boxed{I_0 = V_0/R}$$

NOTE: If $\alpha < 90°$ then it is rectification mode
If $\alpha > 90°$ then it is Inverter mode

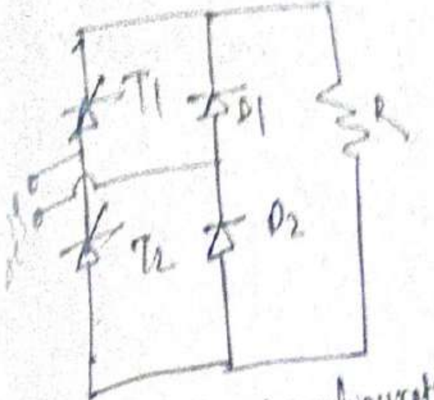
Waveform 1φ fullwave converter with RL load & FD

Single phase half controlled bridge rectifier

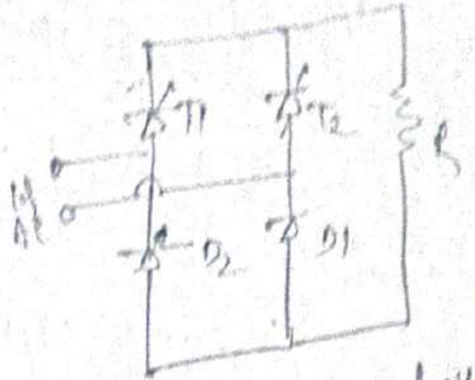
→ When one pair of SCR is replaced by diodes in single phase fully controlled bridge circuit, the resultant circuit obtained is called a half controlled bridge circuit.

→ With this type of circuit, it is possible to provide a continuous control of the mean d.c terminal voltage from maximum to virtually zero, but reversal of the mean voltage is not possible. In otherwords only one quadrant operation can be obtained.

## Half controlled bridge Rectifier with resistive load



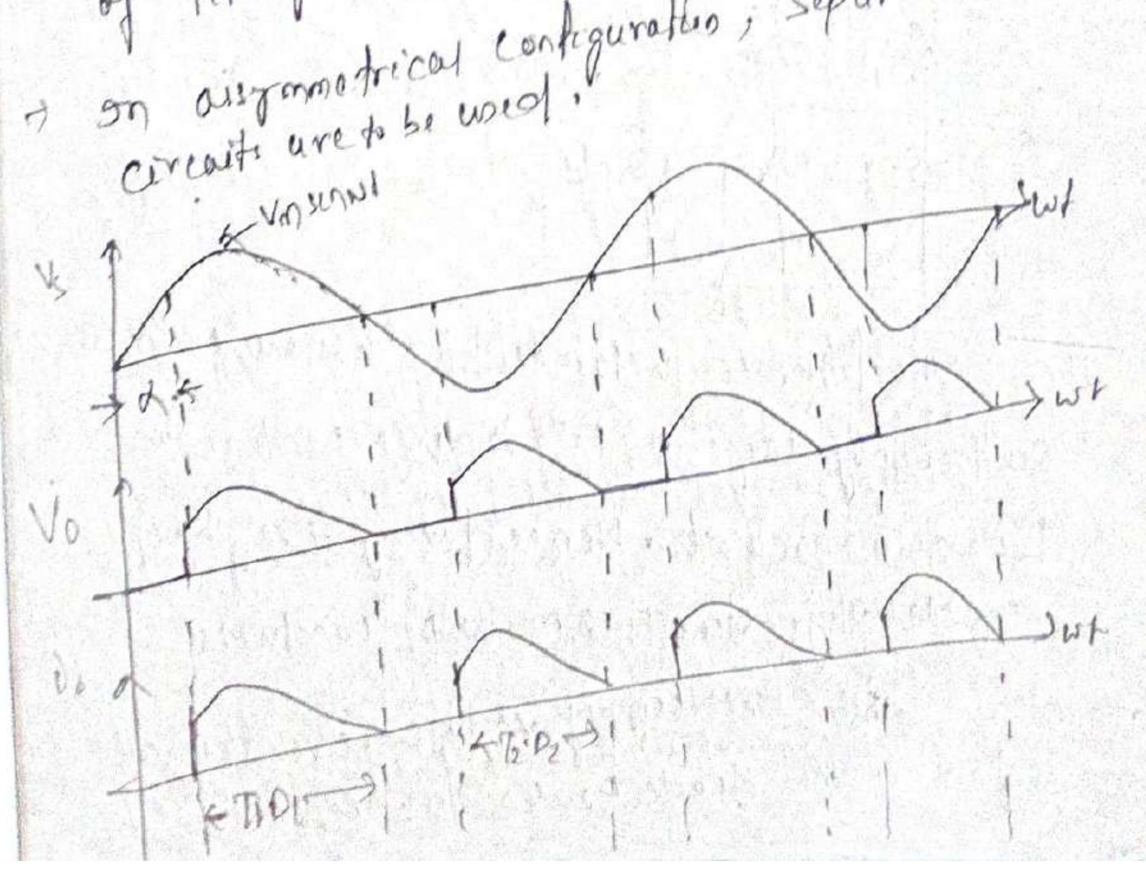

Asymmetrical configuration




Symmetrical configuration

→ In symmetrical configuration, the cathode of two SCRs are at the same potential. So their gates can be connected and a single gate pulse can be used for triggering either SCR. The SCR which is forward biased at the instant of firing will turn on.

→ In asymmetrical configuration; separate triggering circuits are to be used.



(61)

Average dc load voltage

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

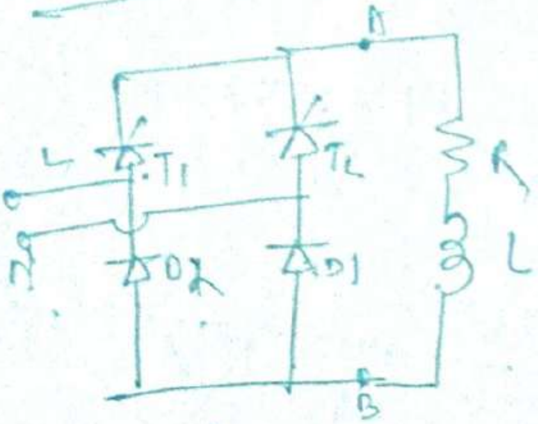
$$= \frac{1}{\pi} V_m \left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$\boxed{V_{dc} = \frac{V_M}{\pi}(1+\cos\alpha)}$$

Average load current

$$\boxed{I_{dc} = \frac{V_{dc}}{R} = \frac{V_M}{\pi R}(1+\cos\alpha)}$$

Half controlled Bridge Rectifier with R-L load

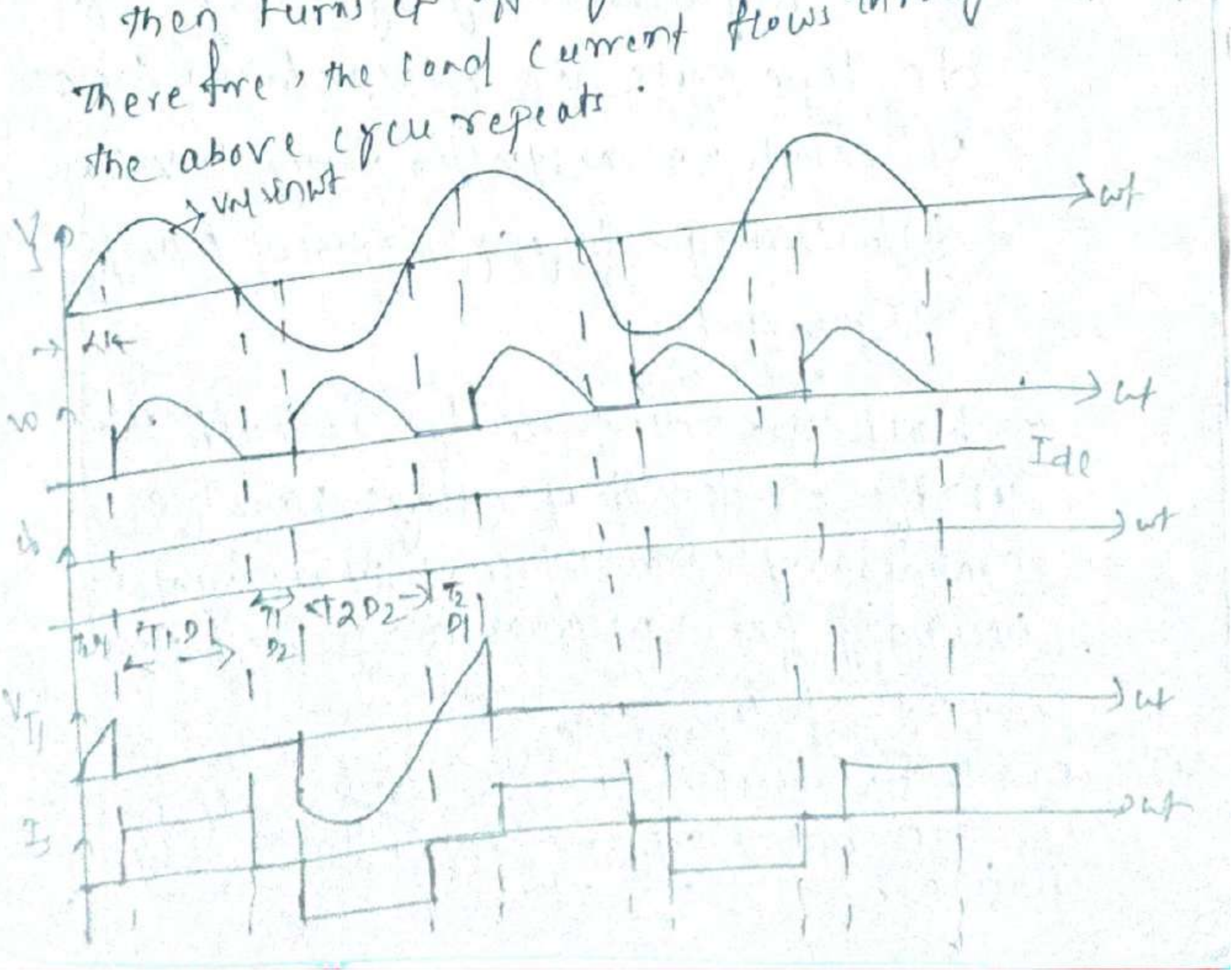



Here the filter inductance 'L' is assumed to be sufficiently large as to produce continuous Load current. Hence during +ve half cycle Thyristor T1 & Diode D1 conducts.

→ Now when the supply voltage reverses at $\omega t = \pi$, the diode $D_2$ is forward biased.

(62)

since $D_1$ is already conducting.
The Diode $D_2$ then turns on & the Load current passes through $D_2$ & $T_1$. The supply voltage reverse biases $D_1$ & turns it off.
Thus, the load current free wheels through the path R - B - $D_2$ - $T_1$ - A - L during the interval from π to (π+α) in each supply cycle.
During the -ve half cycle at the instant (π+α), a triggering pulse is applied to the forward biased thyristor $T_2$. Thyristor $T_2$ is turned on. As thyristor $T_2$ is turned on, the supply voltage reverse biases $T_1$ & then turns it off by the line commutation.
Therefore, the load current flows through $T_2$ & $D_2$.
the above cycle repeats.



$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$ (63)

- comparision b/w half controlled 2 pulse circuit that of fully controlled circuit.

(i) since half the thyristor are replaced by diodes, a half-controlled converter costs less than a fully controlled converter.

(ii) The periods of the negative voltage "swing" at the dc terminal obtained with fully controlled bridge circuit are replaced by "free wheeling" periods of zero voltage on half controlled circuit. The elimination of the negative swing of voltages at dc terminals is advantages bec. it results in reduction of ripple voltage and correspondingly reduced filtering requirement.

(iii) In half controlled bridge circuit the average dc terminal voltage can be continiously controlled from maximum to virtually zero with an increased control range of firing angle α.

(iv) Due to freewheeling action with half controlled bridge circuit, power factor is improved in half controlled converter.

ii) The ac supply current is more distorted due to its zero periods with half controlled circuits, compared to fully controlled bridge circuit

DATE: 03/09/19

## Power factor Improvement:

→ The supply power factor in phase controlled converter is low when the output voltage is less than maximum i.e when the firing angle is large.

→ The displacement angle b/w the supply voltage and current increases as the firing angle increases & the converter draws more lagging reactive power there by decreasing the power factor.

→ The poor power factor operation is a major concern in variable speed drives and in high power applications

→ The various techniques to improve power factor in phase controlled converter are

① phase angle control (PAC)

② Semiconverter operation of full converter

③ Asymmetrical firing

## Phase angle control:

np An alternator with fixed source voltage of 250V, delivers a power to a load. The transmission line reactance is 5Ω and load current is 20A. Calculate the load voltage, voltage regulation, system utilization and energy consumed for a load power factor of (i) unity (ii) 0.8 lagging

The ac supply current is more distorted due to its zero periods with half controlled circuits, compared to fully controlled bridge circuit.

DATE: 03/09/19

## Power factor Improvements:

→ The supply power factor in phase controlled converter is low when the output voltage is less than maximum i.e when the firing angle is large.

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2. semiconverter operation of full converter
3. Asymmetrical firing

## Phase angle control:

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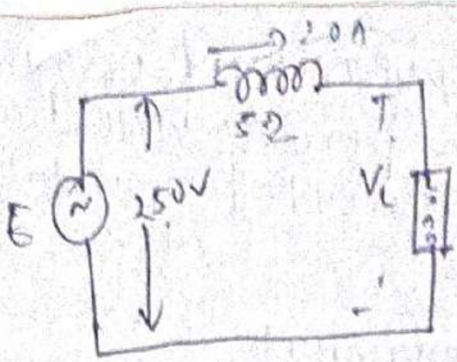
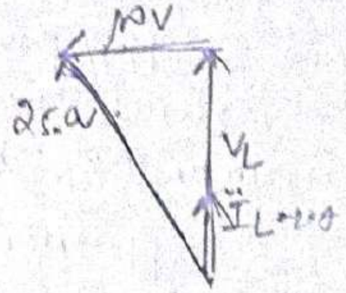



(a) Unity p.f




from fig $V_L^2 + 100^2 = E^2$

$\Rightarrow V_L^2 = E^2 - 100^2$

$V_L = \sqrt{(250)^2 - 100^2} = 229.13V$

$V.R = \frac{250 - 229.13}{250} \times 100 = 8.35\%$

Load power $= V_L I \cos\theta = 229 \times 20 \times 1 = 4582.6$ W

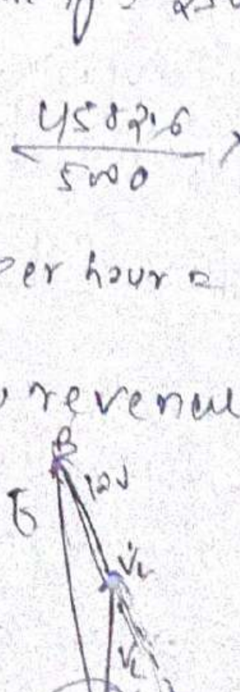
Max$^m$ possible system rating $= 250 \times 20 \times 1 = 5000$

System utilization factor $= \frac{4582.6}{5000} \times 100 = 91.652\%$

Load energy delivered per hour $= \frac{4582.6}{1000} = 4.58$

Assuming 5/- per unit, revenue earned $= 4.58 \times 5 = 23/-$ per hr

(b) 0.5 p.f lag




from fig $OA^2 + AB^2 = OE^2$

$(V_L \cos\theta)^2 + (V_L \sin\theta + IW)^2 = 250^2$

$V_L\cos\theta$ → 0.5, $\sin\theta$ → 0.866

→ $\boxed{V_L = 158.35V}$

$V.R = \frac{250 - 158.35}{250} \times 100 = 36.66\%$

Load power = $V_L I_L \cos\theta$
$= 158.35 \times 20 \times 0.5 = 1583.5$ watt

System utilization factor $= \frac{1583.5}{5000} \times 100 = 31.67\%$

Energy delivered to load per hour $= \frac{1583.5}{1000} = 1.58$ unit

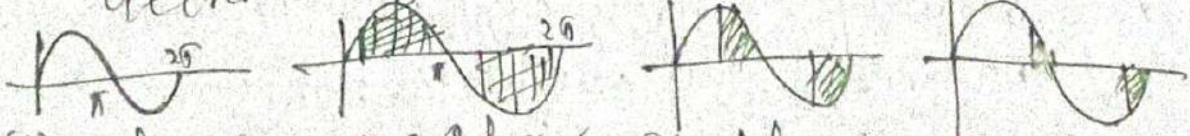
Revenue earned per hour $= 1.58 \times 5 = 7.90$ /- per hour

→ The following methods are used to improve power factor in the phase controlled converter.

(a) phase angle control

→ The output voltage decreases as the firing angle of SCR increases.

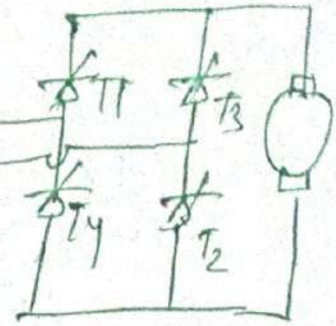
→ The i/p displacement factor and input power factor decreases as the o/p voltage decreases.




(a) 0° firing, (b) 30° firing (c) 90° firing (d) 120° firing

(b) Semiconverter operation of full converter

The change in controlled circuit is necessary in order to operate semiconverter in to full converter.




(1) Rectifier mode!

-> SCR T4 & SCR T2 -> act as switch

-> Output voltage is adjusted by controlling the firing angle of T1 & T3.

-> The firing of T4 & T2 is kept at zero when α=0° for T1 & T3 => o/p voltage = Maxm & when α=180° then o/p = 0V.

(2) Inverter mode

T1 & T3 -> act as switch

T2 & T4 -> firing angle is adjusted to get the o/p voltage

-> The firing angle of positive group T1 & T3 is kept at 180°.

-> When the firing angle of negative group of SCR T2 & T4 is kept at 180° => o/p voltage = Maxm

& the o/p voltage is zero if α=0°.

-> Actually the firing angle is kept less than 180° in order to keep commutation margin.

ii) Asymmetrical firing

-) The firing angle of SCR is kept same in symmetrical firing whereas in asymmetrical firing, firing angle is kept different

-) Let us consider that the firing of SCR $T_1$ is kept at 60° & SCR $T_2$ is kept at 120° in the asymmetrical firing angle control.

-) The powerfactor improves two some extent when firing angle of $T_1$ is kept small.

disadv

(i) It generated 2nd, 4th, 6th harmonics

(ii) The motor current is dis continuous.

-) The power factor of forced commutated converter is done by following method

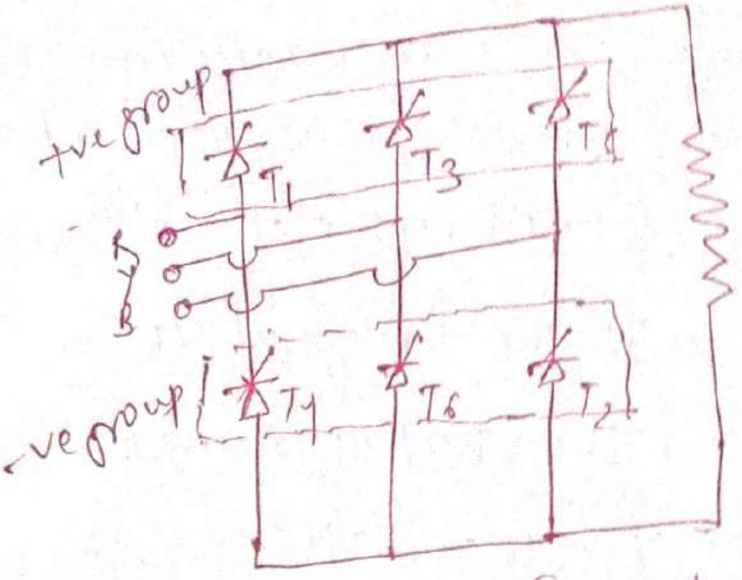
(a) Extinction angle control (EAC)

(b) symmetrical angle control

(c) pulse width modulation method.

(69)

3φ fully controlled Rectifier with R Load




$\frac{2\pi}{6} = 60°$

→ For six pulse operation, each SCR is to be fired twice in its conduction cycle so that firing interval is 60°.

(I) continuous conduction mode: ($0 < \alpha < \pi/3$)

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

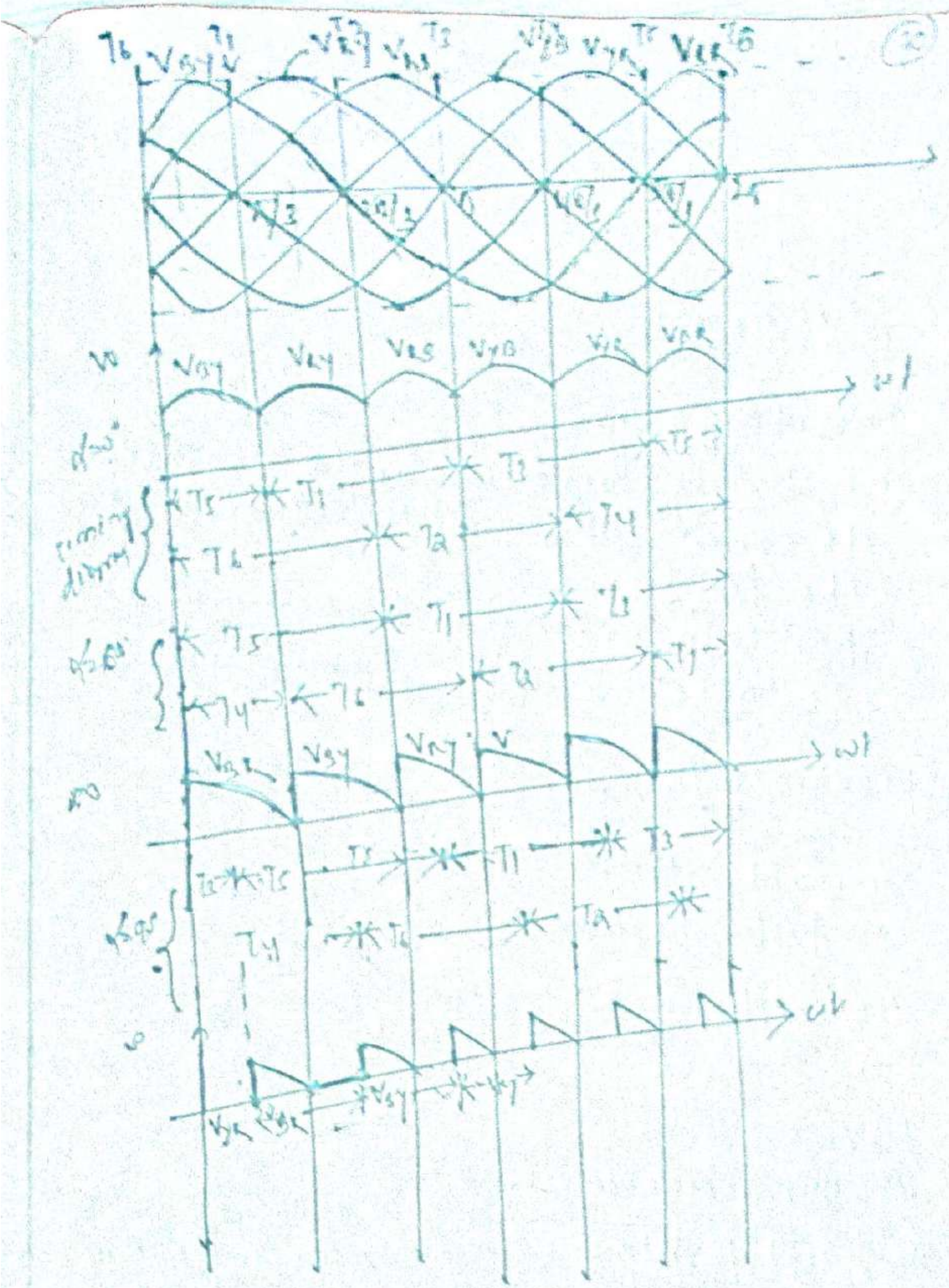
$$V_o = \frac{3V_{ml}}{\pi} \cos\alpha$$

$$I_o = V_o/R$$

(II) discontinuous conduction mode

$$V_o = \frac{1}{\pi/3} \int_{\pi/3+\alpha}^{\pi} V_{ml} \sin\omega t \, d(\omega t)$$

$$V_o = \frac{3V_{ml}}{\pi}\left[1 + \cos\left(\alpha + \frac{\pi}{3}\right)\right]$$


timing diagram

Introduction                    Inverter                    (71)

DC power → AC power at desired o/p voltage & frequency.

for Low and Medium power output → BJT, Mosfet, IGBT, GTO, etc

for high power o/p → Thyristor

→ The dc power i/p to the inverter may be battery, fuel cell, solar cells (or) other dc source. But in most industrial applications it is fed by a rectifier.
This configuration of ac to dc converter & dc to ac inverter is called a dc link.

Application of Inverter

→ variable speed ac motor drive
→ induction heating
→ Aircraft power supplies
→ UPS
→ HVDC
→ Battery vehicle drives
→ Regulated voltage & frequency power supplies

classification of converter!

(a) classification according to Nature of input source!

(1) voltage source inverter
(2) current source inverter

- In case VSI, the i/p to the inverter is provided by ripplefree dc voltage source whereas in CSI, voltage source is first converted into current source and then used to supply ~~to~~ the power to the inverter

(b) Classification according to the waveshape of the output voltage:

(i) Square wave inverter (ii) Quasi square wave inverter — for low and medium power application

(ii) Pulse width modulated inverter → high power application

(c) According to method of commutation

(1) Line commutated inverters

(2) Forced " "

(d) According to connections:

(1) Series inverter

(2) Parallel inverter

(3) Bridge inverter — (1) half bridge / (2) full bridge

(73) AC voltage controller Date 23/09/19

or

AC Regulator

fixed AC ⟶ Variable AC (fixed frequency)

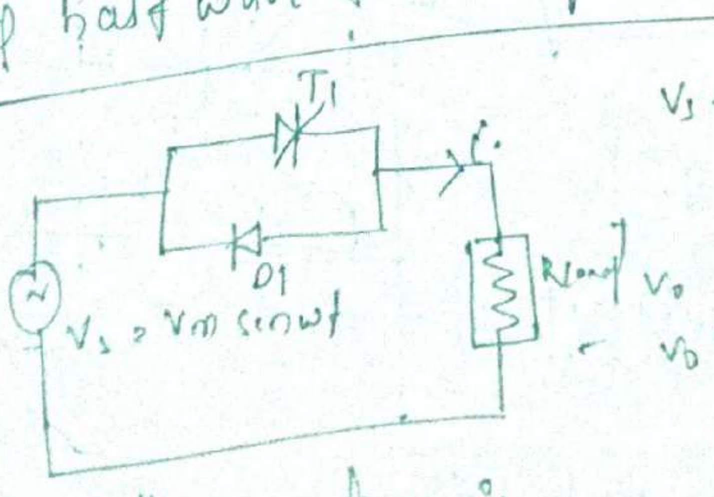
Application

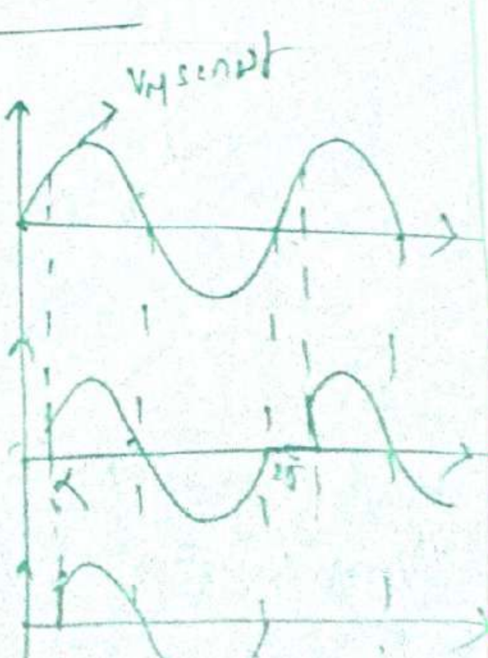
(i) speed control of polyphase Induction Motor
(ii) domestic & Industrial heating
(iii) Light control
(iv) On-load Transformer tap changing
(v) static Reactive power compensator etc

Classification

(1) half wave ac regulator
(2) full wave ac regulator

1φ half wave AC voltage regulator with R-load




-> Since the power flow is controlled during the +ve half cycle of i/p, so this type of controller is also known as unidirectional controller

→ This type of controller is only suitable for low power resistive load such as heating & lighting.

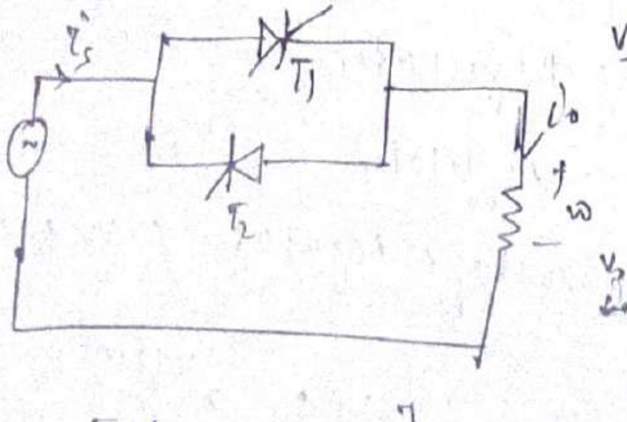
$$V_0 = \frac{1}{2\pi} \int_{\alpha}^{2\pi} V_m \sin\omega t \, d(\omega t)$$

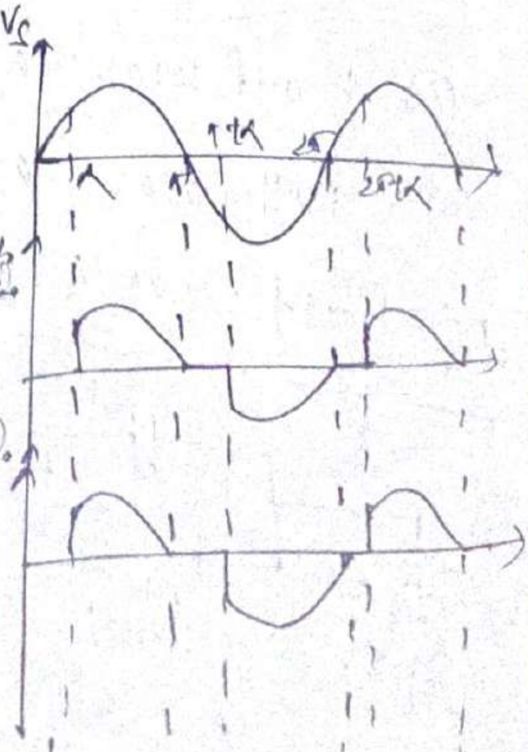
$$V_0 = \frac{V_m}{2\pi} (\cos\alpha - 1)$$

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

$$I_S = I_0 = \frac{V_m}{2\pi R} (\cos\alpha - 1)$$

## Fullwave AC voltage Regulator




$$V_0 = \frac{1}{2\pi} \left[ \int_{\alpha}^{2\pi} V_m \sin(\omega t) \right]$$

$V_0 = 0$ (symmetrical wave form)

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

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

(75) DATE 24/09/19

# SMPS

↳ switch mode power supply

→ In SMPS Transistor operate in the switch at very high frequency, at such a high frequency we can reduce the size of Transformer as well as the filter size. Therefore SMPS is highly efficient & compact in size.

→ For high frequency Transformer used in SMPS we use ferrite core to reduce the core loss.

→ With the availability of high speed device like power MOSFET SMPS is popularly used now a days.

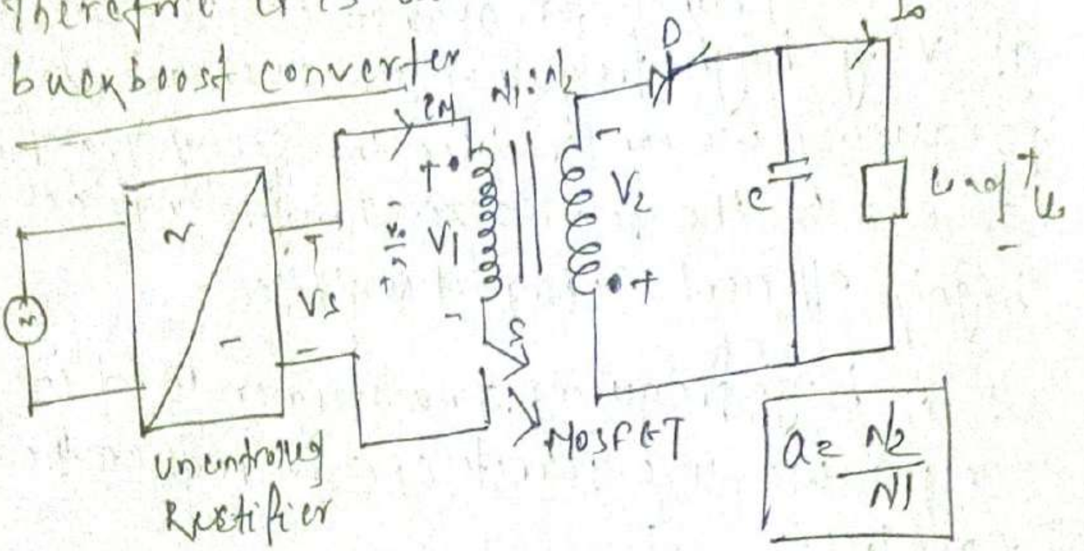
## Types of SMPS

→ The circuit techniques used for SMPS can be separated into following four broad categories.

(1) flyback SMPS
(2) forward SMPS
(3) push pull SMPS
(4) Bridge SMPS.

(1) Flyback converter

It is derived from a buck boost converter, therefore it is also known as isolated buckboost converter




(I) $0 \leq t \leq T_{on}$

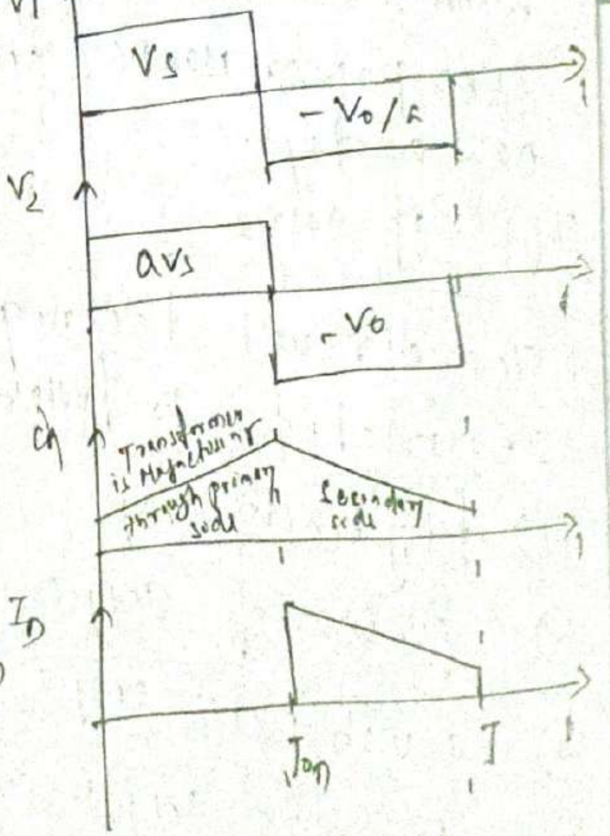
S → on, D off

→ $V_1 = V_s$

$V_2 = \frac{N_2}{N_1} V_1$

$V_2 = aV_s$

→ In this mode Transformer stores energy through primary side i.e. it is Magnetised through primary side




(II) $T_{on} \leq t \leq T$

When the switch is off inductor changes its polarity so $V_2$ in secondary side changes its polarity & forward bias the diode. So when turn off the switch Magnetising current can't flow in the

(77)

primary side, so has to flow in the secondary.

S → off, D → on.

So in this mode T/F is releasing energy through secondary side i.e. it is demagnetising through the secondary side

$V_2 = -V_0$

$V_1 = \frac{N_1}{N_2} V_2$

$V_1 = -\frac{V_0}{a}$

Avg O/P voltage

$V_0 = \frac{a\alpha V_s}{1-\alpha}$

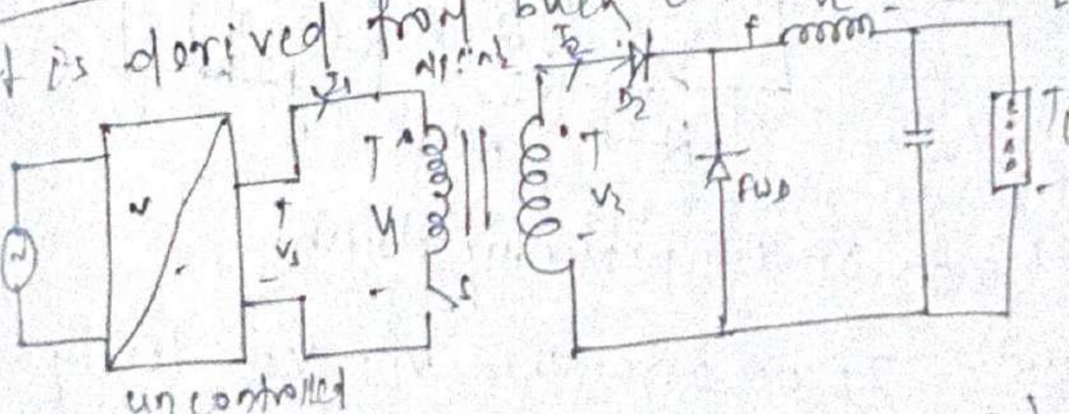
The peak forward blocking capacity of switch $= V_s + \frac{V_0}{a}$

PIV of diode $= aV_s + V_0$

→ used below about SNW

## forward converter

It is derived from buck converter




uncontrolled Rectifier

I Mode ($0 < t < T_{on}$)

$S_1 \to on$, $D_2 \to on$

$V_1 = V_s$ ∴ KVL in secondary

$V_2 = \frac{N_2}{N_1} V_s$

$V_2 = aV_s$

$-V_2 + V_L + V_0 = 0$

$V_L = V_2 - V_0$

$V_L = aV_s - V_0$

II Mode ($T_{on} < t < T$)

when S = off

$I_1 = 0$ so $I_2 = 0$

So S off ⇒ D is off

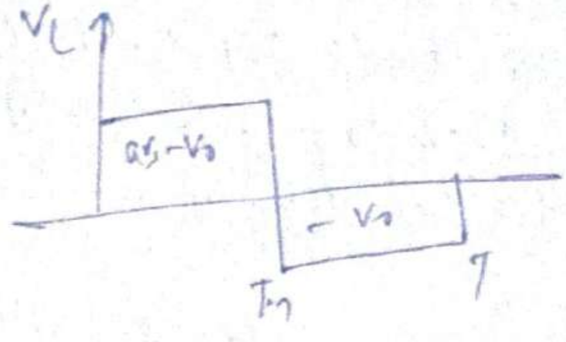
So current free wheel through FWD.

$V_L + V_0 = 0$

⇒ $V_L = -V_0$

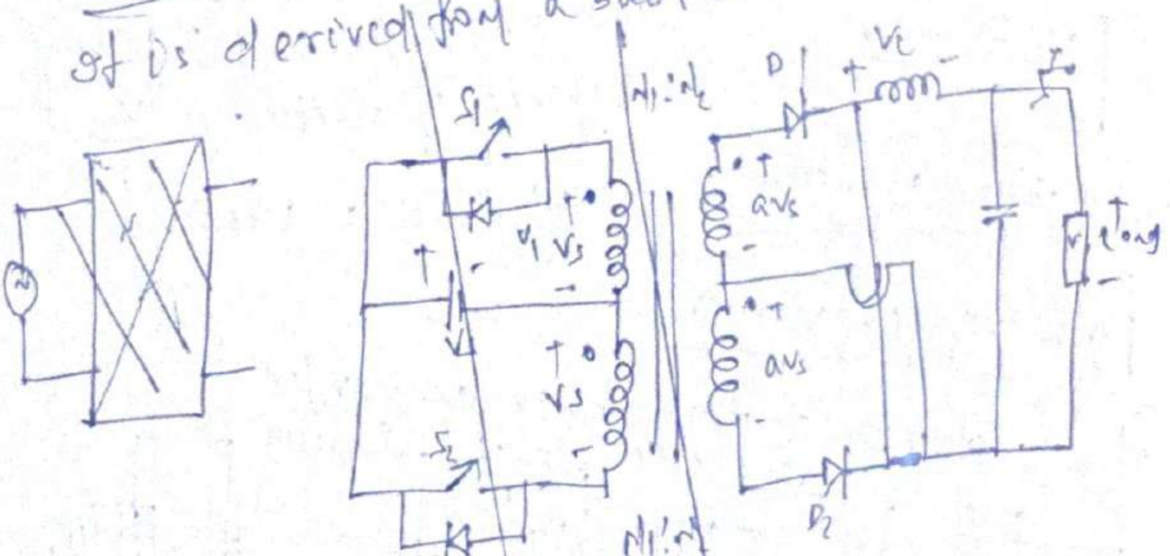
75

Average o/p voltage $V_0 = a\alpha V_s$




③ Push pull converter

It is derived from a buck converter.




$S_1$ & $S_2$ are complementary switch.

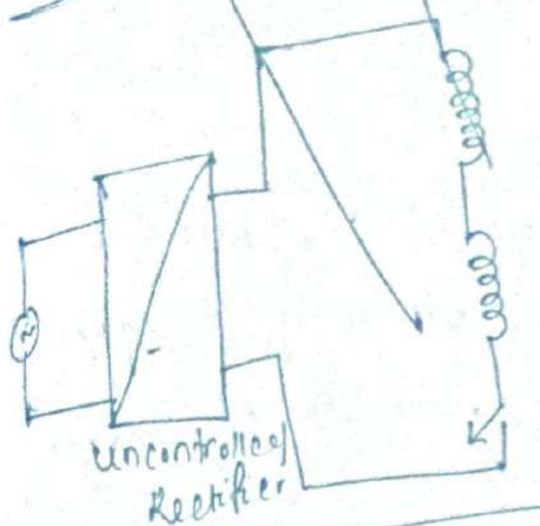
(1) Mode $S_1$ is on then $V_1 = V_s$ develops on upper half of primary.

so corresponding $V_2 = aV_s$ developed in the secondary & hence forward bias diode D1 and force current flow through load.

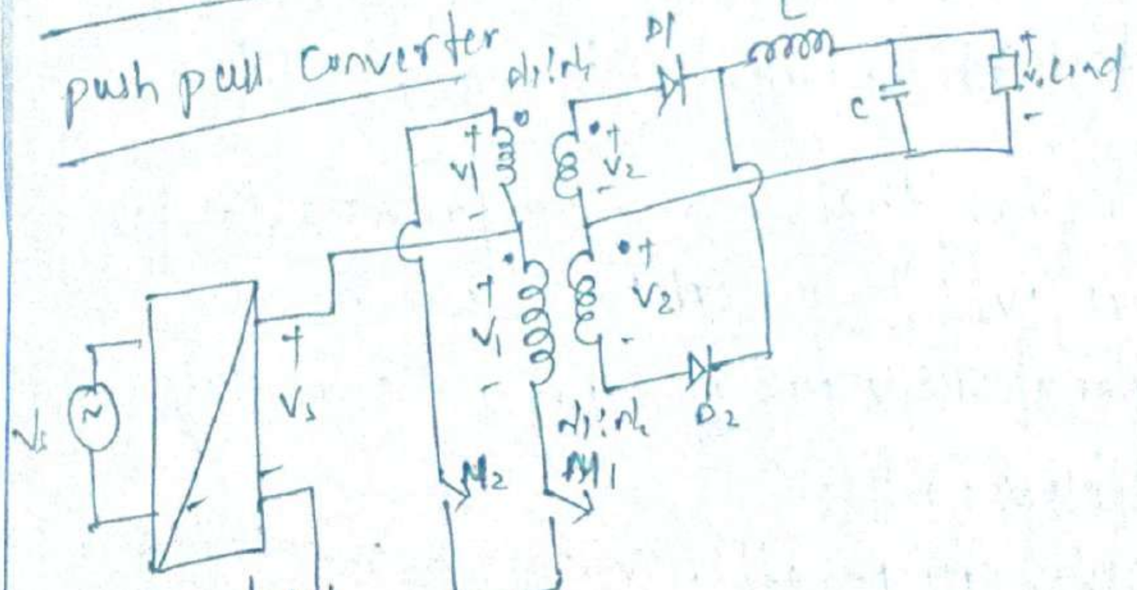
Applying KVL $-aV_s + V_L + V_0 = 0$

$\Rightarrow$ $V_L = aV_s - V_0$

push pull converter!




push pull converter




SMPS with push pull configuration shown above it uses two power MOSFET M1 & M2 and a transformer with mid taps on both primary and secondary sides.

→ When M1 is turned on, $V_1$ is applied to lower half of transformer primary i.e $V_1 = V_s$. As a result $V_2 = \frac{N_2}{N_1} V_s$ is induced in both secondary voltage $V_2$ on upper half secondary forward biases diode $D_1$, therefore load voltage $V_0$ is given by $V_0 = \frac{V_s N_2}{N_1} = aV_s$

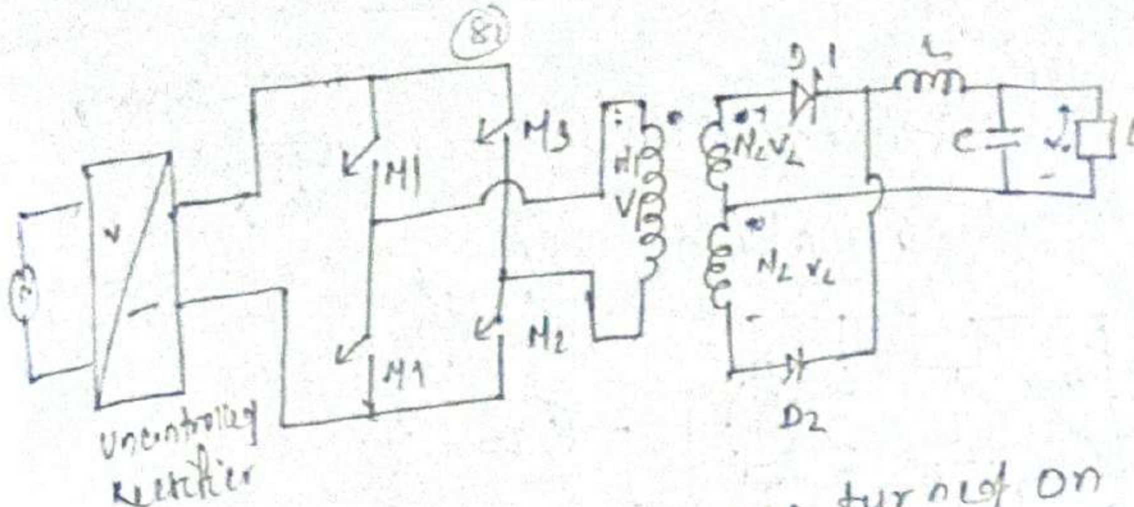
When $M_2$ is turned on, $V_{1} = -V_s$ is applied to upper half of primary winding consequently $V_2 = -\frac{V_s N_2}{N_1}$ is induced in both transformer secondaries. As $V_2$ is -ve, diode $D_2$ gets forward biased and $V_0 = aV_s$

→ This shows that voltage on primary swings from $+V_s$ with $M_1$ ON to $-V_s$ with $M_2$ ON.
power MOSFETs $M_1$ & $M_2$ operates with duty cycle $\alpha = 0.5$.

→ When $M_1$ is off, voltage across $M_1$ terminal is $V_{01} = 2V_s$

Full Bridge Converter:

→ It consists of an uncontrolled rectifier four power MOSFETs, transformer with mid-tap secondary, two diodes and LC filter




When power MOSFET M1 & M2 are turned on together, voltage $V_s$ appears across transformer primary i.e $V_1 = V_s$ and secondary voltage $V_2 = \frac{N_2}{N_1} V_s$ $= aV_s$. Diode D1 get forward biased and $V_0 = aV_s$

→ When M3 & M4 turned on together the primary voltage is reversed i.e $V_1 = -V_s$ and $V_2 = -aV_s$. Therefore diode D2 now begins to conduct and o/p voltage is again $V_0 = +aV_s$.

Advantage of SMPS over conventional linear power supplies

→ For same power rating, SMPS is of smaller size, lighter in weight and possesses higher efficiency because of its high frequency operation

→ SMPS is less sensitive to i/p voltage variation

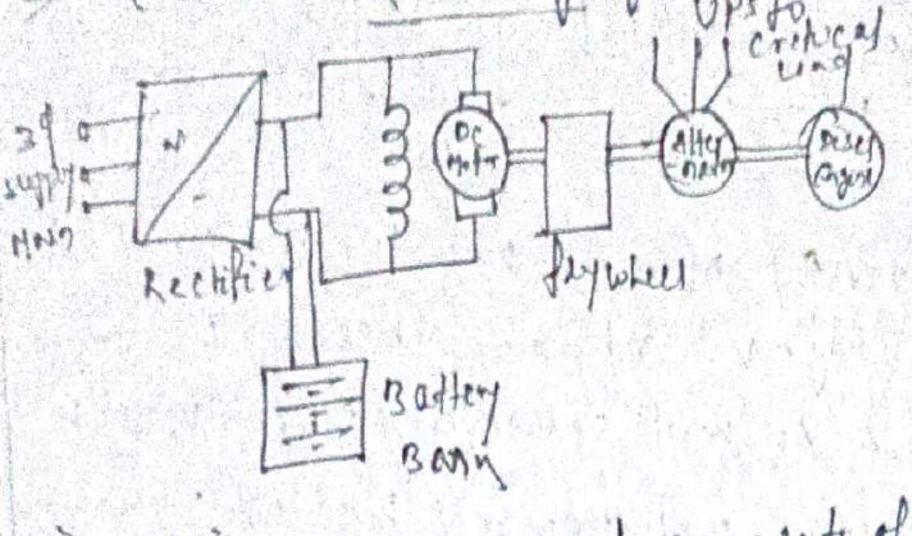
Disadvantage of SMPS

→ SMPS has higher o/p ripple and its regulation is worse.
→ SMPS is a source of both electromagnetic & radio interference due to high frequency switching
→ Control of radio frequency noise requires filters on both i/p & o/p side

(82) DATE: 25/09/19

UPS
↳ Uninterruptible power supply

→ Earlier Rotating type UPS were used.




→ This arrangement consists of DC Motor driven alternator, the shaft of which is also coupled to a Diesel engine.

→ The threephase Mains supply after rectification charges a dc battery bank and feeds the dc Motor as well. The uninterruptible power supply needed is taken from the alternator O/P terminal.

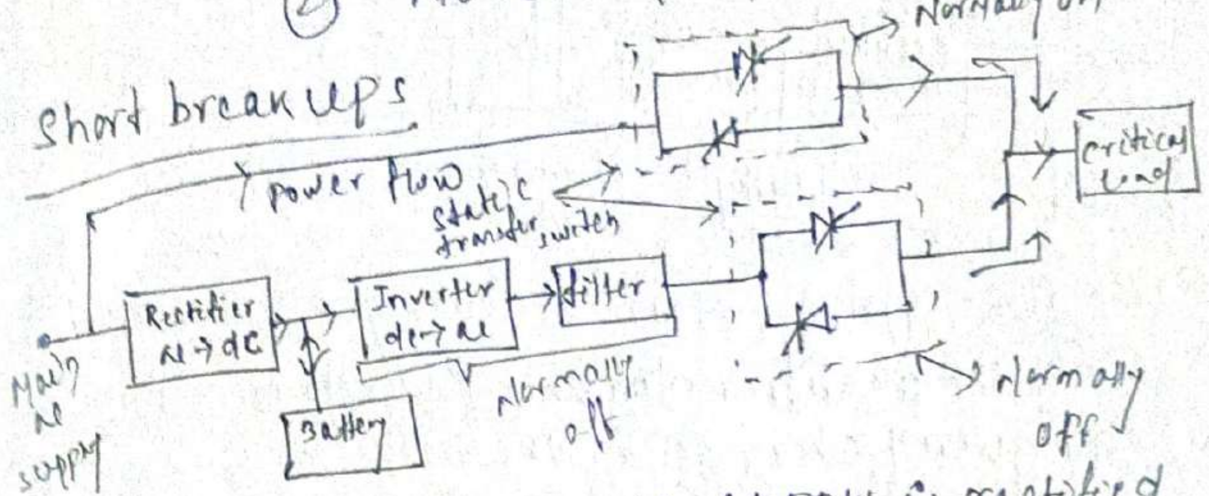
→ When Mains supply fails, the diesel engine is run to take over the load. Starting of diesel engine takes 10s to 15sec. During this period, battery bank is able to maintain the alternator speed through the dc motor and flywheel thus giving no break supply to critical load.

→ Static UPS (83) systems are of two types

① short break UPS (4 to 5 ms)

② No-break UPS (uninterruptible)

Short break UPS




→ In this system main ac supply is rectified to dc. The dc o/p from rectifier charges the batteries and is also converted to ac by an inverter.

→ After passing through the filter, ac can be delivered to load in cas normally off contacts are closed

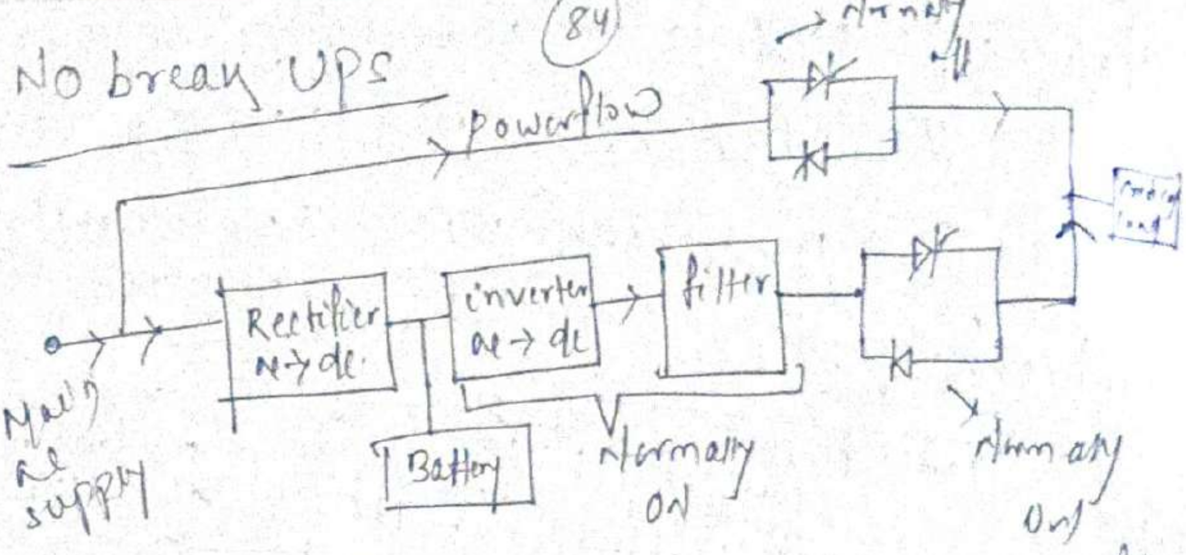
→ under normal situation power flow through normally on switch to critical load. At the same time battery gets charged.

→ In the event of power outage, normally off switch is turned on and battery deliver ac power to critical load through inverter and filter.

→ This type of arrangement is also called Standby Power supply.

(84)

No break UPS




→ In this system, main ac supply is rectified and the rectifier delivers power to maintain required charge on the batteries.

→ Rectifier also supplies power to inverter continuously which is then given to ac type load through filter & normally on switch.

→ In case of main ac supply failure, batteries at once take over with no break of supply to critical load. No discontinuity in the illumination is observed in case of no break UPS.

→ In case of inverter failure is detected, the load is switched on to main ac supply directly by turning on the normally off static switch and opening the normally on static switch.

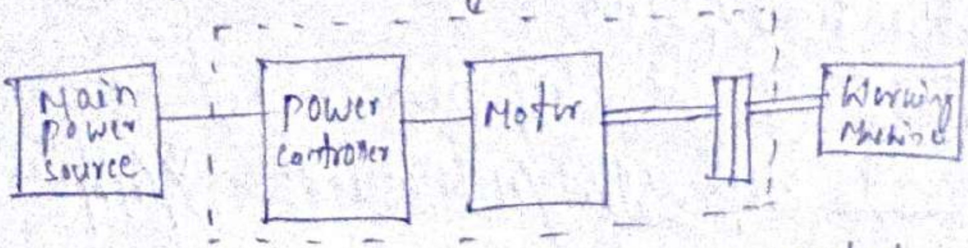
85

AC & DC drives

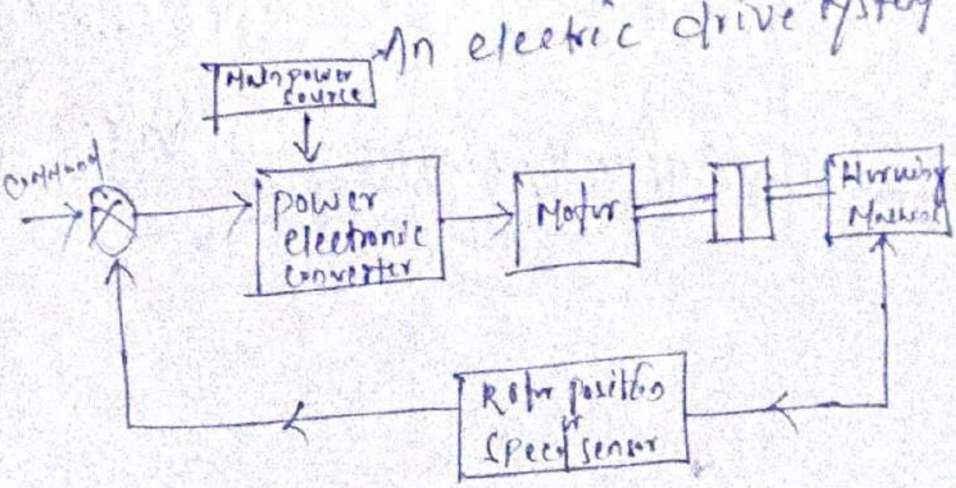
A complete production unit consists primarily of three basic components: an electric motor, an energy transmitting device and the working machine.

→ An electric motor together with its control equipment and energy transmitting device forms an electric drive.

→ An electric drive with its working machine constitutes an electric drive system.




An electric drive system

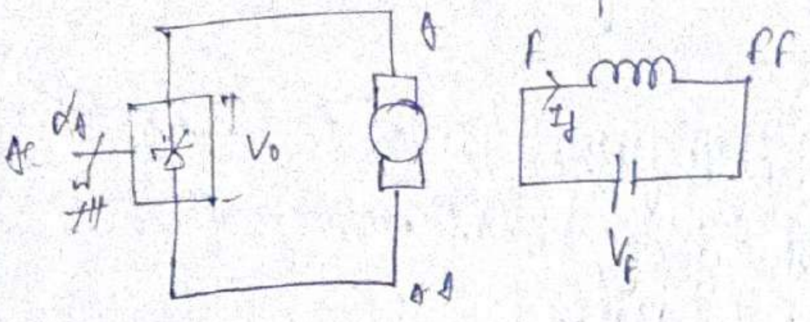



Modern ~~power~~ electric drive system using power electronic converter dc drives

speed control

(1) Armature voltage control ( $\omega < \omega_r$ )

$\phi \rightarrow$ const




$1\phi$ $V_0 = \frac{2V_m}{\pi}\cos\alpha_A$ $3\phi$ $V_0 = \frac{3V_{mL}}{\pi}\cos\alpha_A$

$E_b \propto \phi N$

$E_b \propto N$ (since $\phi \rightarrow$ const)

$\boxed{E_b = kN}$ → emf constant / Motor constant → V/rpm

$\boxed{E_b = k\omega}$ → Emf const / Motor const → $\frac{V \cdot sec}{rad}$

$T_a \propto \phi I_a$

$T_a \propto I_a$ ( $\phi$ = const)

$\boxed{T_a = k I_a}$ → Torque const/motor const → $\frac{NM}{A}$

for motoring mode

$V_0 = E_b + I_a R_a$

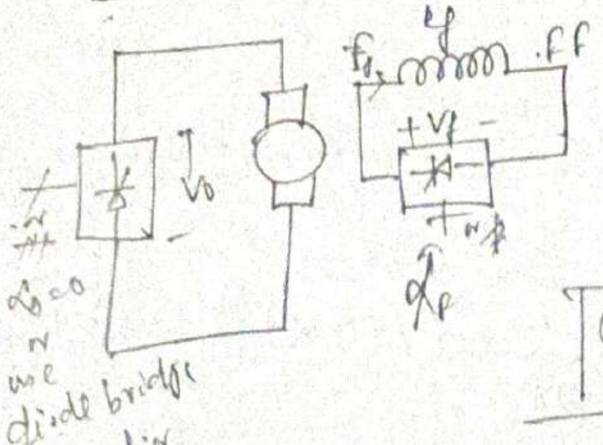
$V_0 = K\omega + I_a R_a$

$\omega = \frac{V_0}{K} - \frac{I_a R_a}{K}$

$$\omega = \frac{V_0}{K} - \frac{R_a T_a}{K^2}$$

If $\alpha \uparrow \Rightarrow V_0 \downarrow \Rightarrow \omega \downarrow \Rightarrow \omega < \omega_r$

② field control ($\omega > \omega_r$)




$I_f = \frac{V_f}{R_f}$

$\phi \propto I_f$

$$\phi = K_f I_f$$

$E_b \propto \phi N$

$\Rightarrow E_b = K_1 \phi N = K_1 K_f I_f N = K I_f N$ → const unit → V/rpm A

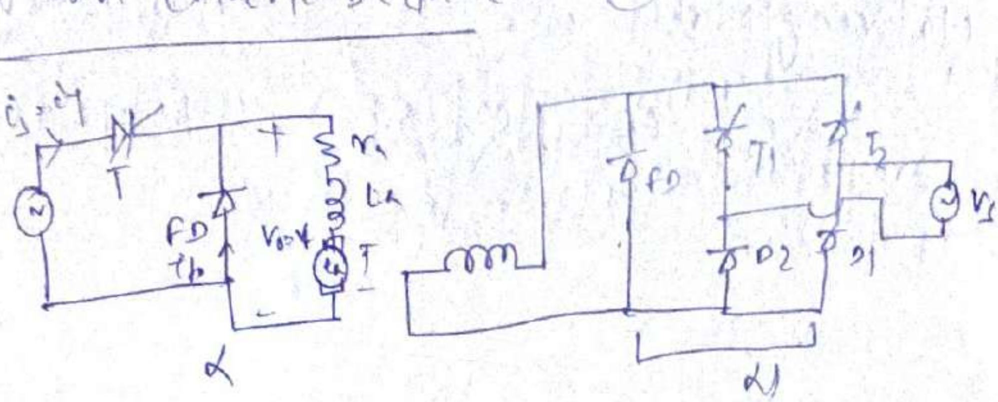
$$E_b = K I_f \omega$$ → V·sec/rad A

$T \propto \phi I_a = K_1 K_f I_f I_a = K I_f I_a$ → Torque const → Nm/A²

for motoring mode

$V_0 = E_b + I_a R_a = K I_f \omega + I_a R_a \Rightarrow \omega = \frac{V_0}{K I_f} - \frac{R_a T_a}{(K I_f)^2}$

1φ half wave converter DC drive (88)




A separately excited dc motor fed through single phase half wave converter is shown.

→ Motor field circuit is fed through a single phase semiconverter ~~feeding a dc~~ in order to reduce the ripple content in the field circuit

→ single phase half wave converter feed a dc Motor armature offers one-quadrant drive

→ for single phase half wave converter, average o/p voltage of converter:

$$V_0 = V_t = \frac{V_m}{2\pi}(1+\cos\alpha) \text{ for } 0<\alpha<\pi$$

$$V_f = \frac{V_m}{\pi}(1+\cos\alpha_1) \quad 0<\alpha_1<\pi$$

rms value of source or thyristor current

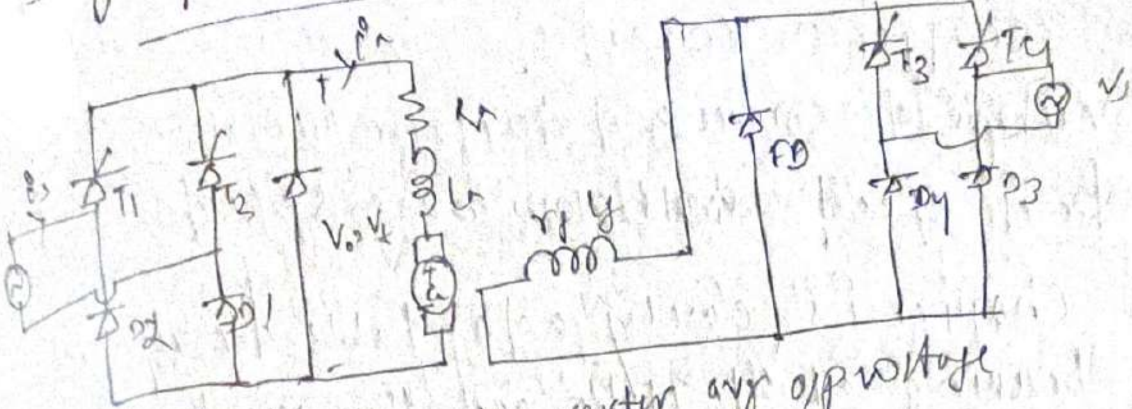
$$I_{sr} = I_a\left(\frac{\pi-\alpha}{2\pi}\right)^{\frac{1}{2}}$$

rms value of free wheeling diode current

$$I_{FDr} = I_a\left(\frac{\pi+\alpha}{2\pi}\right)^{\frac{1}{2}}$$

Input supply pf = $\frac{V_t I_a}{V_s I_{sr}}$

single phase semiconverter drive (89)




for single phase semiconverter avg o/p voltage

$$V_0 = V_t = \frac{V_m}{\pi}(1+\cos\alpha)$$

for field circuit $V_f = \frac{V_m}{\pi}(1+\cos\alpha_1)$

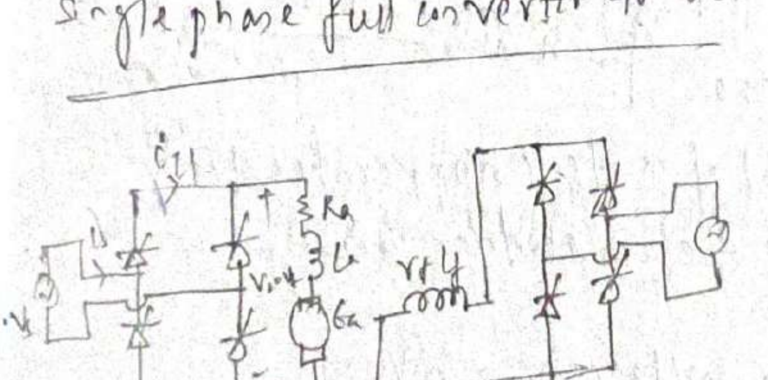
rms value of source current $I_{sr} = I_a\left[\frac{\pi-\alpha}{\pi}\right]^{1/2}$

rms value of f.D current $= I_{dr} = I_a\left[\alpha/\pi\right]^{1/2}$

rms value of thyristor current $= I_{Tr} = I_a\left[\frac{\pi-\alpha}{2\pi}\right]^{1/2}$

i/p pf $= \frac{V_t I_a}{V_{sr} I_{sr}}$

single phase full converter drive.




$$V_0 = V_t = \frac{2V_m}{\pi}\cos\alpha$$

$$V_f = \frac{2V_m}{\pi}\cos\alpha_1$$

rms value of source current $I_{sr} = I_a$

rms value of thyristor current $= \frac{I_a}{\sqrt{2}}$

$$pf = \frac{V_t I_a}{V_s I_{sr}} = \frac{V_t}{V_{sr}}$$

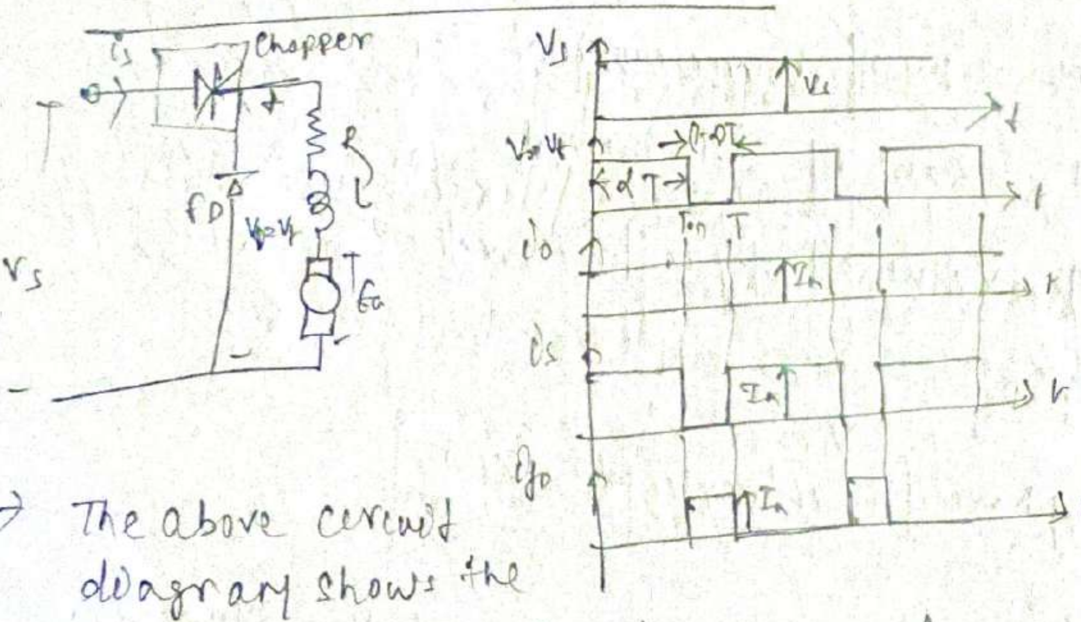
## Chopper drive

(90)

→ A chopper is inserted in between a fixed voltage dc source and dc motor armature for its speed control below base speed.

→ Chopper is easily adaptable for regenerative braking of dc motor and thus kinetic energy of the drive can be returned to dc source.

Chopper drive used for single quadrant motoring control



→ The above circuit diagram shows the basic arrangement of a dc chopper feeding power to a dc series motor.

Average motor voltage $V_0 = \alpha V_s$.

where $\alpha$ = duty cycle = $\frac{T_{on}}{T}$

Power delivered to motor = $V_0 I_a = \alpha V_s I_a$

Avg source current = $\alpha I_a$

The equivalent resistance seen by source = $\frac{V_s}{I_s} = \frac{V_s}{\alpha I_a}$

(91)

input power to chopper $= V_s I_s = V_s(\alpha I_a)$

for motor armature circuit $V_t = \alpha V_s = E_a + I_a(r_a + r_s)$

$$\alpha V_s = K_m \omega_m + I_a(r_a + r_s)$$

$$\Rightarrow \omega_m = \frac{\alpha V_s - I_a(r_a + r_s)}{K_m}$$

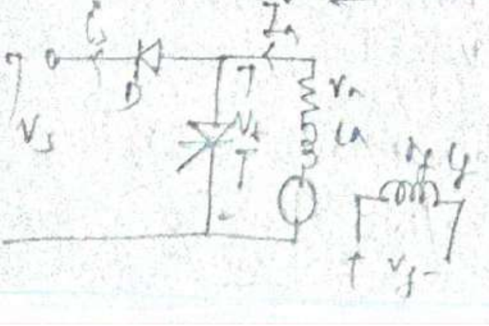
By varying duty cycle we can vary the speed of motor

chopper drive used for single quadrant regenerative braking control

→ In regenerative braking control, the motor acts as a generator and the kinetic energy of the motor and connected load is returned to supply.

→ During motoring mode $I_a = \frac{V_t - E_a}{r_a}$ i.e. armature current is +ve & motor consumes power.

→ In case of load drives the motor at a speed such that average value of motor counter emf exceeds $V_t$ ⇒ $I_a$ reverses & power is delivered to dc source. Then the motor is working as generator in the regenerative braking mode



⇒ For active load, such as a train going down the hill, $E_a > V_s$ ; when chopper is on current through armature inductance $L_a$ rises as the armature terminal gets short circuited through chopper.

⇒ $V_t = 0$ during $T_{on}$

During $T_{off}$ $E_a > V_s$ ⇒ diode conduct

⇒ $\boxed{V_t = V_s}$

$V_t = (1-\alpha) V_s$

power generated by motor $= V_t I_a = (1-\alpha) V_s I_a$

Motor emf generated $E_a = K_m \omega_m = V_t + I_a r_a$

$K_m \omega_m = (1-\alpha) V_s + I_a r_a$

Equivalent load resistance seen by the motor acting as a generator.

$$R_{eq} = \frac{E_a}{I_a} = \frac{(1-\alpha) V_s + r_a I_a}{I_a} = (1-\alpha)\frac{V_s}{I_a} + r_a$$

Motor speed during regenerative braking.

$$\omega_m = \frac{(1-\alpha) V_s + I_a r_a}{K_m}$$

condition for controlling the power during regenerative braking is

$$E_a - I_a r_a \geq V_s$$

Minimum braking speed obtained when $E_a - I_a r_a = 0$

⇒ $K_m \omega_m = I_a r_a$ ⇒ $\boxed{\omega_{min} = \frac{I_a r_a}{K_m}}$

(93)

Maximum braking speed obtained when
$E_a - I_a r_a = V_s$

$\Rightarrow$ Max^m braking speed $\omega_{mu} = \frac{V_s + I_a r_a}{K_m}$

$\Rightarrow$ Thus regenerative braking control is effective only when motor speed is less than $\omega_{mu}$ & more than $\omega_{mn}$.

$$\Rightarrow \boxed{\frac{I_a r_a}{K_m} < \omega_m < \frac{V_s + I_a r_a}{K_m}}$$

**MODULE-5**

## PLC AND ITS APPLICATIONS

### Introduction of Programmable Logic Controller (PLC)

Programmable logic controllers are now the most widely used industrial process control technology. A programmable logic controller (PLC) is an industrial grade computer that is capable of being programmed to perform control functions. The programmable controller has eliminated much of the hardwiring associated with conventional relay control circuits. Other benefits include easy programming and installation, high control speed, network compatibility, troubleshooting and testing convenience, and high reliability. The programmable logic controller is designed for multiple input and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs for the control and operation of manufacturing process equipment and machinery are typically stored in battery-backed or non-volatile memory. A PLC is an example of a real-time system since the output of the system controlled by the PLC depends on the input conditions. The programmable logic controller is, then, basically a digital computer designed for use in machine control. Unlike a personal computer, it has been designed to operate in the industrial environment and is equipped with special input/output interfaces and a control programming language. The common abbreviation used in industry for these devices, PC, can be confusing because it is also the abbreviation for "personal computer." Therefore, most manufacturers refer to their programmable controller as a PLC, which stands for "programmable logic controller."

### Advantages of PLC

Programmable controllers offer several advantages over a conventional relay type of control. Relays have to be hardwired to perform a specific function. When the system requirements change, the relay wiring has to be changed or modified. In extreme cases, such as in the auto industry, complete control panels had to be replaced since it was not economically feasible to rewire the old panels with each model changeover. The programmable controller has eliminated much of the hardwiring associated with conventional relay control circuits. It is small and inexpensive compared to equivalent relay-based process control systems. Modern control systems still include relays, but these are rarely used for logic. In addition to cost savings, PLCs provide many other benefits including:

• *Increased Reliability.* Once a program has been written and tested, it can be easily downloaded to other PLCs. Since all the logic is contained in the PLC's memory, there is no chance of making a logic wiring error. The program takes the place of much of the external wiring that would normally be required for control of a process. Hardwiring, though still required to connect field devices, is less intensive. PLCs also offer the reliability associated with solid-state components.

• *More Flexibility*. It is easier to create and change a program in a PLC than to wire and rewire a circuit. With a PLC the relationships between the inputs and outputs are determined by the user program instead of the manner in which they are interconnected. Original equipment manufacturers can provide system updates by simply sending out a new program. End users can modify the program in the fi eld, or if desired, security can be provided by hardware features such as key locks and by software passwords.

• *Lower Cost.* PLCs were originally designed to replace relay control logic, and the cost savings have been so significant that relay control is becoming obsolete except for power applications. Generally, if an application has more than about a half-dozen control relays, it will probably be less expensive to install a PLC.

• *Communications Capability.* A PLC can communicate with other controllers or computer equipment to perform such functions as supervisory control, data gathering, monitoring devices and process parameters, and download and upload of programs.

• *Faster Response Time.* PLCs are designed for highspeed and real-time applications. The programmable controller operates in real time, which means that an event taking place in the fi eld will result in the execution of an operation or output. Machines that process thousands of items per second and objects that spend only a fraction of a second in front of a sensor require the PLC’s quick-response capability.

• *Easier to Troubleshoot.* PLCs have resident diagnostics and override functions that allow users to easily trace and correct software and hardware problems. To find and fix problems, users can display the control program on a monitor and watch it in real time as it executes.

**Different parts of PLC by drawing the block diagram and purpose of each part of PLC**

A typical PLC can be divided into parts, as illustrated in Figure 1-8. These are the *central processing unit (CPU)*, the *input/output (I/O)* section, the *power supply*, and the *programming device.*

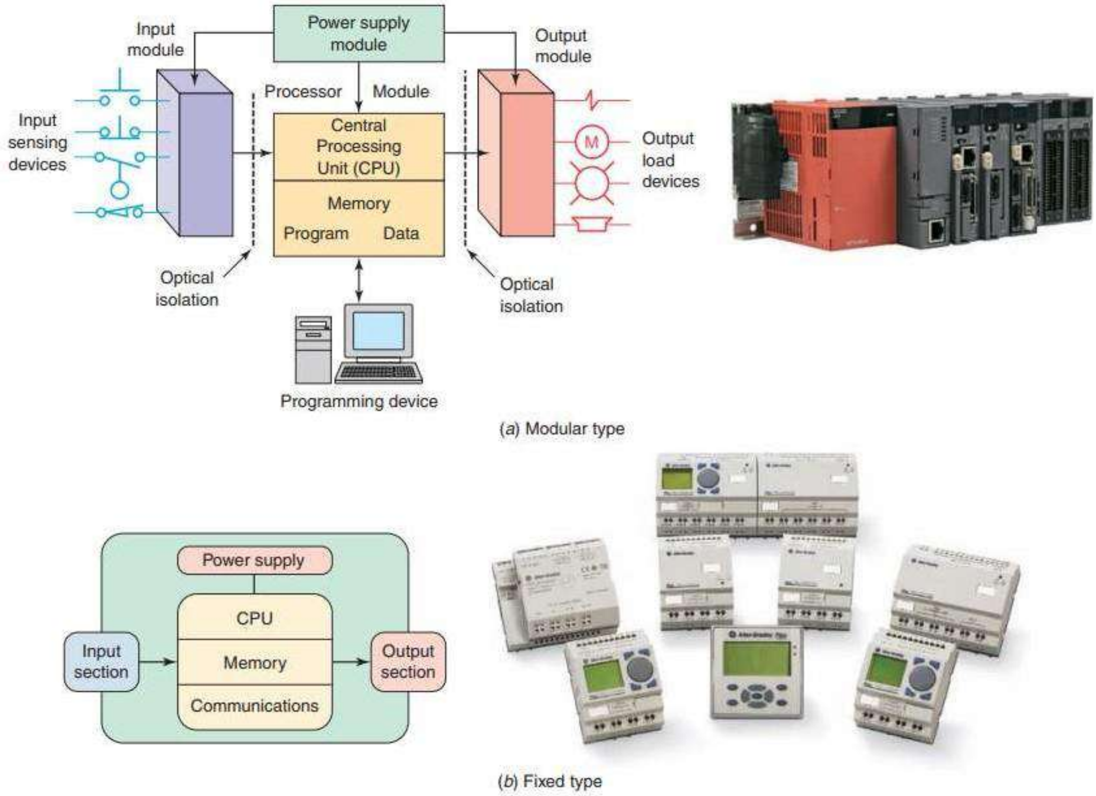



**Figure 1-8** Typical parts of a programmable logic controller.
Source: (a) Courtesy Mitsubishi Automation; (b) Image Used with Permission of Rockwell Automation, Inc.

The term *architecture* can refer to PLC hardware, to PLC software, or to a combination of both. An *open* architecture design allows the system to be connected easily to devices and programs made by other manufacturers.

There are two ways in which I/Os (Inputs/Outputs) are incorporated into the PLC: fixed and modular. *Fixed I/O* is typical of small PLCs that come in one package with no separate, removable units. The processor and I/O are packaged together, and the I/O terminals will have a fixed number of connections built in for inputs and outputs. The main advantage of this type of packaging is lower cost. The number of available I/O points varies and usually can be expanded by buying additional units of fixed I/O. One disadvantage of fixed I/O is its lack of flexibility; you are limited in what you can get in the quantities and types dictated by the packaging. Also, for some models, if any part in the unit fails, the whole unit has to be replaced.

*Modular I/O* is divided by compartments into which separate modules can be plugged. This feature greatly increases your options and the unit's flexibility. You can choose from the modules available from the manufacturer and mix them any way you desire. The basic modular controller consists of a rack, power supply, processor module (CPU), input/output (I/O modules), and an operator interface for programming and monitoring. The modules plug into a rack. When a module is slid into the rack, it makes an electrical connection with a series of contacts called the backplane, located at the rear of the rack. The PLC processor is also connected to the backplane and can communicate with all the modules in the rack.

The *power supply* supplies DC power to other modules that plug into the rack. For large PLC systems, this power supply does not normally supply power to the field devices. With larger systems, power to fi eld devices is provided by external alternating current (AC) or direct current (DC) supplies. For some small micro-PLC systems, the power supply may be used to power field devices.

The *processor* (CPU) is the "brain" of the PLC. A typical processor usually consists of a microprocessor for implementing the logic and controlling the communications among the modules. The processor requires memory for storing the results of the logical operations performed by the microprocessor. Memory is also required for the program EPROM or EEPROM plus RAM. The CPU controls all PLC activity and is designed so that the user can enter the desired program in relay ladder logic. The PLC program is executed as part of a repetitive process referred to as a scan. A typical PLC scan starts with the CPU reading the status of inputs. Then, the application program is executed. Once the program execution is completed, the CPU performs internal diagnostic and communication tasks. Next, the status of all outputs is updated. This process is repeated continuously as long as the PLC is in the run mode.

The *I/O system* forms the interface by which field devices are connected to the controller. The purpose of this interface is to condition the various signals received from or sent to external field devices. Input devices such as pushbuttons, limit switches, and sensors are hardwired to the input terminals. Output devices such as small motors, motor starters, solenoid valves, and indicator lights are hardwired to the output terminals. To electrically isolate the internal components from the input and output terminals, PLCs commonly employ an optical isolator, which uses light to couple the circuits together.

A *programming device* is used to enter the desired program into the memory of the processor. The program can be entered using relay ladder logic, which is one of the most popular programming languages. Instead of words, ladder logic programming language uses graphic symbols that show their intended outcome.

A program in ladder logic is similar to a schematic for a relay control circuit. It is a special language written to make it easy for people familiar with relay logic control to program the PLC.

A personal computer (PC) is the most commonly used programming device. Most brands of PLCs have software available so that a PC can be used as the programming device. This software allows users to create, edit, document, store, and troubleshoot ladder logic programs. The computer monitor is able to display more logic on the screen than can hand-held types, thus simplifying the interpretation of the program. The personal computer communicates with the PLC processor via a serial or parallel data communications link, or Ethernet. If the programming unit is not in use, it may be unplugged and removed. Removing the programming unit will not affect the operation of the user program.

A *program* is a user-developed series of instructions that directs the PLC to execute actions. A *programming language* provides rules for combining the instructions so that they produce the desired actions.

*Relay ladder logic (RLL)* is the standard programming language used with PLCs. Its origin is based on electromechanical relay control. The relay ladder logic program graphically represents rungs of contacts, coils, and special instruction blocks. RLL was originally designed for easy use and understanding for its users and has been modified to keep up with the increasing demands of industry’s control needs.

**Application of PLC**

There are three major types of PLC application: single ended, multitask, and control management.

A *single ended* or stand-alone PLC application involves one PLC controlling one process. This would be a stand-alone unit and would not be used for communicating with other computers or PLCs. The size and sophistication of the process being controlled are obvious factors in determining which PLC to select. The applications could dictate a large processor, but usually this category requires a small PLC.

A *multitask* PLC application involves one PLC controlling several processes. Adequate I/O capacity is a significant factor in this type of installation. In addition, if the PLC would be a subsystem of a larger process and would have to communicate with a central PLC or computer, provisions for a data communications network are also required.

A *control management* PLC application involves one PLC controlling several others. This kind of application requires a large PLC processor designed to communicate with other PLCs and possibly with a computer. The control management PLC supervises several PLCs by downloading programs that tell the other PLCs what has to be done. It must be capable of connection to all the PLCs so that by proper addressing it can communicate with anyone it wishes to

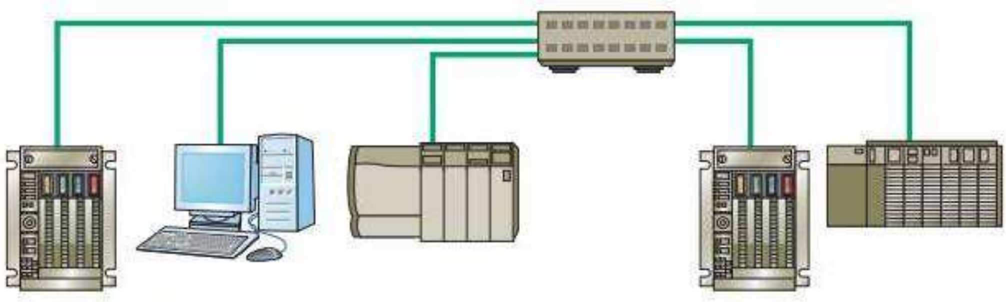


**Figure 1-30** Control management PLC application.

Because of the versatility of PLC, it is used in various places for automation. In industries various processes needs to be controlled at every instant of time such as valve control, pressure control, robotic action, etc. It becomes tedious and infeasible for humans to control all such activities on their own. Thus, relays were used to perform those activities. However, a relay can be used only for a specific and limited operation which makes their use bulky and uneconomic. On the contrary PLC having the ability to perform number of tasks by simply modifying the program has become a prominent device for automation of such activities. There are various places where a PLC can be used. Some of those are listed as below:

- Robotic arm in car manufacturing
- Air compressors
- Airport runway lighting control
- Traffic signal control
- Smoke alarm control
- Process valve control
- Textile equipment
- Vacuum pump system

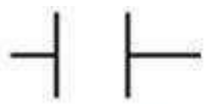
Apart from these applications, PLC is widely used in automation of electrical power system. At electrical substations automatic reclosing, circuit breaker tripping, capacitor switching, etc. can be controlled with PLCs.

## Ladder diagram

• Lets use a PLC in place of the relay.
• The first thing that's necessary is to create what's called a **Ladder Diagram**.
• We have to create one of these because, unfortunately, a PLC doesn't understand a schematic diagram it only recognizes code.
• Most PLCs have software which convert ladder diagrams into code.

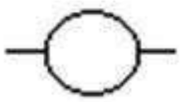
• **First Step :** Translate all of the items we're using into symbols the PLC understands.
• **Second step :** We must tell the PLC where everything is located. In other words we have to give all the devices an address.
• **Final step :** We have to convert the schematic into a logical sequence of events.

**First step:**
• The PLC doesn't understand terms like switch, relay, bell, etc.
• It prefers input, output, coil, contact, etc.
• It doesn't care what the actual input or output device actually is. It only cares that its an input or an output.
• First we replace the battery with a symbol. This symbol is common to all ladder diagrams. We draw what are called **bus bars**.
• These simply look like two vertical bars. One on each side of the diagram. Think of the left one as being + voltage and the right one as being ground. Further think of the current (logic) flow as being from left to right.
• Next we give the **inputs** a symbol. In this basic example we have one real world input. (i.e. the switch).
• We give the input that the switch will be connected to the symbol shown below. This symbol can also be used as the **contact of a relay**.



A contact symbol

• Next we give the **outputs** a symbol. In this example we use one output (i.e. the bell).
• We give the output that the bell will be physically connected to the symbol shown below. This symbol is used as the coil of a relay.



A coil symbol

• The AC supply is an external supply so we don't put it in our ladder. The PLC only cares about which output it turns on and not what's physically connected to it.

**Second step:**

• We must tell the PLC where everything is located. In other words we have to give all the devices an address.

• Where is the switch going to be physically connected to the PLC? How about the bell? We start with a blank road map in the PLCs town and give each item an address.

• Could you find your friends if you didn't know their address? You know they live in the same town but which house? The plc town has a lot of houses (inputs and outputs) but we have to figure out who lives where (what device is connected where).

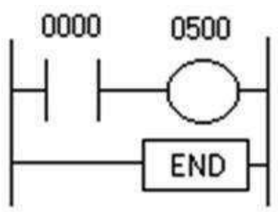
• We'll get further into the addressing scheme later. The PLC manufacturers each do it a different way! For now let's say that our input will be called "0000". The output will be called "500".

**Final step:**

• Convert the schematic into a logical sequence of events.

• The program we're going to write tells the PLC what to do when certain events take place.

• In our example we have to tell the plc what to do when the operator turns on the switch.




• Final converted diagram.

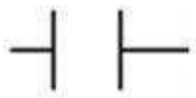
• We eliminated the real world relay from needing a symbol.

**Description of contacts and coils in the following states**

**i) Normally open**

**Load :**

• The load(LD) instruction is a **normally open contact**. It is sometimes also called examine if on (**XIO**).(as in examine the input to see if its physically on). The symbol for a load instruction is shown below.



A LoaD (contact) symbol

• This is used when an input signal is needed to be present for the symbol to turn on.
• When the physical input is on we can say that the instruction is True.
• We examine the input for an on signal. If the input is physically on then the symbol is on.
• An on condition is also referred to as a logic 1 state.

**ii) Normally closed**

**Load Bar :**
• The Load bar instruction is a **normally closed contact**. It is sometimes also called LoaDNot or examine if closed(**XIC**)(as in examine the input to see if its physically closed) The symbol for a loadbar instruction is shown below.

A LoaDNot (normally closed contact) symbol

• This is used when an input signal does not need to be present for the symbol to turn on.
• When the **physical input is off** we can say that the **instruction is True**.
• We examine the input for an off signal. If the input is physically off then the symbol is on.
• With most PLCs this instruction (**Load** or **Loadbar**) MUST be the first symbol on the left of the ladder.

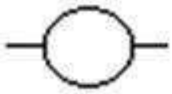
| Physical State | Instruction | Logic |
|---|---|---|
| OFF | TRUE | 0 |
| ON | FALSE | 1 |

**iii) Energized output**

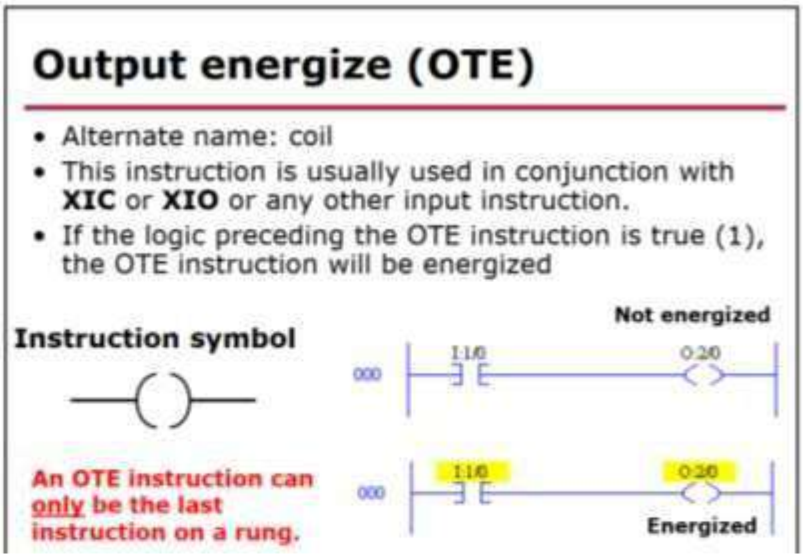
**out:**
• The Out instruction is sometimes also called an **Output Energize instruction**. The output instruction is like a **relay coil**. Its symbol looks as shown below.

• When there is a path of True instructions preceding this on the ladder rung, it will also be True.

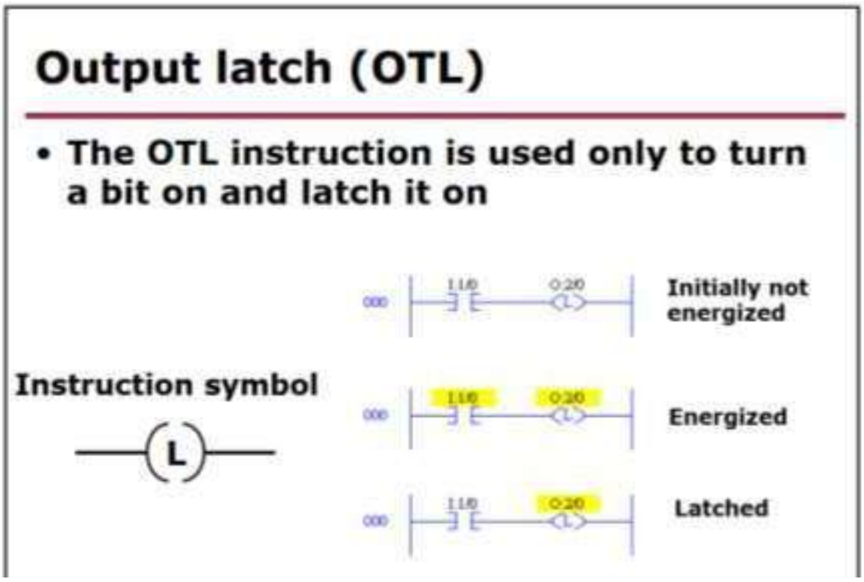
• When the **instruction is True it is physically ON**.
• We can think of this instruction as a normally open output.



An OUT (coil) symbol




### iv) Latched output



**Out bar:**

• The Outbar instruction is sometimes also called an OutNot instruction.

• The Outbar instruction is like a **normally closed relay coil**. Its symbol looks like that shown below.

An OUTBar (normally closed coil) symbol

**Ladder diagrams**

**i)AND gate**

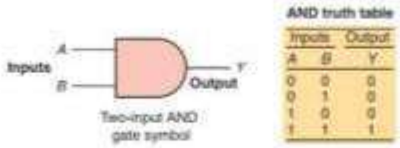



Figure 4-3 AND gate

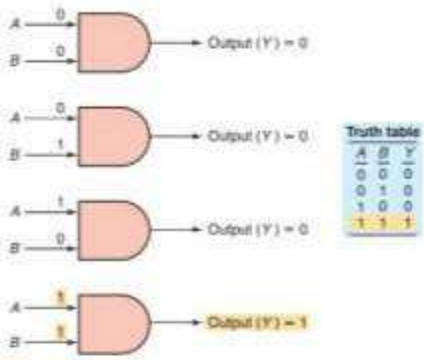



Figure 4-4 AND logic gate digital signal states

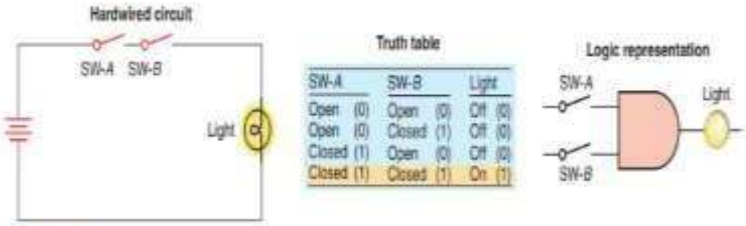
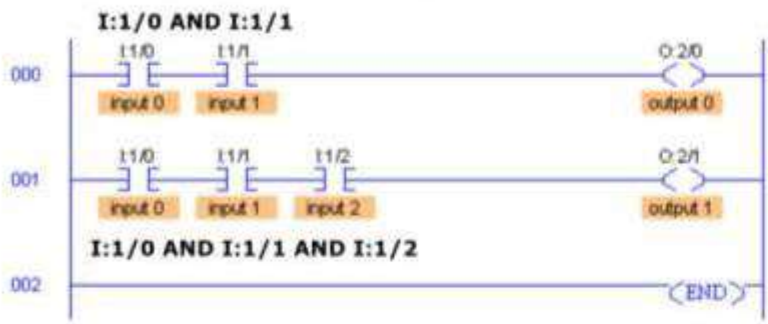



Figure 4-5 AND logic gate operates similarly to control devices connected in series.

## Logical AND ladder diagram

- The logical AND function is constructed by series combinations of digital (discrete) inputs
  - Two (or more) series components



## ii) OR gate

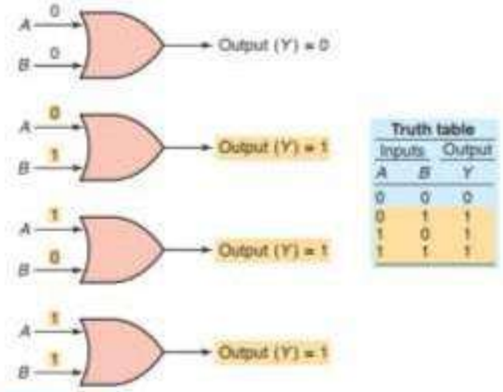



**Figure 4-7** OR logic gate digital signal states.

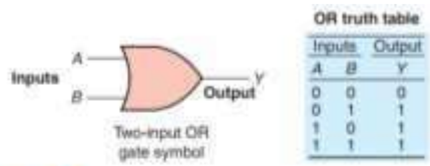



**Figure 4-6** OR gate.

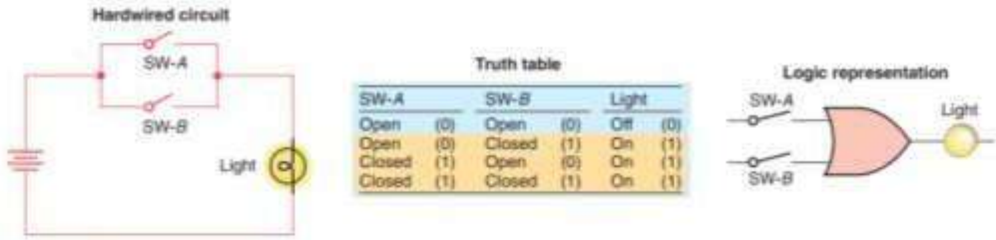
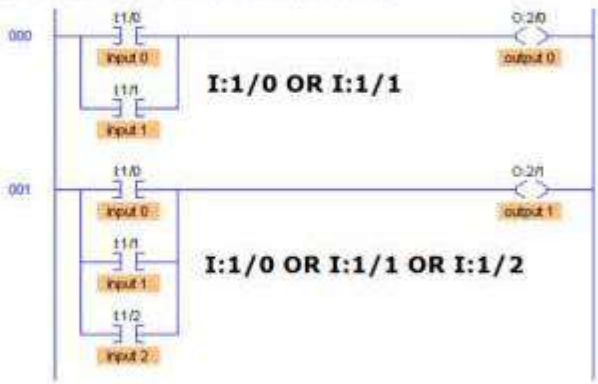


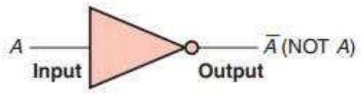

**Figure 4-8** OR logic gate operates similarly to control devices connected in parallel.

# Logical OR ladder diagram

- The logical OR function is constructed by parallel combinations of digital (discrete) inputs
  - Two (or more) parallel components



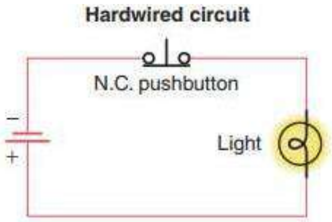
## iii) NOT gate




NOT truth table

| A | NOT A |
|---|---|
| 0 | 1 |
| 1 | 0 |

**Figure 4-9** NOT function.




Truth table

| Pushbutton | Light |
|---|---|
| Not pressed (0) | On (1) |
| Pressed (1) | Off (0) |

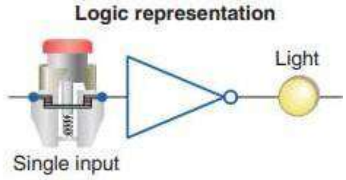
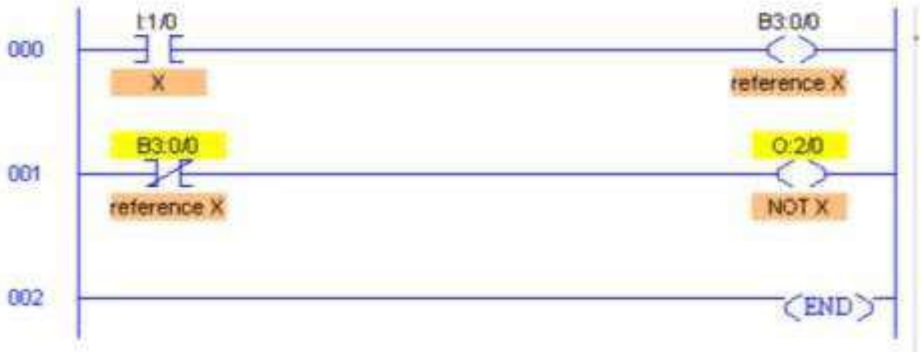



**Figure 4-10** NOT function constructed using a normally closed pushbutton.

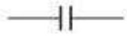
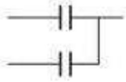
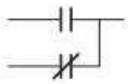
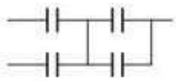
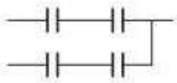
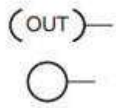
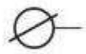
# Logical NOT

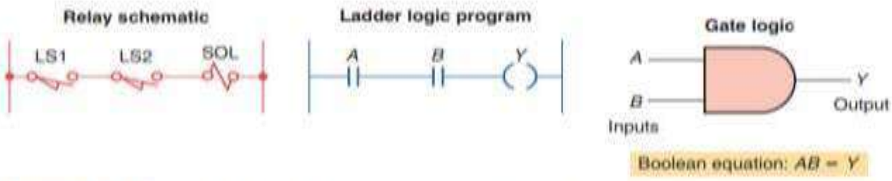
- The logical NOT function is constructed by referencing the input signal with a normally closed contact (XIO instruction)



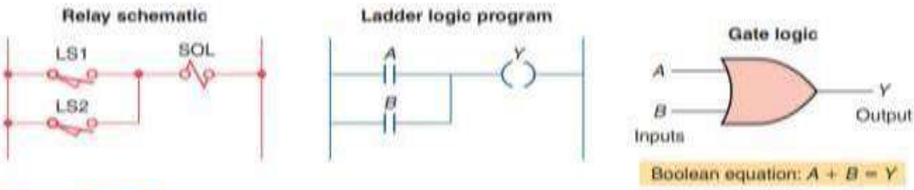
## Ladder diagrams for combination circuits using NAND, NOR, OR and NOT

**Table 4-1 Typical Boolean Instruction or Statement List**

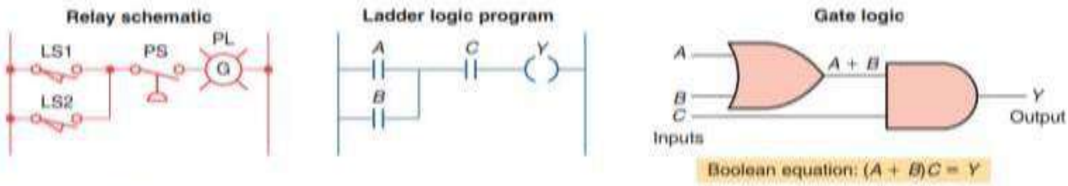
| Boolean Instruction and Function | Graphic Symbol |
|---|---|
| **Store (STR)–Load (LD)**<br>Begins a new rung or an additional branch in a rung with a normally open contact. |  |
| **Store Not (STR NOT)–Load Not (LD NOT)**<br>Begins a new rung or an additional branch in a rung with a normally closed contact. |  |
| **Or (OR)**<br>Logically ORs a normally open contact in parallel with another contact in a rung. |  |
| **Or Not (OR NOT)**<br>Logically ORs a normally closed contact in parallel with another contact in a rung. |  |
| **And (AND)**<br>Logically ANDs a normally open contact in series with another contact in a rung. |  |
| **And Not (AND NOT)**<br>Logically ANDs a normally closed contact in series with another contact in a rung. |  |
| **And Store (AND STR)–And Load (AND LD)**<br>Logically ANDs two branches of a rung in series. |  |
| **Or Store (OR STR)–Or Load (OR LOAD)**<br>Logically ORs two branches of a rung in parallel. |  |
| **Out (OUT)**<br>Reflects the status of the rung (on/off) and outputs the discrete (ON/OFF) state to the specified image register point or memory location. |  |
| **Or Out (OR OUT)**<br>Reflects the status of the rung and outputs the discrete (ON/OFF) state to the image register. Multiple OR OUT instructions referencing the same discrete point can be used in the program. |  |
| **Output Not (OUT NOT)**<br>Reflects the status of the rung and turns the output OFF for an ON execution condition; turns the output ON for an OFF execution condition. |  |



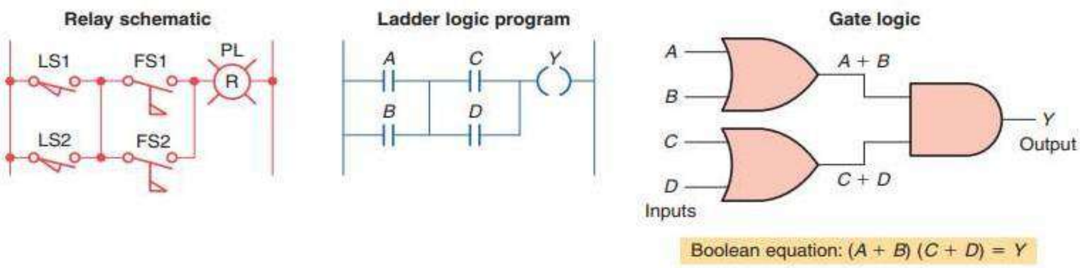

**Example 4-1** Two limit switches connected in series and used to control a solenoid valve.



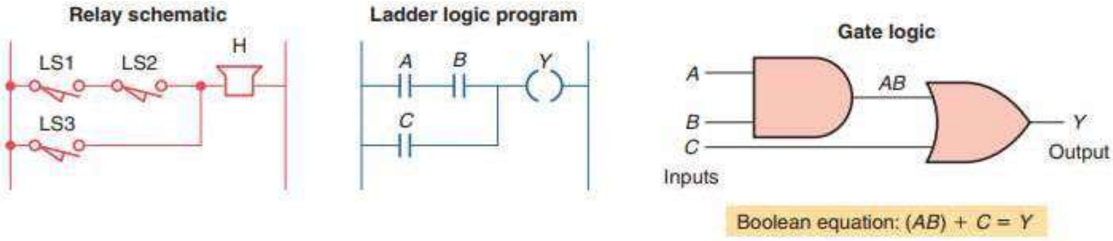

**Example 4-2** Two limit switches connected in parallel and used to control a solenoid valve.



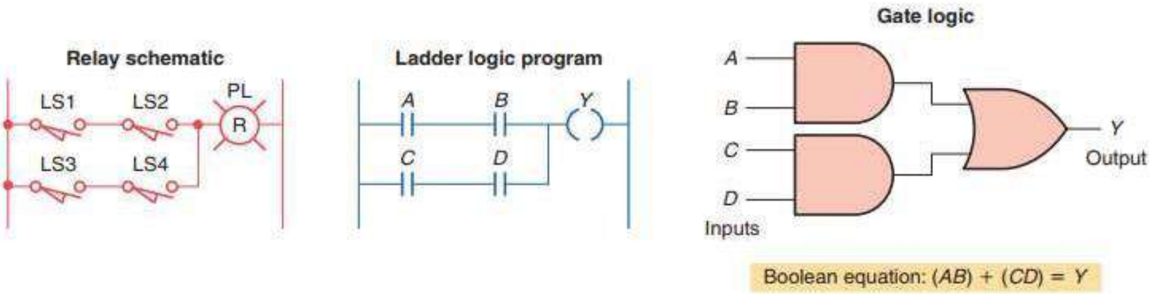

**Example 4-3** Two limit switches connected in parallel with each other and in series with a pressure switch.



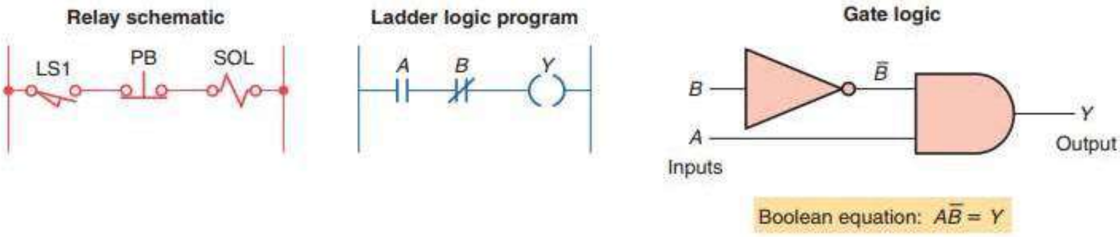

**Example 4-4** Two limit switches connected in parallel with each other and in series with two sets of flow switches (that are connected in parallel with each other), and used to control a pilot light.



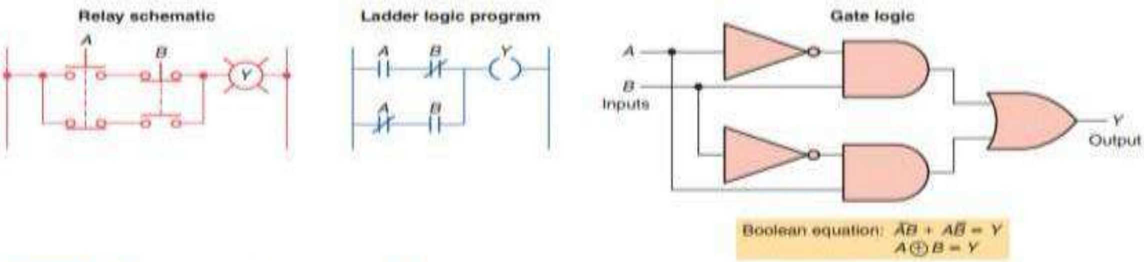

**Example 4-5** Two limit switches connected in series with each other and in parallel with a third limit switch, and used to control a warning horn.



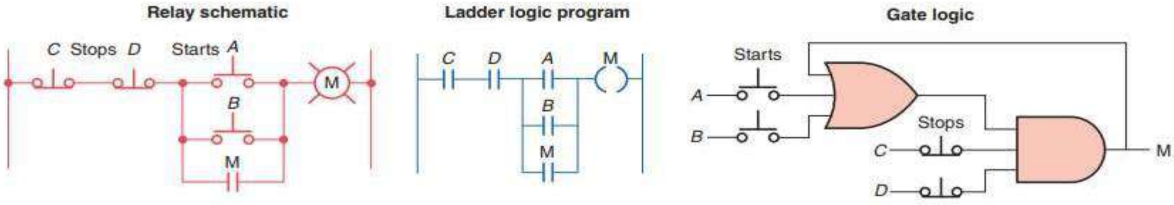

**Example 4-6** Two limit switches connected in series with each other and in parallel with two other limit switches (that are connected in series with each other), and used to control a pilot light.




**Example 4-7** One limit switch connected in series with a normally closed pushbutton and used to control a solenoid valve. This circuit is programmed so that the output solenoid will be turned on when the limit switch is closed and the pushbutton is *not pushed*.




**Example 4-8** Exclusive-OR circuit. The output lamp of this circuit is ON only when pushbutton A or B is pressed, but not both. This circuit has been programmed using only the normally open A and B pushbutton contacts as the inputs to the program.



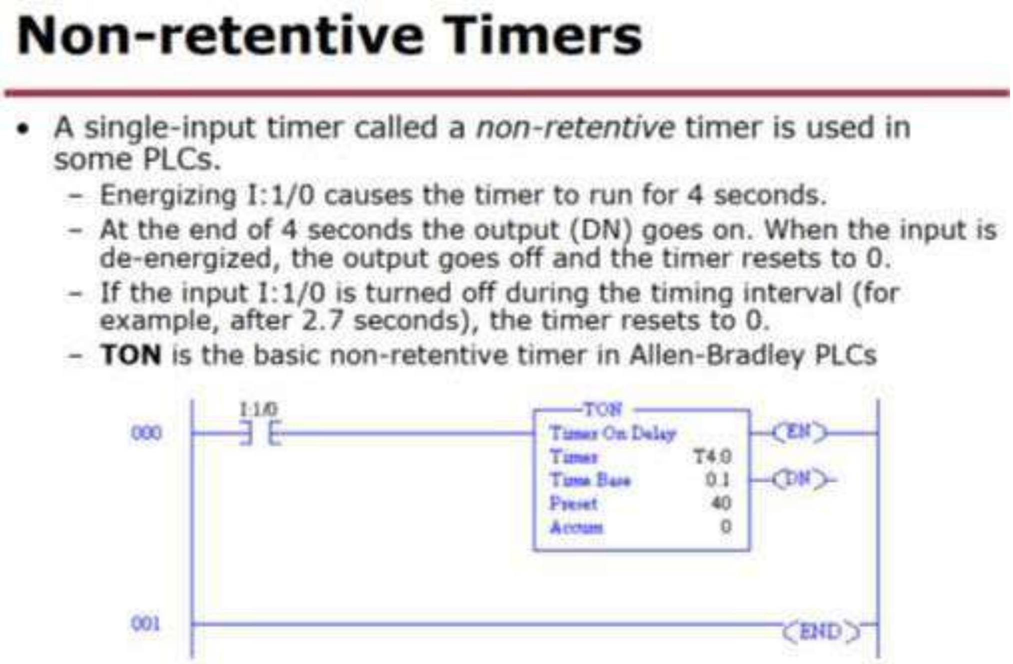

**Example 4-9** A motor control circuit with two start/stop buttons. When either start button is depressed, the motor runs. By use of a seal-in contact, it continues to run when the start button is released. Either stop button stops the motor when it is depressed.

**Timersi)T**
**ON**

• **TIMER :** It is an instruction that waits a set amount of time before doing something.
• Type of Timers : On-Delay Timer and Off-Delay Timer.

**On-Delay Timer :**

• Simply "delays turning on".
• After sensor (input) turns ON, wait x-seconds before activating a solenoid valve(output).
• This is the most common timer. It is often called **TON**(timer on-delay), **TIM**(timer) or **TMR**(timer).



# Timer Information


- The timer table contains all information for that timer
  - /EN: Timer is enabled (i.e. the input rung is energized)
  - /TT: Timer is timing
  - /DN: Timer is done
  - .PRE: Timer preset value (point at which the timer stops timing)
  - .ACC: Timer accumulator (accumulated time value)

**ii) T OFF**

**Off-Delay Timer :**

• Simply "delays turning off".

• After sensor (input) sees a target it turn on a solenoid (output).

• When the sensor no longer sees the target it hold the solenoid on for x-seconds before turning it off.

• It is called a TOF (timer off-delay).

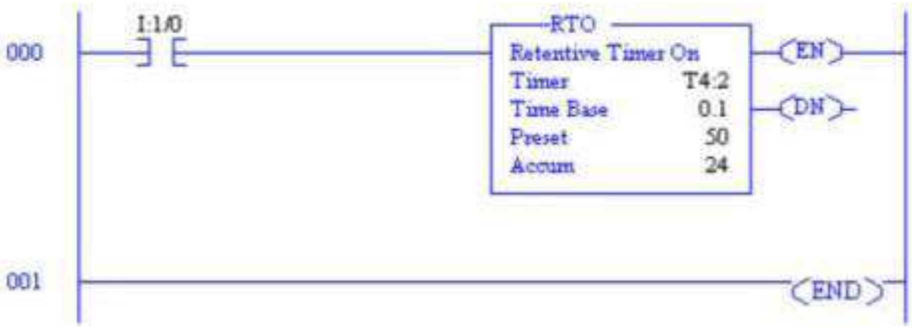
# Timer Delay Off (TOF)

- The TOF timer functions the opposite of the TON timer.
  - De-Energizing I:1/0 causes the timer to run for 4.5 seconds. The DN bit is initially set.
  - At the end of 4.5 seconds the output (DN) goes off. When the input is energized the timer resets to 0.
  - If the input I:1/0 is turned on during the timing interval (for example, after 2.7 seconds), the timer resets to 0.

**iii) Retentive timer**

## Retentive Timers (RTO)

- Functions exactly like TON except the accumulated time value is retained even if the input rung is de-energized.




**CountersCTU**

## Up Counter (CTU)

- The CTU is an instruction that counts false-to-true rung transitions.
  - Rung transitions can be caused by events occurring in the program (from internal logic or by external devices) such as parts traveling past a detector or actuating a limit switch.
- When rung conditions for a CTU instruction have made a false-to-true transition, the accumulated value is incremented by one count, provided that the rung containing the CTU instruction is evaluated between these transitions.
  - The ability of the counter to detect false–to–true transitions depends on the speed (frequency) of the incoming signal.
- The accumulated value is retained when the rung conditions again become false.
- The accumulated count is retained until cleared by a reset (RES) instruction.

**CTD**

## Down Counter (CTD)

- The CTD is an instruction that counts false-to-true rung transitions.
  - Rung transitions can be caused by events occurring in the program such as parts traveling past a detector or actuating a limit switch.
- When rung conditions for a CTD instruction have made a false-to-true transition, the accumulated value is decremented by one count, provided that the rung containing the CTD instruction is evaluated between these transitions.
- The accumulated counts are retained when the rung conditions again become false.
- The accumulated count is retained until cleared by a reset (RES) instruction.

**Ladder diagram using Timers and Counters**

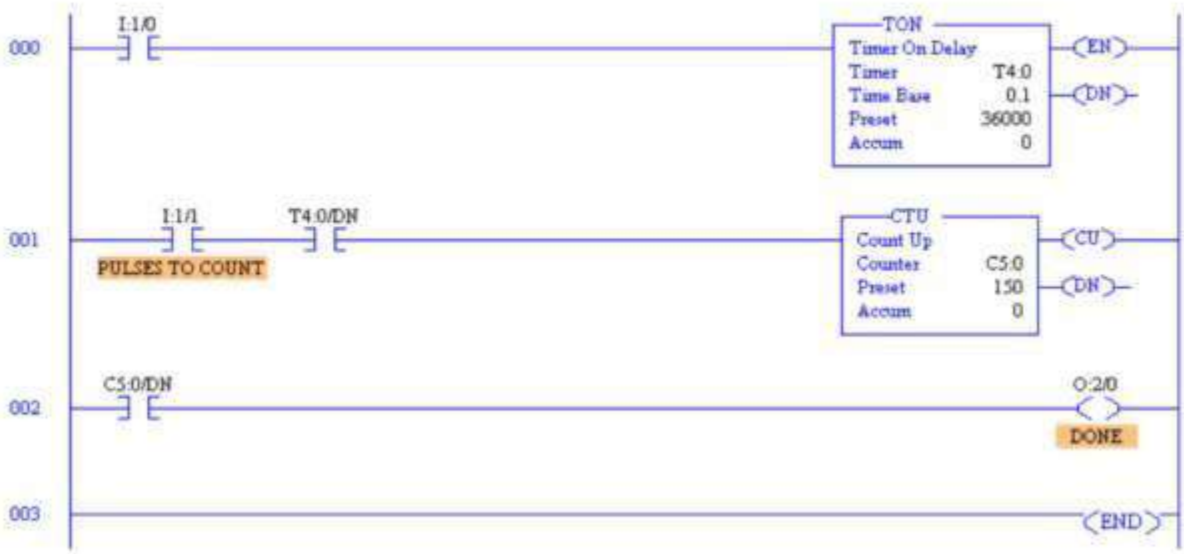
## Up Counter Example

- Accumulated count is reset only by the (RES) instruction
- The counter will increment the accumulator value even after the preset is reached

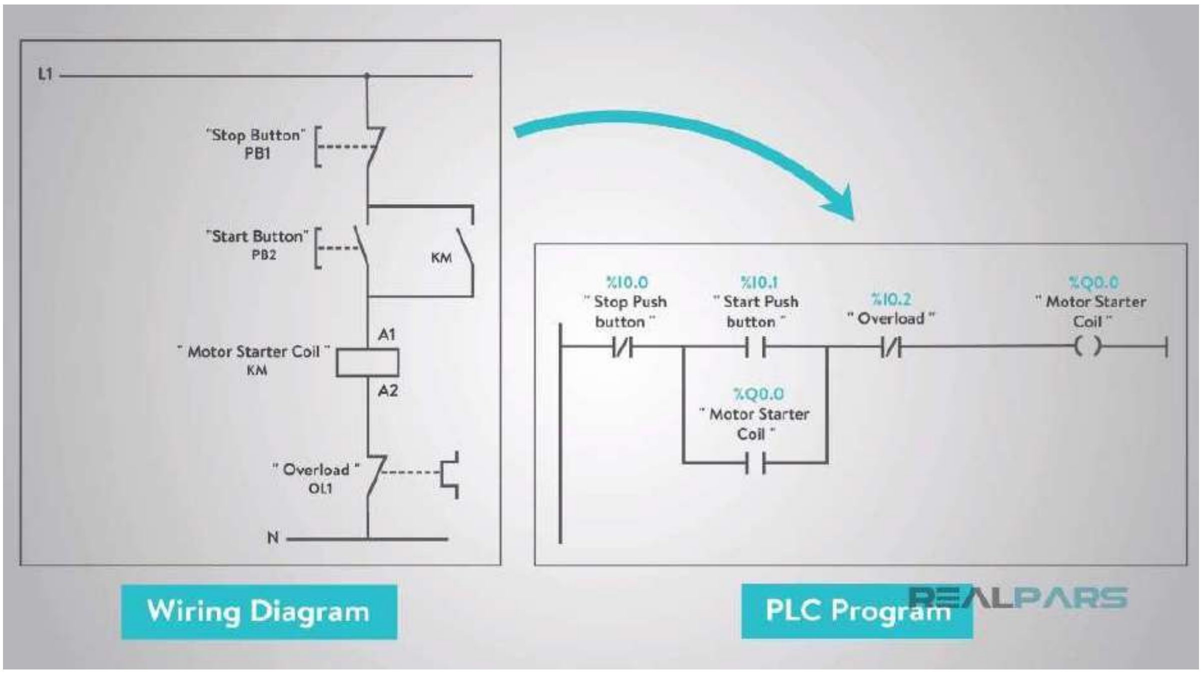
# Down Counter Example

- Accumulated count is reset only by the (RES) instruction
- The counter will decrement the accumulator value even after a 0 count is reached

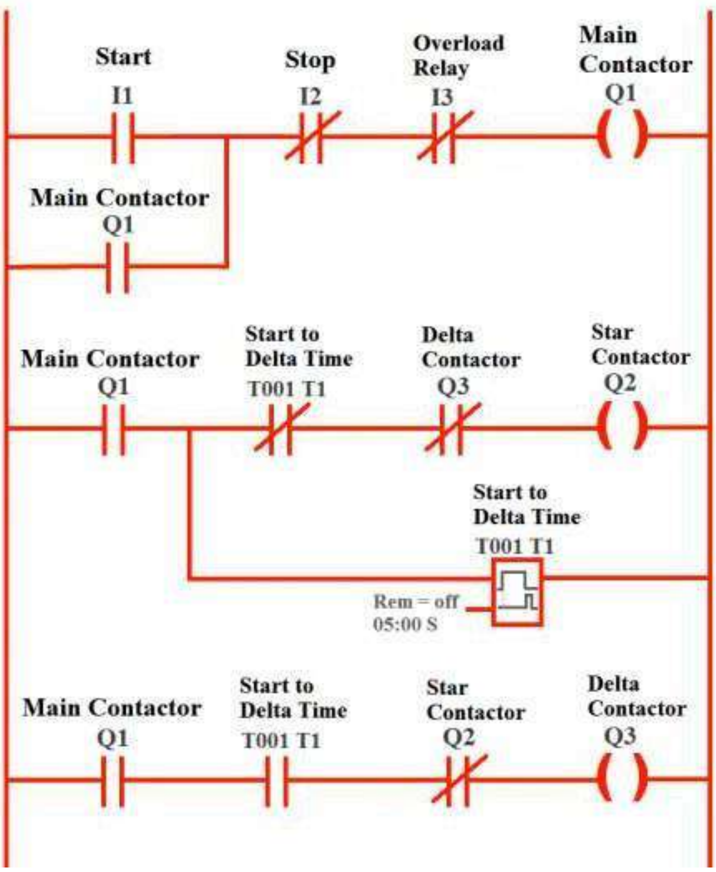

# Ladder Logic Example



# Ladder diagram for DOL starter




## STAR-DELTA MOTOR STARTER LADDER LOGIC



## SPECIAL CONTROL SYSTEMS

### DCS:

A distributed control system (DCS) is part of a manufacturing system.

Distributed control systems (DCS) are used in industrial and civil engineering applications to monitor and control distributed equipment with remote human intervention.

It is generally, since the 1970s, digital, and normally consists of field instruments, connected via wiring to computer buses or electrical buses to multiplexer/demultiplexers and A/D's or analog to digital and finally the Human-Machine Interface (HMI) or control consoles. A DCS is a process control system that uses a network to interconnect sensors, controllers, operator terminals and actuators. A DCS typically contains one or more computers for control and mostly use both proprietary interconnections and protocols for communications. See PAS.

DCS is a very broad term that describes solutions across a large variety of industries, including:

* Electrical power grids and electrical generation plants
* Environmental control systems
* Traffic signals
* Water management systems
* Refining and chemical plants
* Pharmaceutical manufacturing

### SCADA:

SCADA is the acronym for Supervisory Control And Data Acquisition. SCADA may be called Human-Machine Interface (HMI) in Europe. The term refers to a large-scale, distributed measurement (and control) system. SCADA systems are used to monitor or to control chemical, physical or transport processes.

The three components of a SCADA system are:

1. Multiple Remote Terminal Units (also known as RTUs or Outstations).
2. Master Station and HMI Computer(s).
3. Communication infrastructure

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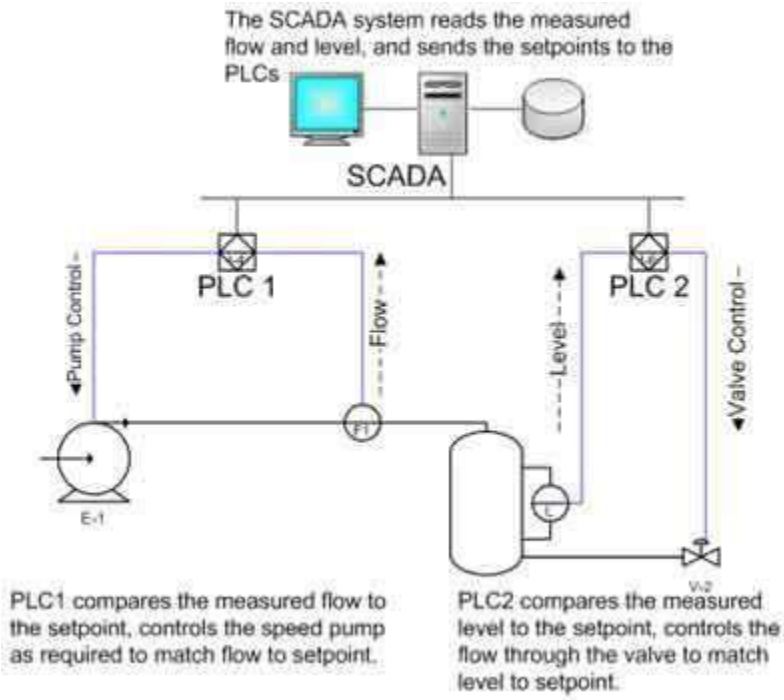
The term SCADA usually refers to a central system that monitors and controls a complete site. The bulk of the site control is actually performed automatically by a Remote Terminal Unit (RTU) or by a Programmable Logic Controller (PLC). Host control functions are almost always restricted to basic site over-ride or supervisory level capability.

SCADA systems typically implement a distributed database which contains data elements called points. A point represents a single input or output value monitored or controlled by the system. Points can be either "hard" or "soft". A hard point is representative of an actual input or output connected to the system, while a soft point represents the result of logic and math operations applied to other hard and soft points. The point values are normally stored as value-timestamp combinations; the value and the timestamp when the value was recorded or calculated. A series of value-timestamp combinations is the history of that point.

**DCS vs. SCADA**

DCS and SCADA are monitoring and control mechanisms that are used in industrial installations to keep track and control of the processes and equipment; to ensure that everything goes smoothly, and none of the equipment work outside the specified limits. The most significant difference between the two is their general design. DCS, or Data Control System, is process oriented, as it focuses more on the processes in each step of the operation. SCADA, or Supervisory Control and Data Acquisition, focuses more on the acquisition and collation of data for reference of the personnel who are charged with keeping track of the operation.




DCS is process state driven, while SCADA is even driven. DCS does all its tasks in a sequential manner, and events are not recorded until it is scanned by the station. In contrast, SCADA is event driven. It does not call scans on a regular basis, but waits for an event or for a change in value in one component to trigger certain actions. SCADA is a bit more advantageous in this aspect, as it lightens the load of the host. Changes are also recorded much earlier, as an event is logged as soon as a value changes state.

In terms of applications, DCS is the system of choice for installations that are limited to a small locale, like a single factory or plant, while SCADA is preferred when the entire system is spread across a much larger geographic location, examples of which would be oil wells spread out in a large field. Part of the reason for this is the fact that DCS needs to be always connected to the I/O of the system, while SCADA is expected to perform even when field communications fail for some time. SCADA does this by keeping a record of all current values, so that even if the base station is unable to extract new information from a remote location, it would still be able to present the last recorded values.

Summary:

1. DCS is process oriented, while SCADA is data acquisition oriented.

2. DCS is process state driven, while SCADA is event driven.

3. DCS is commonly used to handle operations on a single locale, while SCADA is preferred for applications that are spread over a wide geographic location.