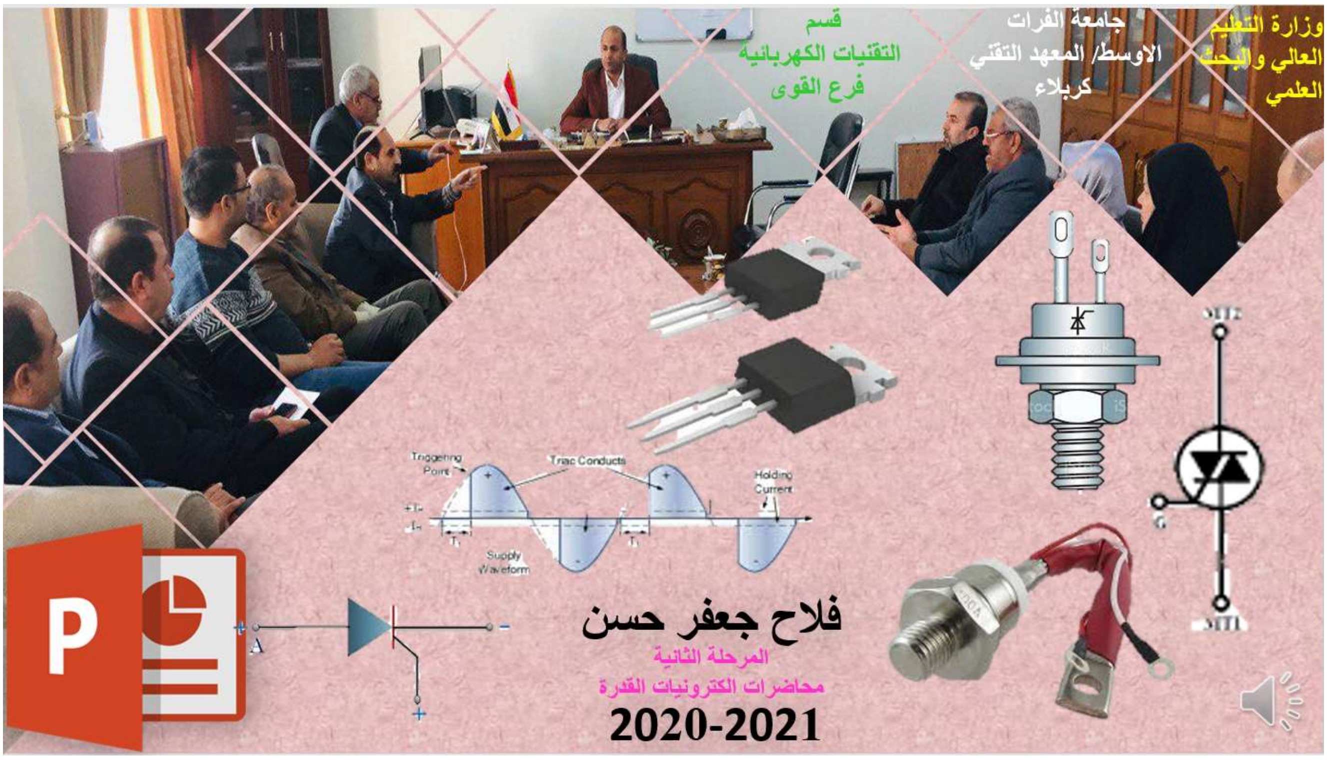
KARBALA TECHNICAL INSTITUE
SECOND YEAR

POWER ELCTRONICS



What is power electronics?

The power electronics combine power, electronics, and control application of solid-state electronics for the control and conversion of electric power.

Power electronics is based primarily on the switching of the power semiconductor devices.

power semiconductor devices:

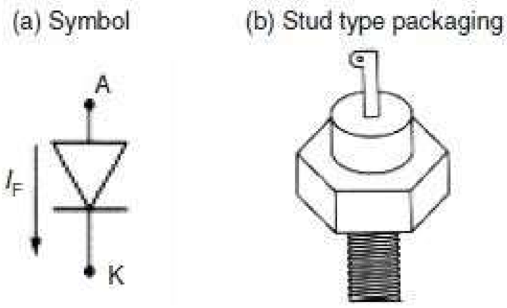
1-power diode. 2-Thyristors.

3- power bipolar junction transistor (BJTs).

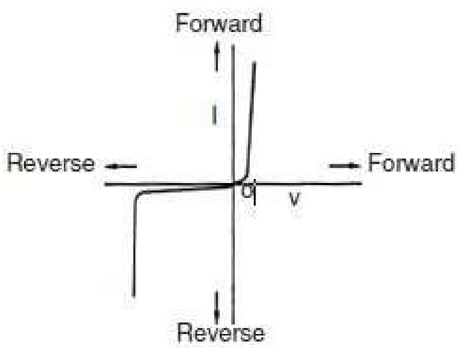
power diode

Introduction: -

1- A power diode is designed for high forward current and high reverse breakdown voltage.
2- The area of pn junction in power diodes is much larger than in a signal diode because it is designed for large current flow.
3- The frequency response or switching speed is low compared to signal diodes.



Fig(1) Power Diode



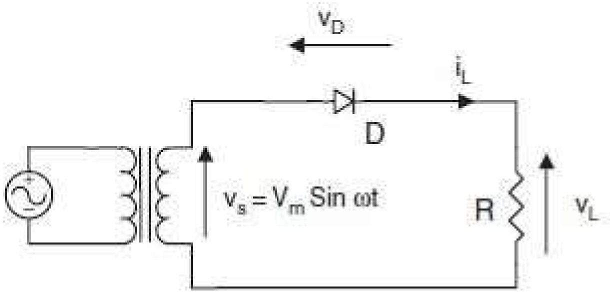
Fig(2) Diode characteristics

Single Phase Uncontrolled Rectifier

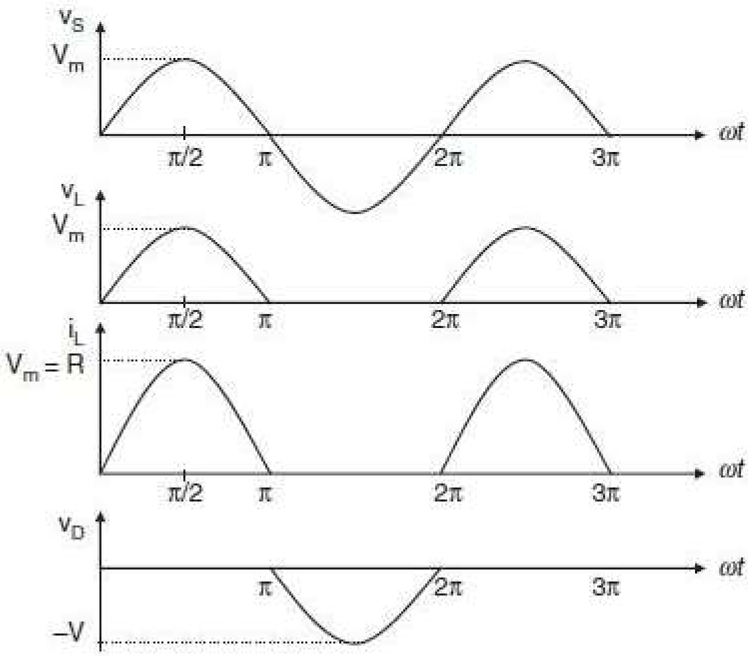
Rectification is a process of converting an alternating current or voltage into a direct current or voltage. This conversion can be achieved by variety of circuits based on and using switching devices. The widely used switching devices are diodes, thyristors, power transistors etc.

Uncontrolled Rectifiers: It uses only diodes & the output DC voltage is fixed in amplitude by giving the amplitude of the AC supply.

a-Half Wave Rectifier with R Load: This is the simplest type of uncontrolled rectifier. In a half wave rectifier, for one cycle of supply voltage, there is one half cycle of output, or load voltage and other half cycle blocked.



Fig(3-a) single phase rectifier half wave uncontrolled rectifier



Fig(3-b) voltage and current waveforms

$$Vdc = \frac{1}{2\pi}\int_{0}^{\pi} Vin\ dwt = \frac{1}{2\pi}\int_{0}^{\pi} Vm\sin(wt)\ dwt = \frac{Vm}{\pi}$$

$$Idc = \frac{Vdc}{Rl}$$

$$Vrms = \sqrt{\frac{1}{2\pi}\int_{0}^{\pi}(Vin)^2\ dwt} = \sqrt{\frac{1}{2\pi}\int_{0}^{\pi}(Vm\sin(wt))^2\ dwt} = \frac{Vm}{2}$$

$$Irms = \frac{Vrms}{Rl}$$

Ripple factor(r):- The ripple factor (r) which is a measure of the ripple content is defined as

$$r = \sqrt{(\frac{Vrms}{Vdc})^2 - 1} = \sqrt{(\frac{Vm/2}{Vm/\pi})^2 - 1} = 1.21$$

Efficiency(η)

$$\eta = \frac{Po}{Pin} \times 100\% = \frac{Vdc \times Idc}{Vrms \times Irms} \times 100\% = 40.5\%$$

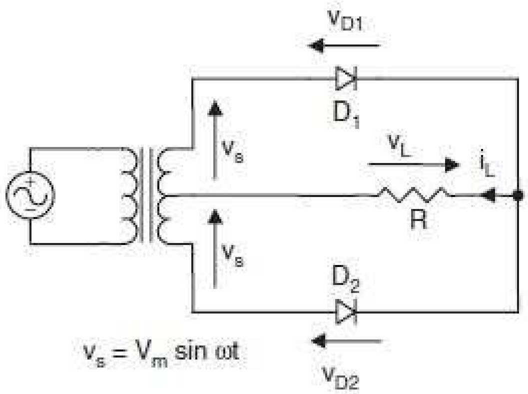
Peak inverse voltage(PIV)

PIV=-Vm

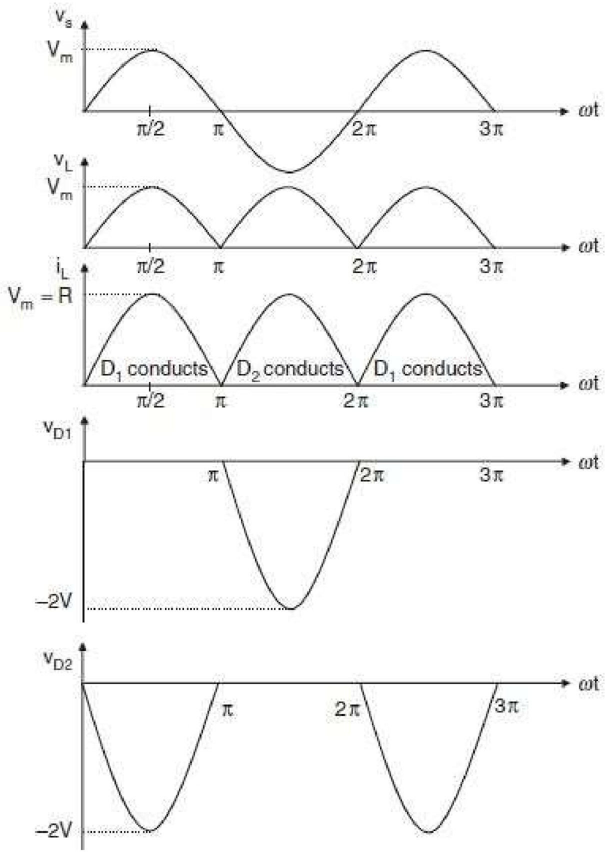
b- Full-wave rectifiers.

1-Center-tap Full- wave rectifiers.

Full wave rectifier using two diode and center tapped transformer. diode D1 conducts for the positive. half cycle, while D2 conducts for the negative cycle. . diode D2 is subjected to a reverse voltage of 2VS. In the next half cycle, diode D1 is a reverse voltage of 2VS. Thus, for diodes D1 and D2, peak inverse voltage is 2Vm. So that for one cycle of source voltage, there are two pulses of output voltage.



Fig(4-a) Single phase Center-tap Full- wave rectifiers



Fig(4-b) voltage and current waveforms

$$\mathbf{Vdc} = \frac{1}{\pi}\int_0^{\pi} \mathbf{Vin\ dwt} = \frac{1}{\pi}\int_0^{\pi} \mathbf{Vm\ sin(wt)\ dwt} = \frac{2\mathbf{Vm}}{\pi}$$

$$\mathbf{Idc} = \frac{\mathbf{Vdc}}{\mathbf{Rl}}$$

$$\mathbf{Vrms} = \sqrt{\frac{1}{\pi}\int_0^{\pi}(\mathbf{Vin})^2\ \mathbf{dwt}} = \sqrt{\frac{1}{\pi}\int_0^{\pi}(\mathbf{Vm\ sin(wt)})^2\ \mathbf{dwt}} = \frac{\mathbf{Vm}}{\sqrt{2}}$$

$$\mathbf{Irms} = \frac{\mathbf{Vrms}}{\mathbf{Rl}}$$

Ripple factor(r)

$$r = \sqrt{\left(\frac{Vrms}{Vdc}\right)^2 - 1} = \sqrt{\left(\frac{Vm/\sqrt{2}}{2Vm/\pi}\right)^2 - 1} = 0.48$$

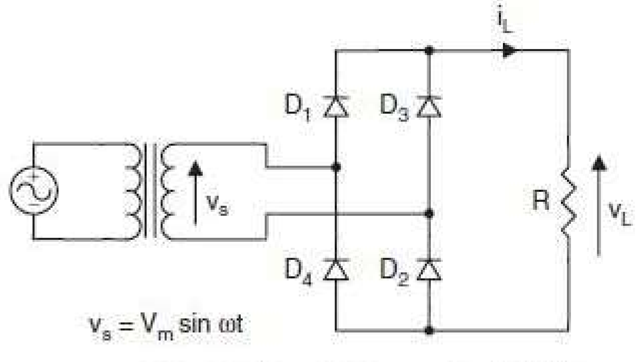
Efficiency(η)

$$\eta = \frac{Po}{Pin} \times 100\% = \frac{Vdc \times Idc}{Vrms \times Irms} \times 100\% = 81\%$$

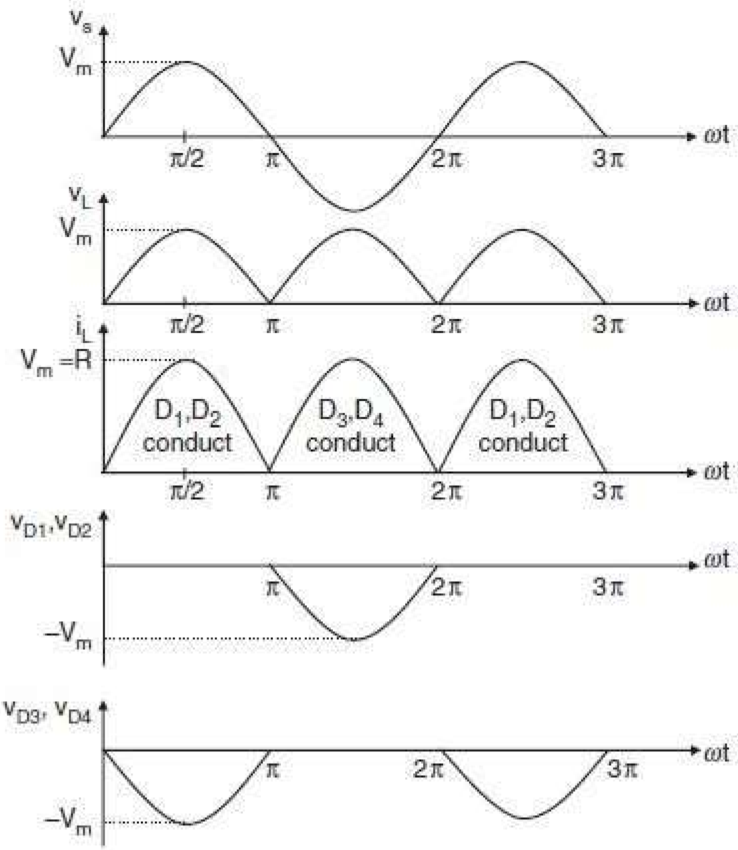
Peak Inverse voltage(PIV)

PIV =-2Vm

2-Bridge Rectifier: Bridge rectifier using four diodes. bridge rectifier does not need
center tapped transformer. Diodes D1, D2 conduct at the positive half cycle. Each of the diodes D3 and D4 is subjected to a reverse voltage of Vs.
Diodes D3, D4 conduct at the negative half cycle. Each of the two diodes D1 and D2 are reverse voltage of Vs.



Fig(5-a) Single phase bridge Full- wave rectifiers



Fig(5-b) voltage and current waveforms

$$\mathbf{Vdc = \frac{1}{\pi}\int_0^{\pi} Vin\ dwt = \frac{1}{\pi}\int_0^{\pi} Vm\ sin(wt)\ dwt = \frac{2Vm}{\pi}}$$

$$\mathbf{Idc == \frac{Vdc}{Rl}}$$

$$\mathbf{Vrms = \sqrt{\frac{1}{\pi}\int_0^{\pi}(Vin)^2\ dwt} = \sqrt{\frac{1}{\pi}\int_0^{\pi}(Vm\ sin(wt))^2\ dwt} = \frac{Vm}{\sqrt{2}}}$$

$$\mathbf{Irms = \frac{Vrms}{Rl}}$$

Ripple factor(r)

$$\boldsymbol{r = \sqrt{(\frac{Vrms}{Vdc})^2 - 1} = \sqrt{(\frac{Vm/\sqrt{2}}{2Vm/\pi})^2 - 1} = 0.48}$$

Efficiency(η)

$$\boldsymbol{\eta = \frac{Po}{Pin} \times 100\% = \frac{Vdc \times Idc}{Vrms \times Irms} \times 100\% = 81\%}$$

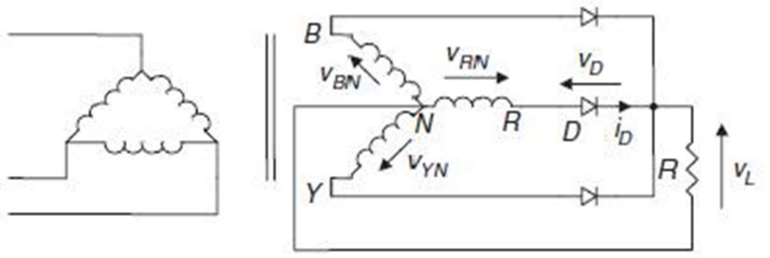
Peak Inverse voltage(PIV)

PIV =-Vm

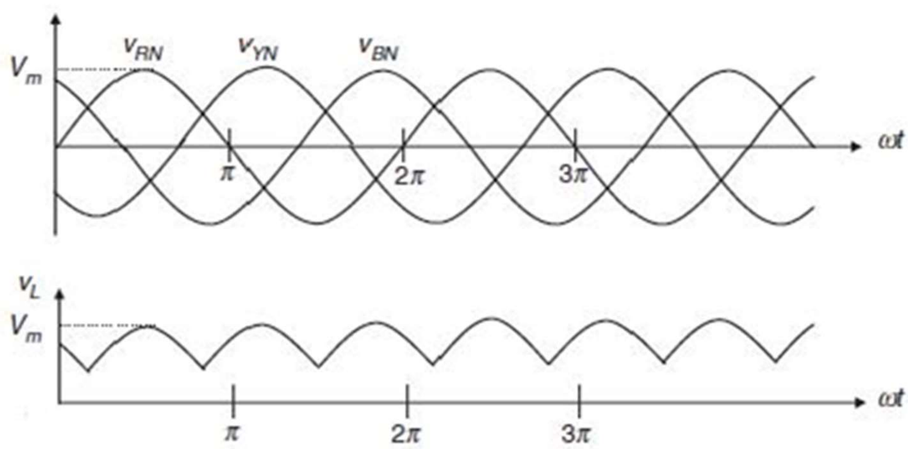
Three Phase Rectifier

(A) Three Phase Uncontrolled Rectifier: Three phase rectifier converts AC into DC.
(1) Three Phase Half Wave Rectifier
(2) Three Phase Bridge Rectifier

1. **Three Phase Half Wave Rectifier (Common Cathode): -**
Three phase half wave rectifier is consists of three diodes D1, D2, D3. These diodes are
connected to a common load. The other load terminal is connected to neutral N of the supply. The cathode of three diodes are connected together. This configuration is called common cathode three phase half wave rectifier. The three phase supply voltage is Va, Vb, Vc. A diode with the highest positive voltage will begin to conduct at the cross over points of the three phase supply. Diode D1 will conduct from $\omega t = 30^\circ$ to $\omega t = 150^\circ$ as the most positive as compared to other two diodes during this interval. Diode D2 will conduct from $\omega t = 150^\circ$ to $\omega t = 270^\circ$ and diode D3 will conduct from $\omega t = 270^\circ$ to $\omega t = 390^\circ$. When a diode is conducting, the common cathode terminal P rises to highest positive voltage of the phase and other two blocking diodes are reverse biased. The voltage across the load Vo follow the positive supply voltage envelope and waveform is shown.



Fig(6-a) Three phase uncontrolled half- wave rectifier



Fig(6-b) voltage and current waveforms

Equations:-

$$\mathbf{Vdc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} \mathbf{Vin\ dwt} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} \mathbf{Vm\ sin(wt)\ dwt} = \frac{3\sqrt{3}\mathbf{Vm}}{2\pi} = \mathbf{0.827Vm}$$

$$\mathbf{Idc} = \frac{\mathbf{Vdc}}{\mathbf{Rl}}$$

$$\mathbf{Vrms} = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6}(\mathbf{Vin})^2\ \mathbf{dwt}} = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6}(\mathbf{Vm\ sin(wt)})^2\ \mathbf{dwt}} = 0.84\ \mathrm{Vm}$$

$$\mathbf{Irms} = \frac{\mathbf{Vrms}}{\mathbf{Rl}}$$

Ripple factor(r)

$$r = \sqrt{\left(\frac{Vrms}{Vdc}\right)^2 - 1} = \sqrt{\left(\frac{0.84\ Vm}{0.827\ Vm}\right)^2 - 1} = 0.178$$

Efficiency(η)

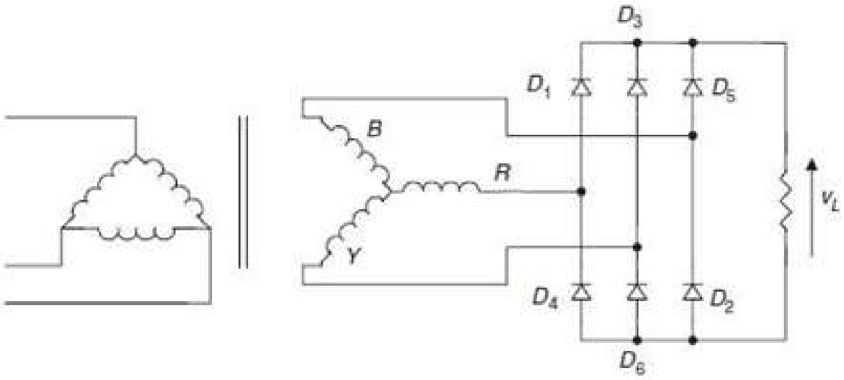
$$\eta = \frac{Po}{Pin} \times 100\% = \frac{Vdc \times Idc}{Vrms \times Irms} \times 100\% = 96.9\%$$

Peak Inverse voltage (PIV)

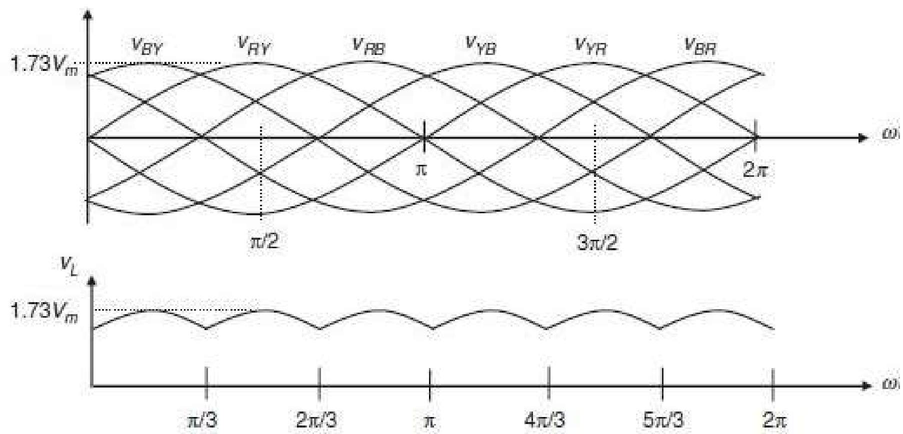
PIV =- $\sqrt{3}\ \mathbf{Vm}$

2. **Three Phase Full Wave Bridge Rectifier: -**

Three phase bridge rectifier is consists of 6 diodes. Diodes D1, D2, D3 is for positive group and diodes D4, D5, D6 is for negative group. Three phase bridge rectifier configuration and waveform is shown.



Fig(7-a) Three phase uncontrolled bridge full- wave rectifier



Fig(7-b) voltage and current waveforms

Equations:

$$\mathbf{Vdc} = \frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} \sqrt{3}\mathbf{Vm}\sin(\mathbf{wt})\,\mathbf{dwt} = \frac{3\mathbf{Vm}}{\pi} = \mathbf{1.654Vm}$$

$$\mathbf{Idc} = \frac{\mathbf{Vdc}}{\mathbf{Rl}}$$

$$\mathbf{Vrms} = \sqrt{\frac{3}{\pi}\int_{\pi/3}^{2\pi/3}(\mathbf{Vin})^2\,\mathbf{dwt}} = \mathbf{Vrms} = \sqrt{\frac{3}{\pi}\int_{\pi/3}^{2\pi/3}\left(\sqrt{3}\mathbf{Vm}\sin(\mathbf{wt})\right)^2\mathbf{dwt}} = 1.655\ \mathrm{Vm}$$

$$\mathbf{Irms} = \frac{\mathbf{Vrms}}{\mathbf{Rl}}$$

Ripple factor(r)

$$r = \sqrt{\left(\frac{Vrms}{Vdc}\right)^2 - 1} = \sqrt{\left(\frac{1.655Vm}{1.654Vm}\right)^2 - 1} = 0.035$$

Efficiency(η)

$$\eta = \frac{Po}{Pin} \times 100\% = \frac{Vdc \times Idc}{Vrms \times Irms} \times 100\% = 99.9\%$$

Peak Inverse voltage (PIV)

PIV =- $\sqrt{3}\ \mathbf{Vm}$

The power transistor

The transistor is a three layers N-P-N or P-N-P device as shown in fig. 9. Within the working range the collector current I_C is a function of the base current I_B a change in base current gives a corresponding amplified change in the collector current for a given collector-emitter voltage VCE. The ratio of these two currents is in the order of 15 to 100.

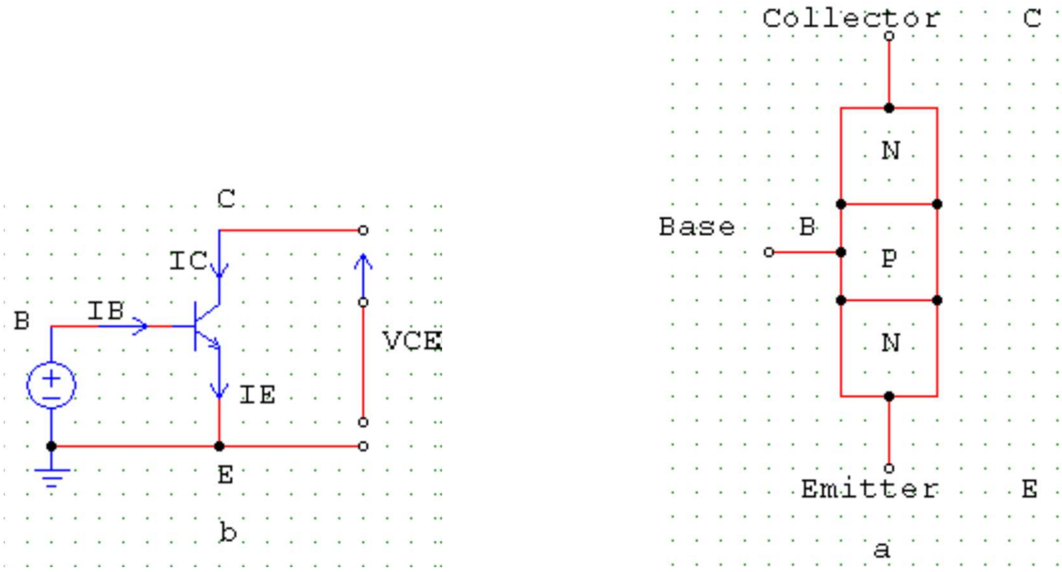
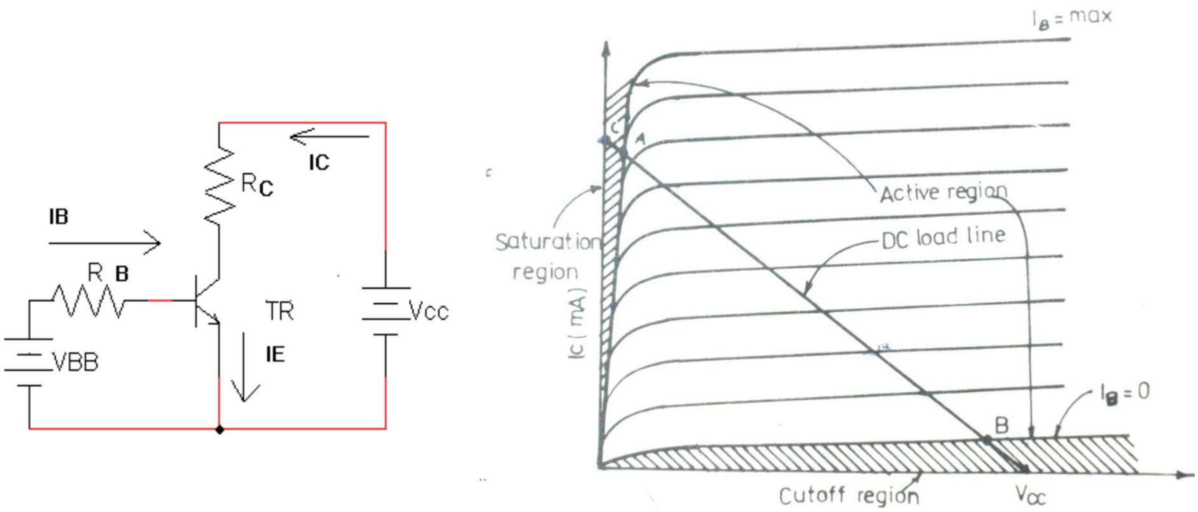


Fig (9) N-P-N Transistor a) Structure, b) Symbol

In practice for power applications the transistor is operated as a switch, with zero bases current. Power transistors have controlled turn on and turn off characteristics. The transistors are operated in the saturation region resulting in a low ON state voltage drop. The switching speed of modern transistors is much higher than that of thyristors but voltage and current ratings are lower than those of thyristors.



(a) (b)

Fig(10) (a)transistor circuit (b)transistor characteristic, dc load line

There are three operating regions of transistor (cutoff, active, saturation).
In the cutoff region the transistor is OFF or the base current is not enough to turn it
ON and both junctions are reverse biased.
In the active region, the transistor acts as an amplifier. In the saturation region, the base current is sufficiently high so that the collector – emitter voltage is low
and the transistor acts as a closed (ON) switch.

For the input circuit:

$$V_{BB} = I_B R_B + V_{BE}$$

$$R_B = \frac{V_{BB} - V_{BE}}{I_B}$$

And for the output circuit:

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

The equation above can be used to draw the dc load line by choosing two points as follows:
1- At cut off region:

$I_{C(cut\ off)} \approx 0$

$V_{CE(cut\ off)} \approx V_{CC}$

2- At saturation region:

$V_{CE(sat)} \approx 0$

$$I_{C(sat)} \approx \frac{V_{CC}}{R_C}$$

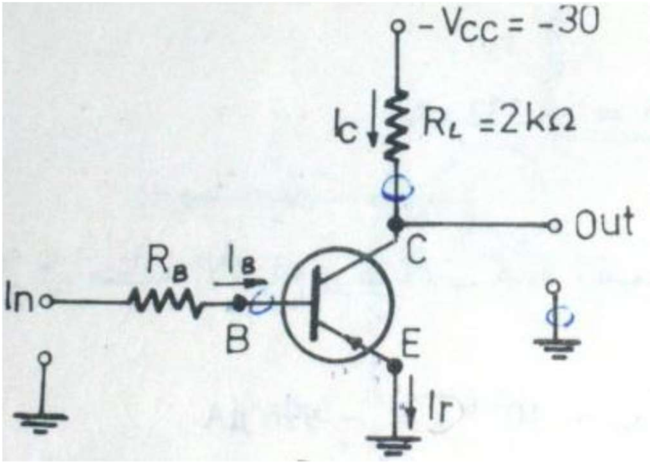
$$I_{B(sat)} = \frac{I_{C(sat)}}{\beta}$$

The perfect switch ON condition is: $I_{B(per)} > 3 * I_{B(sat)}$

Examples:-
Ex1:- For transistor as a switch if the transistor has the following specification $V_{CE(sat)} = 0.15$; $V_{BE(sat)} = 0.65$; $\beta = 45$; $V_{in} = 1.5$ V. Calculate the value of R_B which make the transistor works in saturation region.

$$I_C(\text{sat}) = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{30 - 0.15}{2 \times 10^3} = 0.014A$$

$$I_{B(sat)} = \frac{I_C(sat)}{\beta} = \frac{0.014}{45} = 0.3 \times 10^3 A$$



Choose

$I_{B(per)} = 3^* \, I_{B(sat)}$
$I_{B(per)} = 3 \times 0.3 \times 10^3 = 0.9 \times 10^3$ A
Vin = $I_{B(per)}$ x R_B + V_{BE}

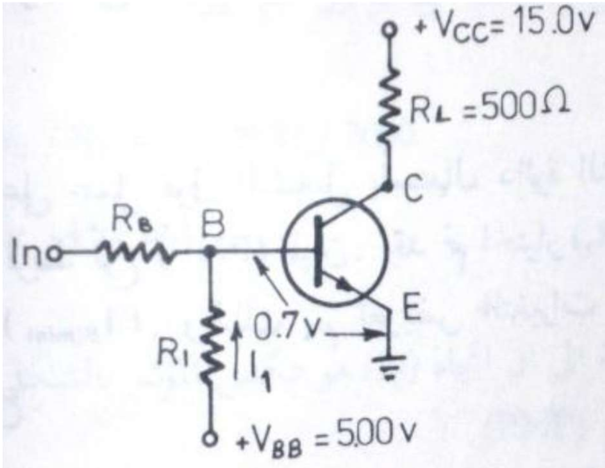
$$R_B = \frac{V_{in} - V_{BE}}{IB(per)}$$

$$R_B = \frac{1.5 - 0.65}{9 \times 10^3} = 944\Omega \approx 1K\Omega$$

EX: 2

For the circuit shown below (VBE= 0. 7 V, β= 50, and Vin=1V) Calculate the value of (R1, RB) which make the transistor works in saturation region.

$$I_C(sat) = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{15-0}{500} = 0.03A$$



$$I_{B(sat)} = \frac{I_C(sat)}{\beta} = \frac{0.03}{50} = 0.6 \times 10^{-3} A$$

Choose

I_B (per) = 3* $I_{B(sat)}$
I_B (per) $= 3 \times 0.6 \times 10^{-3} = 1.8 \times 10^{-3} A$

To certify the operation of the transistor in saturation region we may use
$I_1 = 2 \times I_{B(sat)} = 2 \times 0.6 \times 10^{-3} = 1.2 \times 10^{-3} A$

$$R_1 = \frac{V_{BB} - V_{BE}}{I_1} = \frac{5-0.7}{1.2 \times 10^{-3}} = 3.625\ K\Omega$$

$$I_2 = I_{B(sat)} = 0.6 \times 10^{-3} A$$

$$R_B = \frac{V_{in} - V_{BE}}{I_2} = \frac{1 - 0.7}{0.6 \times 10^{-3}} = 0.583\ K\Omega$$

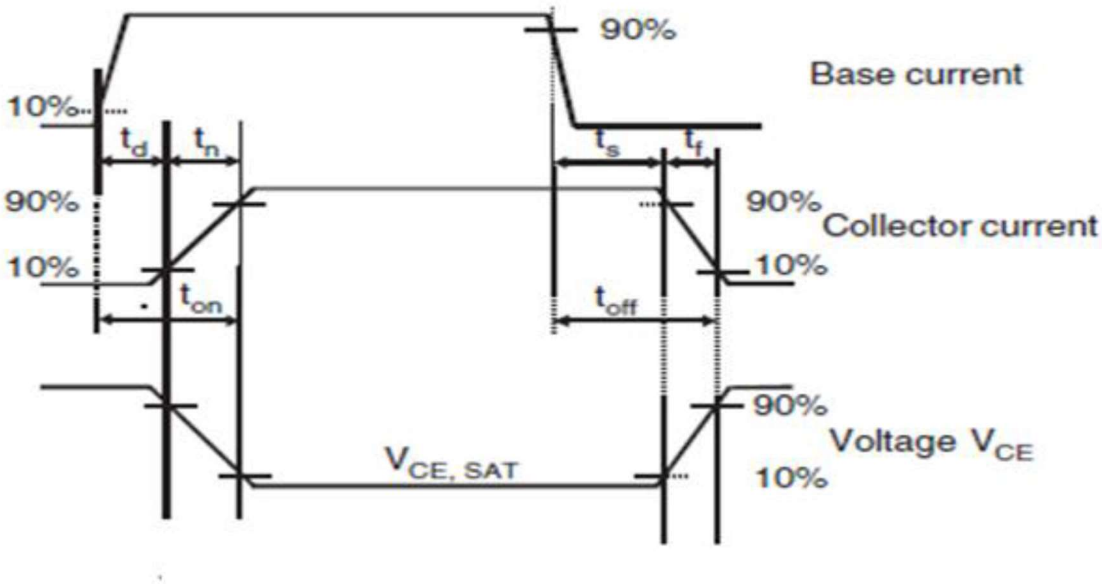
Dynamic Switching Characteristics:

Time delay (t_d):

Is the time taken for I_C to reach 10 % of its final value $I_{C(sat)}$.

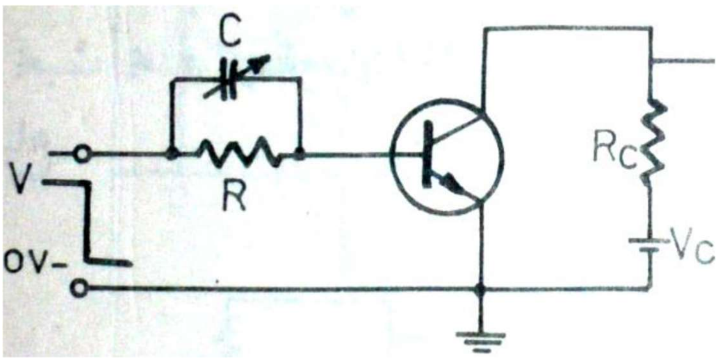
Rise time (t_r):
Is the time taken for (I_C) to change from 10% to 90 % of Its final value $I_{C(sat)}$.
Conduction time (t_{ON})
$t_{ON} = t_d + t_r$
Storage time (t_s):
Is the time interval between the input and the point at which Ic reaches 90% of its final value $I_{C(sat)}$.

Fall time (t_f):
Is the time taken for (I_C) to fall from 90% to 10% of its final value $I_{C(sat)}$.
Cut off time (t_{off}):
$t_{off} = t_s + t_f$



Fig(11) transistor switching times

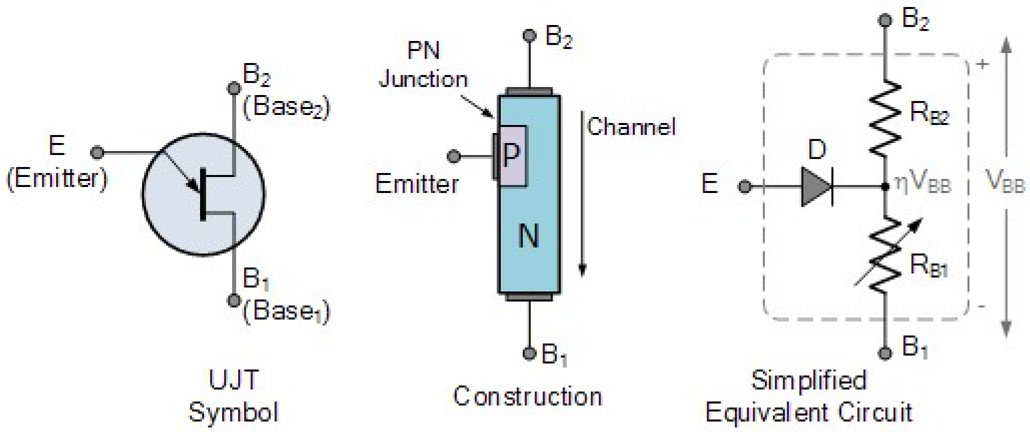
Improvement of Switching Time:
The Switching Time can be improved by connecting a capacitor in parallel with the base resistor R_B.



Fig(12) transistor Improvement switiching time

UNIJUNCTION TRANSISTOR (UJT)

It consists of a lightly doped N-type silicon bar with a heavily doped P-type material attached to its one side closer to B_2, so that a single p-n junction is produced. As shown in fig (13) there are three terminals an emitter (E & two bases B_1 & B_2 at the bottom & the top respectively of the silicon bar.



Fig(13) Unijunction Transistor(a) Symbol (b) Construction (c) Equivalent circuit

Standoff ratio(η)=R_{B1}/R_{BB}
Peak-point voltage (V_P)= ηV_{BB} + V_D
Peak-point current (I_P)
Valley voltage (V_v)
Valley current (I_v)
UJT OFF: When $I_E < I_P$
UJT ON : When $I_E > I_P$

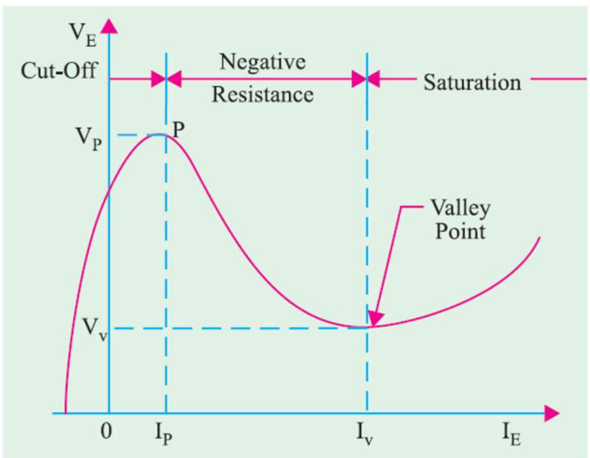


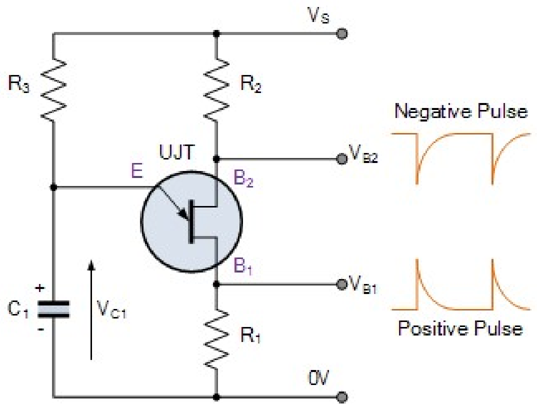
Fig (14) UJT Characteristics

When $V_E < \eta V_{BB}$ ∴ PN is reverse biased I_E is negative.
When $V_E > \eta V_{BB}$ ∴ PN is forward & biased I_E is positive.

UJT applications

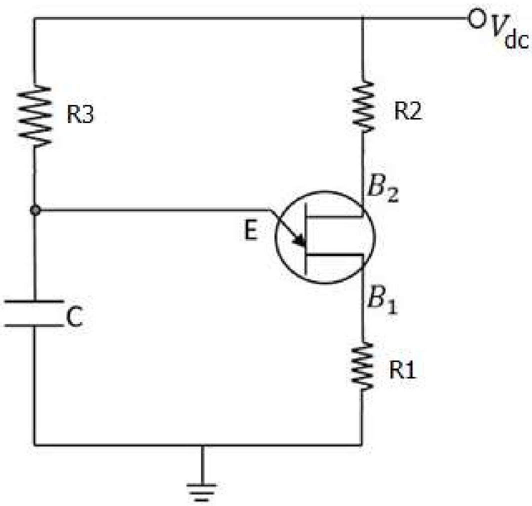
UJT is used in the following applications:

1- Relaxation oscillator.
2- Triggering circuit.
3- Pulse generator.



<u>Relaxation Oscillator:</u>

The following figure shows how to use a UJT as a relaxation oscillator. Initially, the voltage across the capacitor is zero. The UJT is in OFF condition. The capacitor chargers through the resistor R according to the voltage $V_P = V_C = \eta V_{BB} + V_D$. Then the UJT becomes in ON condition. The capacitor dischargers to the V_V voltage through the resistor R_1.



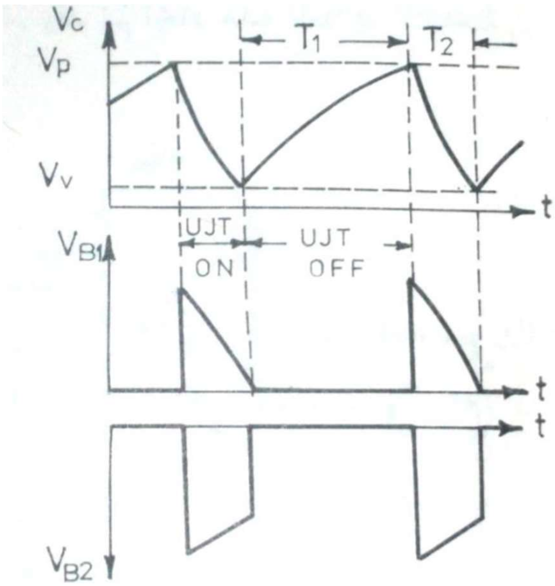


Fig (15) Relaxation oscillator circuit (saw-tooth generator)

$V_C = V_{dc}(1-e^{\wedge}(-t/R_3C))$

V_V = valley point voltage, I_V = valley point current, V_P = Peak voltage, I_V = Peak current,

$V_C / V_{dc} = 1-e^{\wedge}(-t/R_3C)$

$e^{\wedge}(-t/R_3C) = 1- V_C / V_{dc}$

$e^{\wedge}(-T/R_3C) = 1- V_P / V_{dc} = 1- \eta$

$$e^{\wedge}(\frac{T}{R_3C}) = ln\frac{1}{1-\eta}$$

$$\frac{T}{R_3C} = ln\frac{1}{1-\eta}$$

$$T = R_3 C \ ln \frac{1}{1-\eta}$$

$$\tau = R_3 C \qquad F = \frac{1}{T}$$

The frequency of oscillation is normally controlled by the time constant R_3C.

$R_{3min} = \frac{Vdc - Vv}{Iv}$

$R_{3max} = \frac{Vdc - Vp}{Ip}$

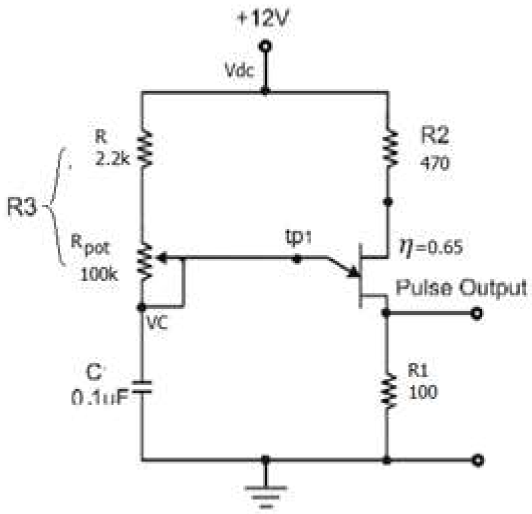
$R_3 = 10^4 / \eta V_{BB}$

UJT Relaxation Oscillator can be used as a pulse generator when the voltage across the discharge resistor is used. By connecting a potentiometer at the place of the charging resistor R_3, sawtooth waveforms with different frequency ranges can be obtained across the capacitor. Pulses with different frequency range can be obtained across the discharge resistor R_1.

UJT is OFF (UJT Relaxes): [$V_{out} \approx 0$ {i.e. $V_{out} = V_{dc} * R_1/(R_1+R_2+R_{BB})$ }]. Capacitor is charged through R_3 to the voltage [$V_C \approx V_P$ {i.e. $V_C = V_P + V_{out}$ }]. Then UJT turns ON.
UJT is ON: [$V_{out} = V_C - V_D - V_{RB1}$] & Capacitor is discharged through R_1 to the voltage $V_E = V_D + V_v$.

Example 1

Using the UJT to construct an oscillator as shown below, calculate?
1- Minimum & Maximum frequency of pulses which can be generated.
2- Maximum capacitor voltage.



$$T = R_3 * C * \ln \frac{1}{1-\eta}$$

$$T = (R_{pot} + R_1) * C * \ln \frac{1}{1-\eta}$$

When $R_{pot} = 100k\Omega$

$$T_{max} = (100 \times 10^3 + 2.2 \times 10^3) \times 0.1 \times 10^{-6} \times \ln \frac{1}{1-0.65}$$

$$T_{max} = 10.8 \times 10^{-3} sec$$

$$F_{min} = \frac{1}{T_{max}} = \frac{1}{10.8\times10^{-3}} = 93.2Hz$$

When $R_{pot} = 0$

$$T_{min} = (0 + 2.2 \times 10^3) * 0.1 * 10^{-6} * \ln\frac{1}{1 - 0.65}$$

$$T_{min} = 0.23 \times 10^{-3}\text{sec}$$

$$F_{max} = \frac{1}{T_{min}} = \frac{1}{0.23\times10^{-3}} = 4.33\text{kHz}$$

Maximum capacitor voltage

$$V_C = V_P = \eta V_{BB} + V_D = 0.65 \times 12 + 0.6 = 8.4\text{v}$$

Example 2

The data sheet for a 2N2646 Unijunction transistor gives the intrinsic stand-off ratio as 0.65. If a 100nF capacitor is used to generate the timing pulses, calculate the timing resistor required to produce an oscillation frequency of 100Hz.

1- the timing period is given as:

$$T = \frac{1}{F} = \frac{1}{100} = 10\text{mS}$$

2- the value of the timing resistor R_3 is calculated as:

$$T = R_3 C \ln\frac{1}{1 - \eta}$$

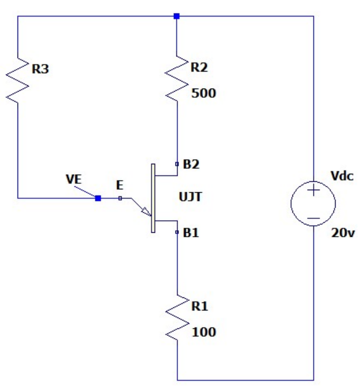
$$R_3 = \frac{T}{C\ln\frac{1}{1-\eta}} = \frac{10\text{mS}}{100nF * \ln\frac{1}{1-0.65}} = \frac{1}{0.0000001F * \ln 2.857} = \frac{10000000}{\ln 2.857} = 95238\ \Omega =$$

95.3 kΩ

Homework 05 UJT

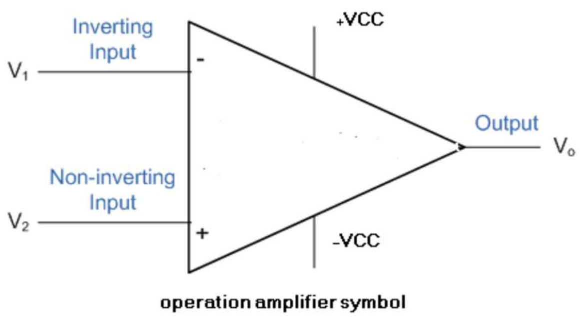
The specifications of UJT in the circuit shown below, are: R_{B1}=3900Ω, R_{B2}=3500Ω, I_V = 2mA & I_P = 1μA & R_{B1}=100Ω if the UJT is ON, calculate?

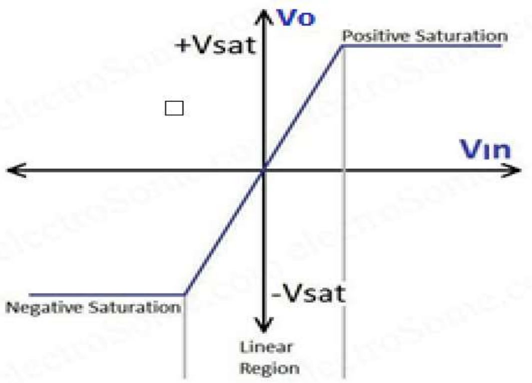
2- Standoff ratio(η)
3- Current in E, B_1, B_2 & V_P in OFF state.
4- Current in E, B_1, B_2 & V_V in ON state.



Operational Amplifier

Op-amps are one of the basic building blocks of Analogue Electronic Circuits. It is a linear device that has all the properties required for nearly ideal DC amplification and is used to perform mathematical operations such as add, subtract, integration and differentiation. The output signal is a differential signal between the two inputs and the input stage of an operational Amplifier is in fact a differential amplifier as shown fig (16).





(a) (b)

Fig (16) (a) op amp symbol (b) op amp Characteristics

Ideal op amp

Ideal op amp has following specifications: -

1- Input resistance very high.

2- Output resistance very small.

3- Voltage gain in open loop very high.

4- $V_o = 0$ when $v_1=v_2$

5- An ideal operational amplifier has an infinite Frequency Response.

6-Most (but not all) operational amplifiers require a symmetrical supply (of typically
±6V to ±15 V) which allows the output voltage to swing both positive (above 0 V) and negative (below 0 V).

The voltage gain (AV): -

$V_{in} = V_2 - V_1$

$$A_V = \frac{V_O}{V_{in}} = \frac{V_O}{V_2 - V_1} = \infty$$

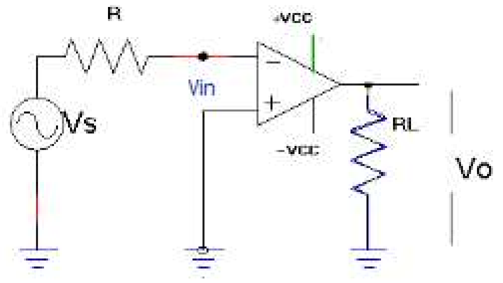
$V_O = 0$ when $V_{in} = 0$

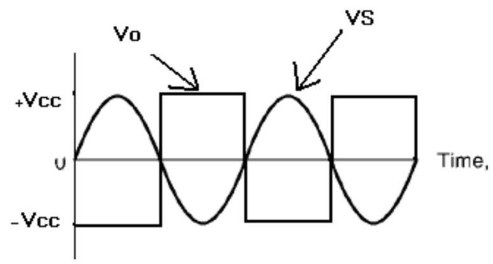
$V_O = -V_{CC}$ when $V_{in} < 0$

$V_O = +V_{CC}$ when $V_{in} > 0$

Application of op amp

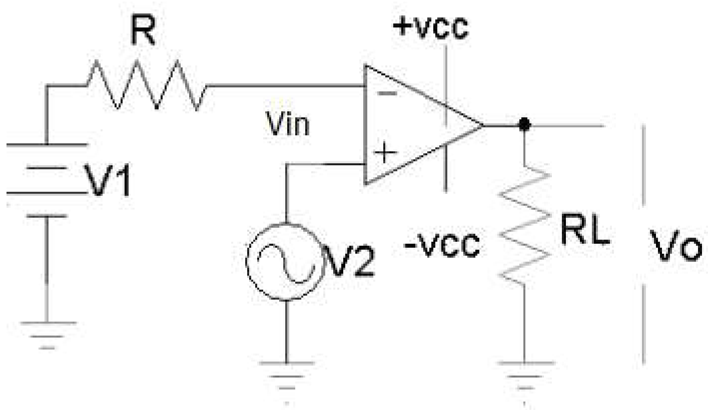
1- **Zero crossing detector**: -
The output will go high when the input sine wave is positive while the output will go low when the input sine wave is ne
$V_{in} = 0 - V_s = - V_s$

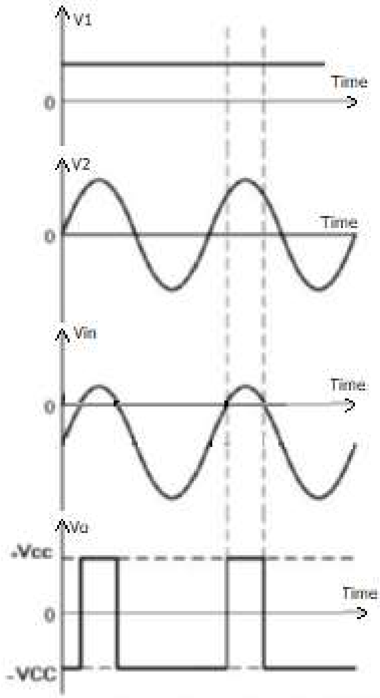




(a) (b)
Fig (17) Zero crossing detector (a) Circuit diagram (b) Input and Output waveform

2- **Comparator**: -
The comparator is used to compare a signal voltage with a reference voltage**.**



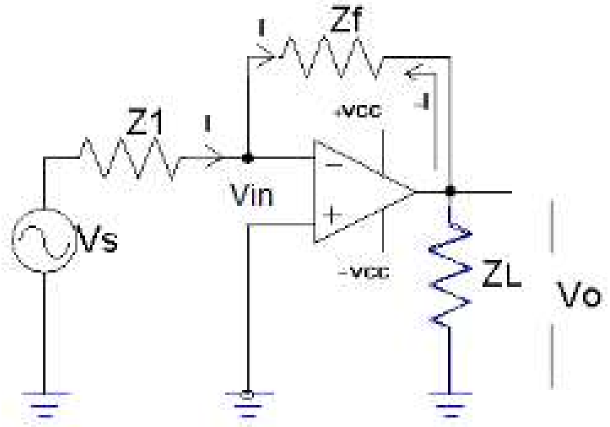


(a) (b)
Fig (18) Comparator (a) Circuit diagram (b) Input and Output waveform

3- **Inverting amplifier**: -

The closed-loop voltage gain of an operational amplifier is defined as the ratio of output voltage to input voltage

Fig(19) Inverting amplifier



$$V_1 = V_2 = 0$$

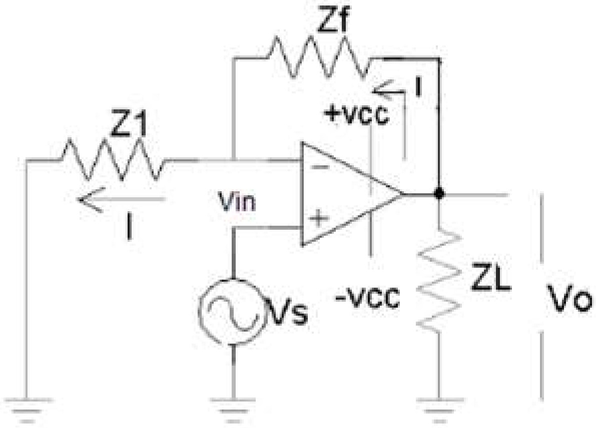
$$V_O = -IZ_f$$

$$V_S = I\,Z_1$$

$$A_V = \frac{V_O}{V_S} = \frac{-IZ_f}{I\,Z_1} = -\frac{Z_f}{Z_1}$$

4- **Noninverting amplifier**: -

Fig (20) Noninverting amplifier



$$V_O = IZ_f + IZ_1$$

$$V_S = V_2 = V_1 = I\,Z_1$$

$$A_V = \frac{V_O}{V_S} = \frac{IZ_f + IZ_1}{I\,Z_1} = 1 + \frac{Z_f}{Z_1}$$

5- <u>Multivibrators</u>

A multi-vibrator circuit oscillates between a “HIGH” state and a “LOW” state producing a continuous output.

1- **Bistable** – a bistable multi-vibrator has **TWO** stable states producing a single pulse either HIGH or LOW in value.

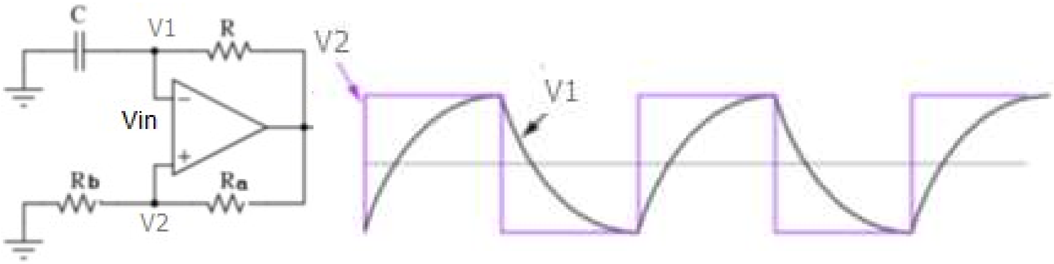
2- **Astable** – A free-running multi-vibrator that has **NO** stable states but switches continuously between two states this action produces a train of square wave pulses at a fixed known frequency.

3- **Monostable** – A one-shot multi-vibrator that has only **ONE** stable state as once externally triggered it returns back to its first stable state. The timing period of a monostable is:

5.2-Astable Multivibrator: -

When the output is saturated positive, the (V_2) will be positive, and the capacitor will charge up in a positive direction. When (V_1) exceeds V_2, the output will saturate negative, and the capacitor will charge in the opposite direction, Oscillation occurs.

The frequency of this oscillator may be adjusted by varying R and C.



(a) (b)

Fig (21) Astable Multivibrator (a) Circuit diagram (b) voltage waveforms

$$V_O = A_V(V_2 - V_1)$$

$$V_2 = \frac{R_b}{(R_a + R_b)} V_O$$

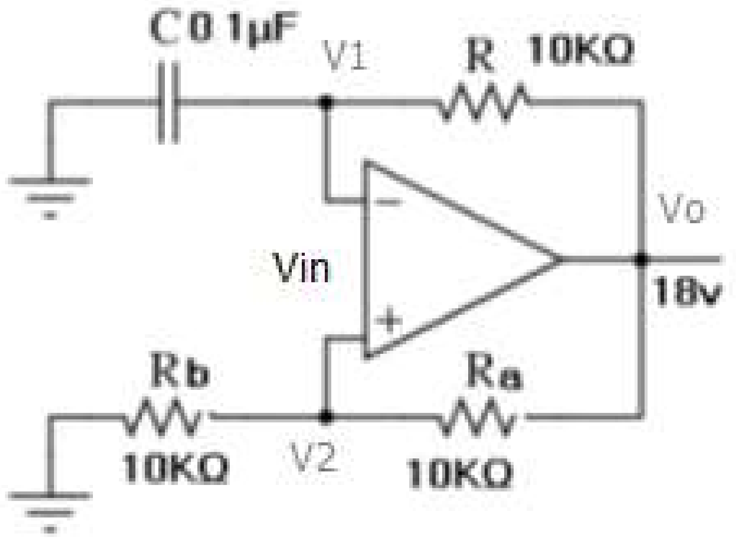
$$K = \frac{R_b}{(R_a + R_b)}$$

$$T = 2\,RC\,ln\frac{1+K}{1-K}$$

$$F = \frac{1}{T}$$

Example

The circuit shown in fig if $R_a = R_b$ = 10KΩ, R =10KΩ and C = 0.1μF. When maximum output voltage V_O = ±18 V calculate (V_2) and operation frequency(F).



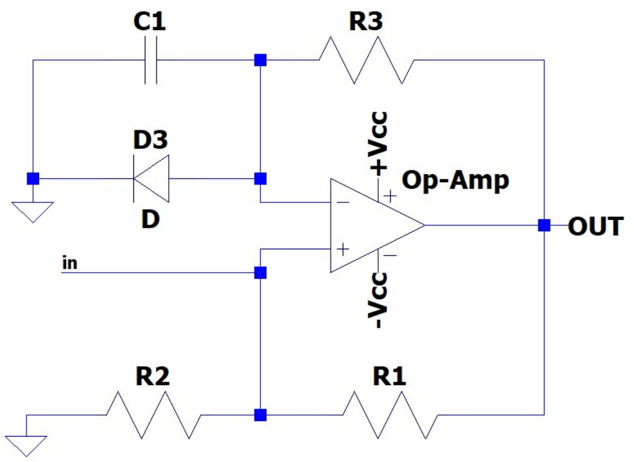
$$V_2 = \frac{R_b}{(R_a + R_b)} V_O = \frac{10}{(10+10)} \times 18 = 9V$$

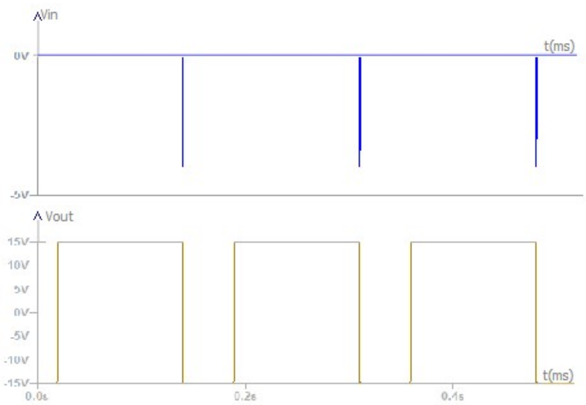
$$K = \frac{R_b}{(R_a + R_b)} = \frac{10}{(10+10)} = 0.5$$

$$T = 2\,RC\,ln\frac{1+K}{1-K} = 2 \times 10 \times 10^3 \times 0.1 \times 10^{-6} \times\ ln\frac{1+0.5}{1-0.5} = 2.19msec$$

$$F = \frac{1}{T} = \frac{1}{2.19 \times 10 \times 10^{-3}} = 455H_Z$$

5.3-**Monostable** – A one-shot multi-vibrator that has only **ONE** stable state as once externally triggered it returns back to its first stable state. The timing period of a monostable is:





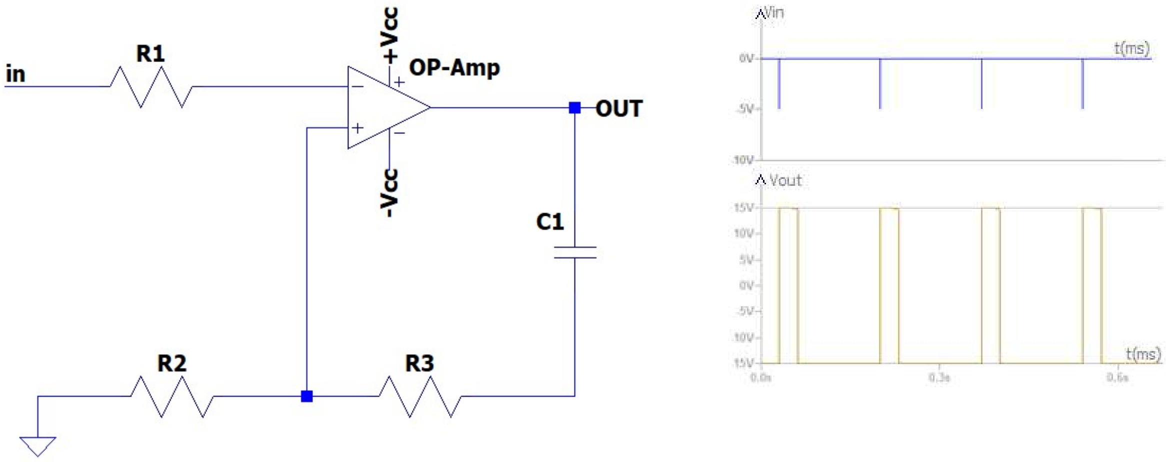


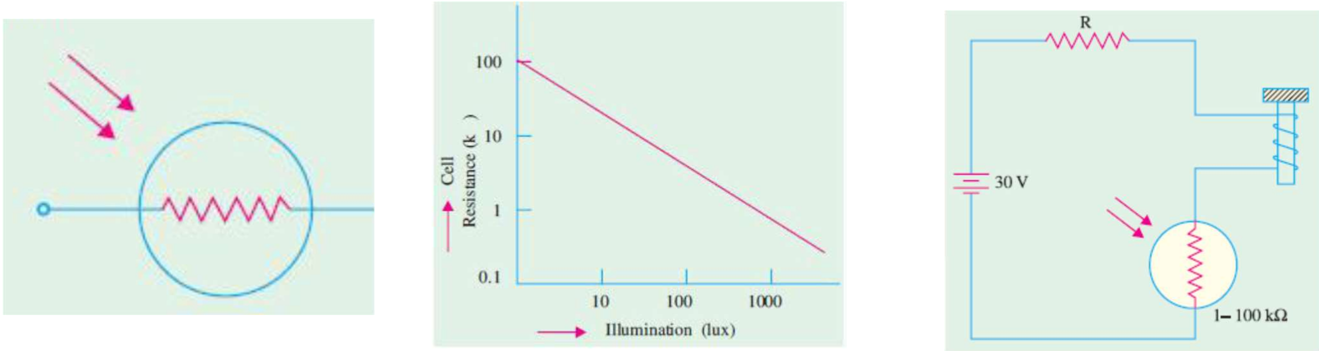
Fig (21B) Monostable multi-vibrator (a) Non-inverting input (b) Inverting input

(c) Input & output waveforms

Opto-electronic devices

1- Photoconductive cells: -

The photoconductive cell is a semiconductor device in which its resistance varies inversely with the intensity of light that falls on it.

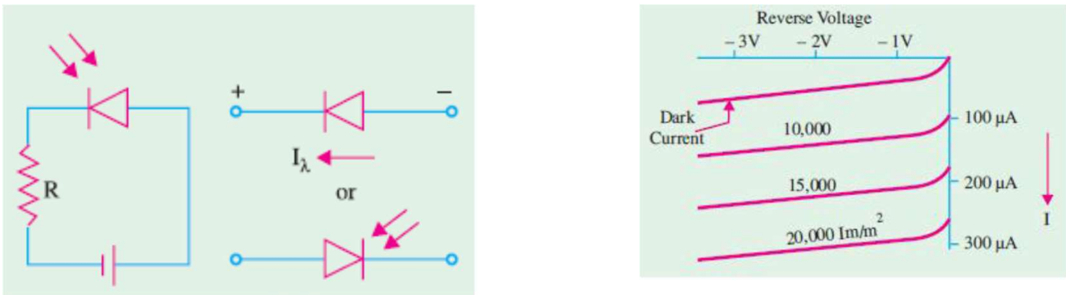


(a) (b) (c)

Fig (22) photoconductive cell (a) symbol (b) Characteristics (c)Practical circuit

2- Photo diodes: -

The Photo diodes are pn junction devices which operate in reverse bias. The reverse current increases with the intensity that falls on pn junction.

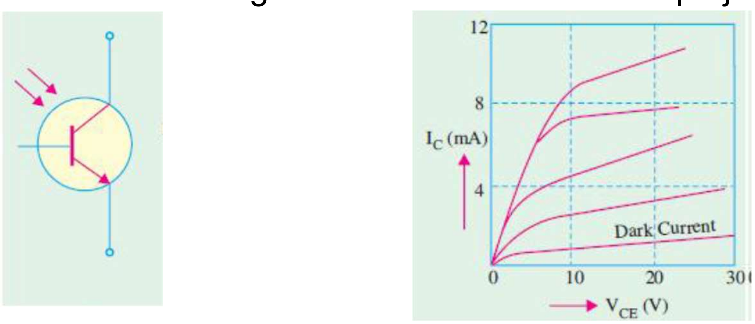


(a) (b)

Fig (23) Photo diodes (a) symbol (b) Characteristics

3- Photo transistor: -

The Photo transistor has a light sensitive collector base pn junction.

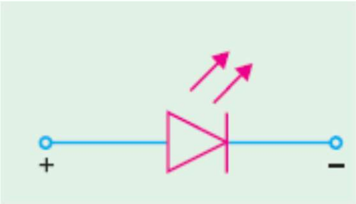


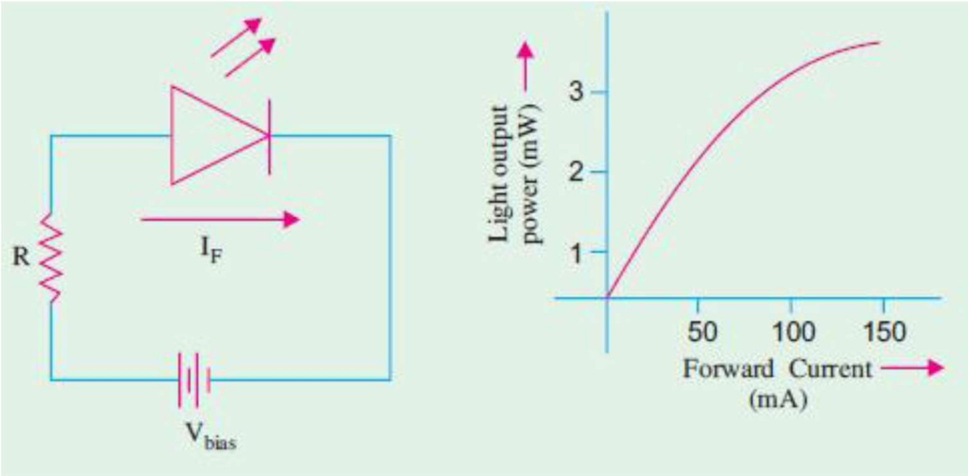
(a) (b)

Fig (24) Photo transistor (a) symbol (b) Characteristics

4- light emitting diode (LED): -

The light emitting diode (LED) is a semiconductor diode that emits light, in a response to a sufficient forward current.





(a) (b)

Fig (25) light emitting diode (LED) (a) symbol (b) Characteristics

5- Optical couplers

Optical couplers are designed to electrically isolate one circuit from another. The purpose of isolation is to provide protection from high voltage transient, surge voltages and low-level noise that could result damage to the device.

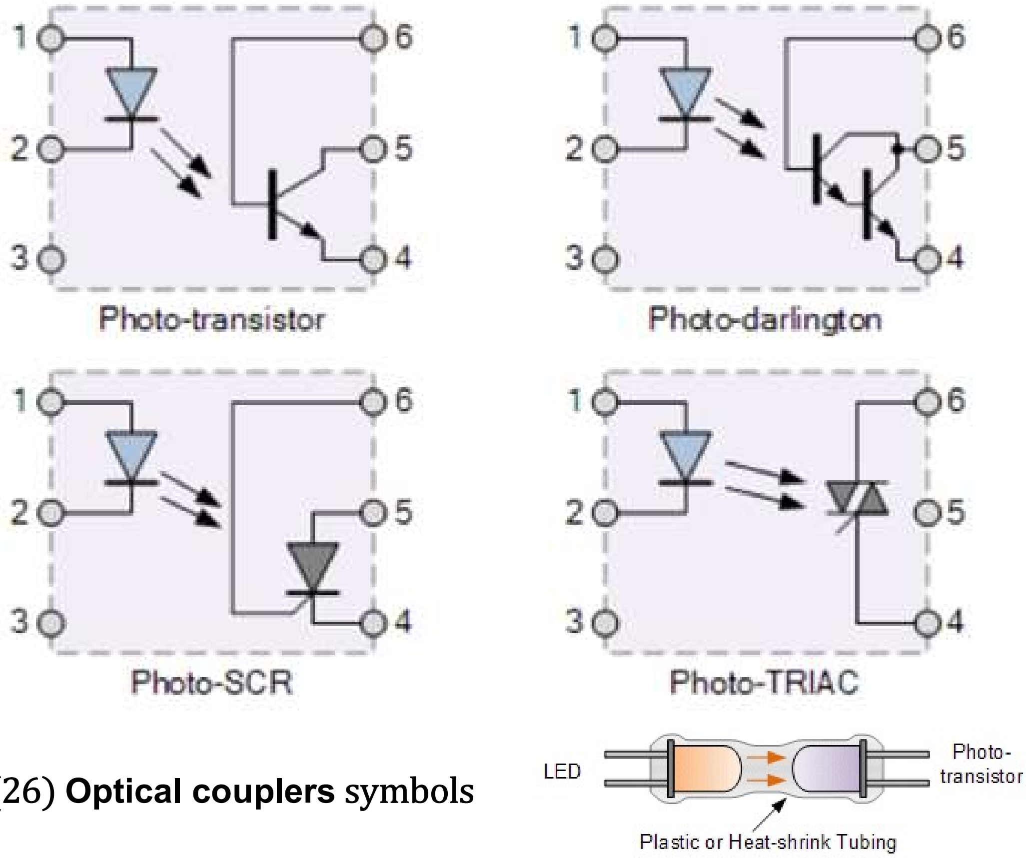
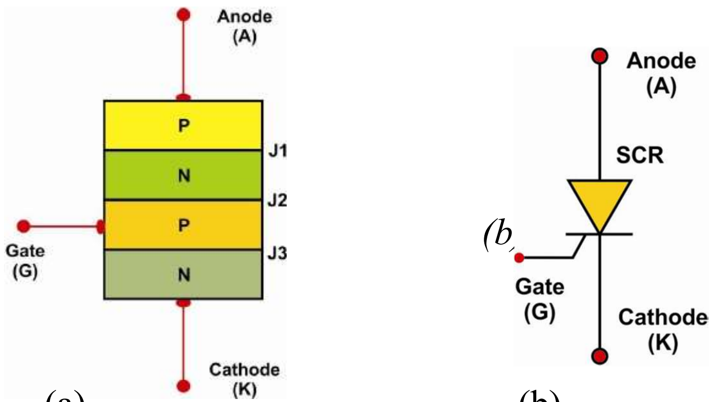


Fig (26) **Optical couplers** symbols

Thyristor (SCR)

A Silicon Controlled Rectifier (SCR) is a 4-layered PNPN switching device, having three junctions J1, J2 and J3. It has three external terminals, namely, the Anode (A), Cathode (K), & Gate (G). The anode & cathode are connected to the main power circuit. The Gate terminal carries a low level Gate current in the direction from Gate to cathode. The internal structure and the symbol of the SCR is shown in fig(27).

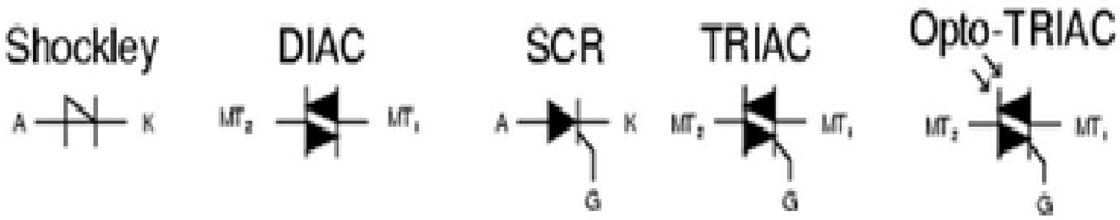


(a) (b)

Fig(27) Thyrsistor (a) Structure (b) Symbol

Thyristor family

SHOCKLY DIODE	(Unidirectional)
SCR	(Unidirectional)
TRIAC	(Bidirectional)
DIAC	(Bidirectional)



V-I Characterstics of SCR:

The static V-I characterstic of an SCR is shown here V_{AK} is the anode-cathode voltage and I_A is the anode current. The SCR V-I characterstics is divided into three regions of operation. These three rigions of operation are:

1. Reverse Blocking Region ($V_{AK} < 0$, $I_A \approx 0$): When the anode is made negative with respest to the cathode, the thyristor becomes reverse biased, and acts as open switch. In OP is the reverse blocking rigion. In this rigion, the thyristor exhibits a blocking characterstics similar to that of a diode. In this reverse biased condition, the outer junction J1 and J3 are reverse biased and the middle junction J2 is forward biased. Therefore only a small leakage current (in mA) flows. If the reverse voltage is increased when at a critical breakdown level called reverse breakdown voltage VBR an avalanche will occure at J1 and J3 increasing the current sharply. If this current is not limited to a safe value, power dissipation will increase to a dangerous level that may destroy the device.

Region PQ is the reverse avalanche region. If the reverse voltage applied across the devise is below this critical value, the device will behave as a high impedance device in the reverse direction. The inner two region of the SCR are lightly doped compared to the outer layers. Hence, the thickness of the J2 depletion layer during the forward biased conditions will be greater than the total thickness of the two depletion layers at J1 and J3 when the device is reverse biased. Therefore, the forward breakover voltage VBO is generally higher than the reverse break over voltage VBR.

2. Forward Blocking Region ($V_{AK} > 0$, $I_A \approx 0$): In this region, the anode is made positive with respect to the cathode and therefore, junction J1 and J3 are forward biased while the junction J2 remains reverse biased. Hence, the anode current is small forward leakage current. The region OM of the V-I characteristic is known as the forward blocking region when the device does not conduct.

3. Forward Conduction Region ($V_{AK} > 0$, $I_A > I_L$): When the anode to cathode forward voltage is increased with the Gate circuit kept open, avalanche breakdown occurs at the junction J2 at a critical forward breakover voltage (VBO), and the SCR switches into a low impedance condition (high conduction mode). The forward breakover voltage is corresponding to the point M. When the device latches on to the conducting state. The region MN of the characteristic shows that as soon as the device latches on to its on state, the voltage across the device drops from say, several hundred volts to 1-2 volt, depanding on the rating of the SCR, and suddenly a very large amount of current starts flowing through the device. The part NK of the characteristic is called as the forward conduction state. In this high conduction mode, the anode current is determined essentially by the external load impedance. Therefore when the thyristor conducts forward current, it can be regarded as a closed switch.

When a Gate current is applied, the thyristor turns on before VBO is reached. The forward voltage at which the device switches to on state depends upon the magnitude of the Gate current, when the Gate current IG =0, the forward breakover voltage is VBO. For IG1, the forward breakover voltage is less than VBO and for IG2>IG1, it is still further reduced. In practice، the magnitude of the Gate current is more than the minium Gate current required to turn on the SCR. The typical Gate current magnitudes are of the order of 20mA to 200mA. The SCR is conducting a forward current that is greater than the minimum value، called the latching current(IL), the Gate signal is no longer required to maintain the device in its on state. Removel of the Gate current does not affect the conduction of the anode current. The SCR will return to its orignal forward blocking state if the anode current falls below a low level called the holding current (IH).

Holding current (I_H):-is the maximum value of anode current which lets the thyrister to switch from the forward conduction region to the forward blocking region.
Latching current (I_L):- is the minimum value of anode current at which the thyrister switches to the forward conduction region when sufficient gate current applied to the gate.

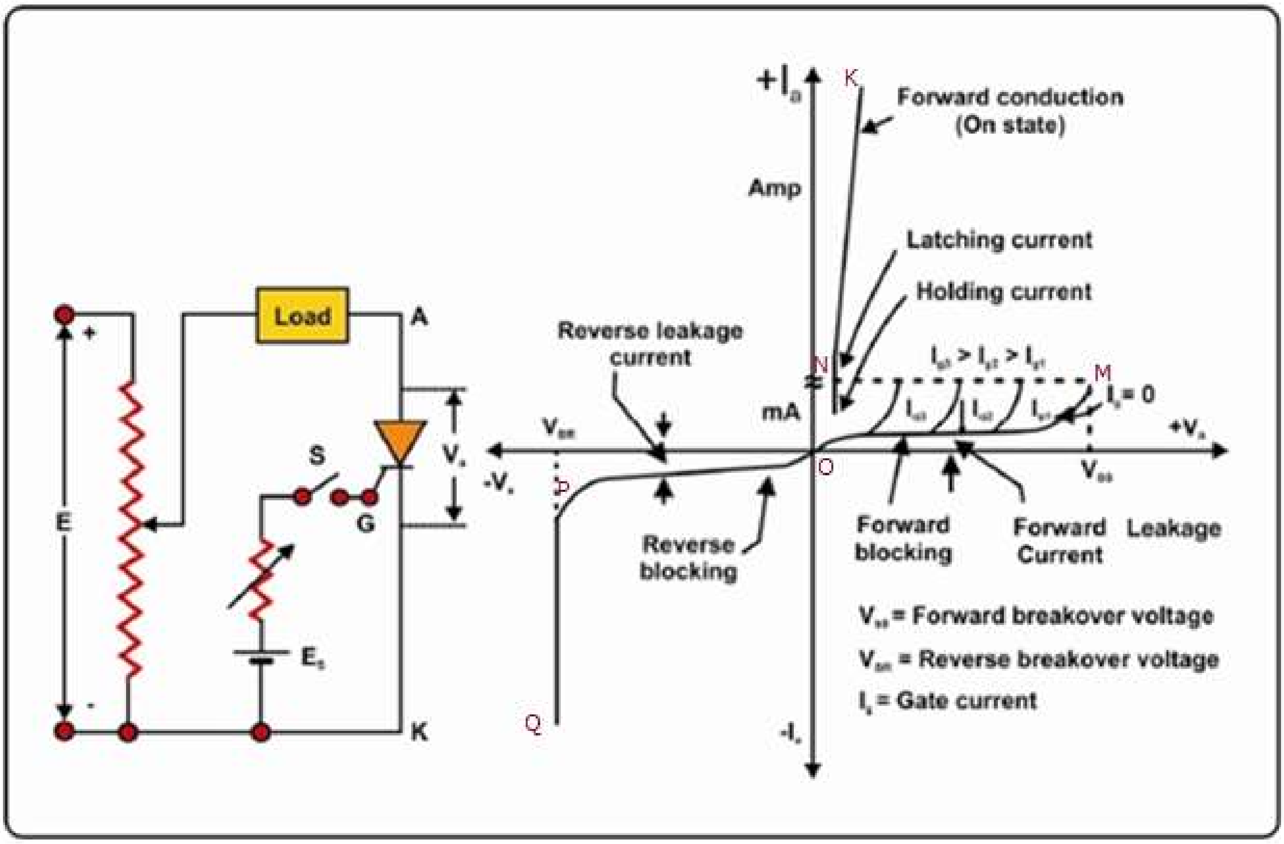
$I_L > I_H$

Forward Blocking Region ($V_{AK} > 0$, $I_A < I_L$, $I_A \approx 0$): In this region, the anode is made positive with respect to the cathode and therefore, the anode current is small forward leakage current. The thyrsistor does not conduct.

Forward Conduction Region ($V_{AK} > 0$, $I_A > I_L$): In this region, the anode is made positive with respect to the cathode. With applying voltage geater than the forward breackover voltage ($V_{AK} > V_{BO}$) The thyrsistor conducts. or with applying sufficient gate current ($I_G > 0$) with anode cathode voltage less than forward breackover voltage ($V_{AK} < V_{BO}$) The thyrsistor conducts.

Reverse Blocking Region ($V_{AK} < 0$, $I_A \approx 0$): In this region, the anode is made negative with respect to the cathode and therefore, the anode current is small reverse leakage current. The thyrsistor does not conduct.

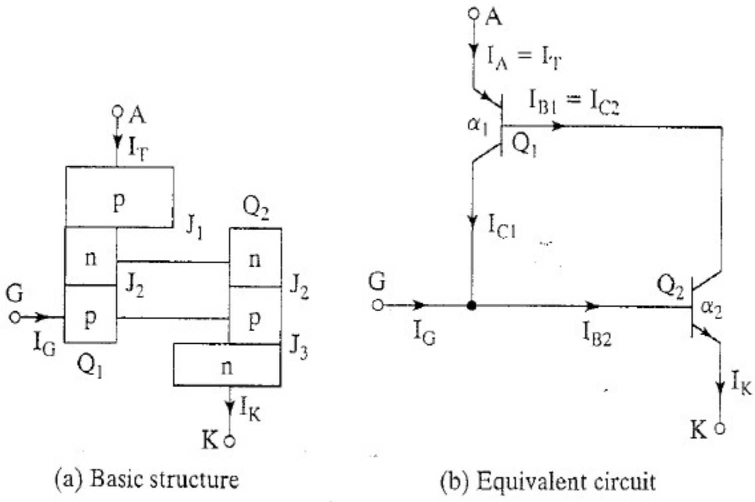
forward breackover voltage ($V_{AK} = V_{BO}$):
This is anode cathode voltage at which avalanche breakdown occurs and The thyrsistor conducts with the Gate circuit kept open.



Fig(28) Characterstics of SCR

Two transistor model for thysistor:

The positive pulse of current at the gate turns on Q2 providing a path for IB1 Q1 then turns on providing more base current for Q2 even after the trigger is removed.
Thus, the device stays on (latches).



Fig(29) Two transistor model for thysistor

Thyristor conduction methods

The thyristor can be turned on by any one of the following techniques :

(a) Forward voltage triggering **($V_{AK} = V_{BO}$)**
(b) gate triggering **($I_G > 0$)**
(c) high instantaneous voltage **(dv/dt >>0)**
(d) Temperature triggering **(Temp > >0)**
(e) Light triggering **(Light)**

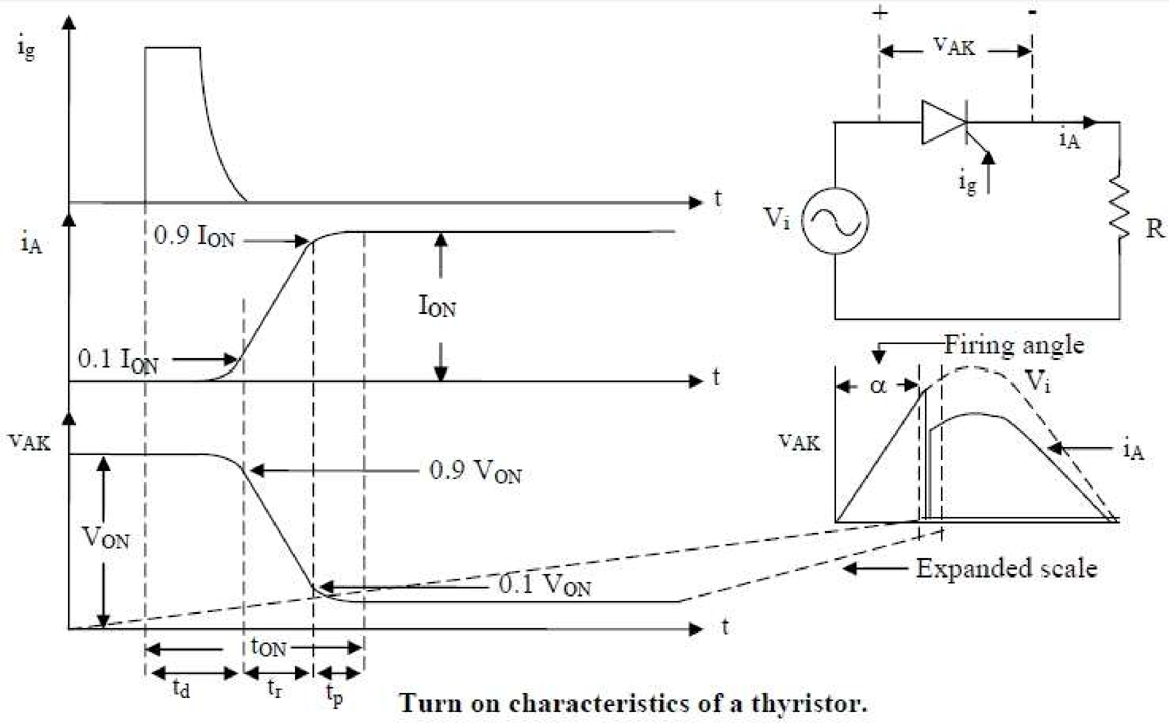
(a) Forward Voltage Triggering: When anode to cathode forward voltage is increased with gate circuit open, the reverse biased junction J2 will break. This is known as avalanche breakdown and the voltage at which avalanche occurs is called forward break over voltage V_{BO}. At this voltage, thyristor changes from off-state (high voltage with low leakage current) to on-state characteristic by low voltage across thyristor with large forward current.

(b) Gate Triggering : Turning on of thyristors by gate triggering is simple, reliable and efficient, it is therefore the most usual method of firing the forward biased SCRs. when turn-on of a thyristor is required, a positive gate voltage between gate and cathode is applied. With gate current thus established, charges are injected into the inner p layer and voltage at which forward break over occurs is reduced. The forward voltage at which the device switches to on-state depends upon the magnitude of gate current. Higher the gate current, lower is the forward break over voltage.

(c) high instantaneous voltage(dv/dt): This is undesrible method and it is caused by sudden instantaneous voltage across SCR with values exceeding break over voltage.
(d) Temperature triggering: With increasing the temperature leakage current through junction J2 further increases. This cumulative process may turn on the SCR at some high temperature.
(e) Light triggering: With increasing the light leakage current through junction J2 further increases. This cumulative process may turn on the SCR.

Thyristor turn on mechansim

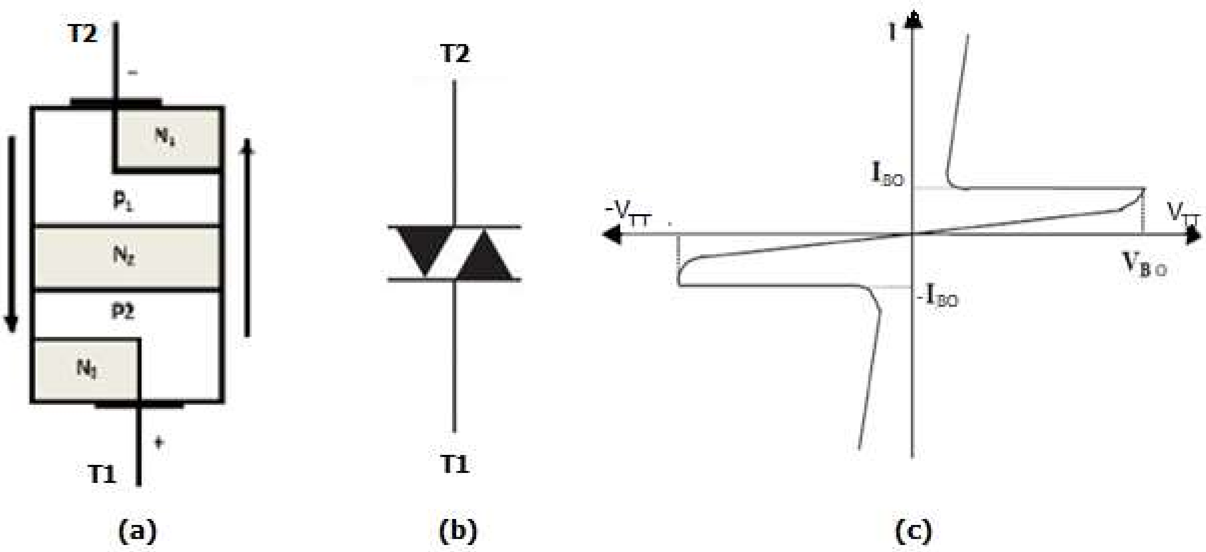
Delay time(t_d):it is the time in which the anode current reach 10% of its final value.
Rise time(t_r): it is the time in which the anode current to rise from10% to 90% of its final value.
Conduction time(t_{on}): $t_{on}= t_d+ t_r$



Fig(30) Turn on charcteristics of thyrsistor

Diac

Diac is pnpn 4-layer device Switching device bilateral diode conducts both ways. It remains off at low voltages as voltage increases to the breakover voltage it conducts with voltage drop results, and flow of current useful for triggering signals. typical breakover voltage is 20 to 40 volts, breakover current is 50 to 200µA and power dissipation ranging from 0.5 to 1 watt



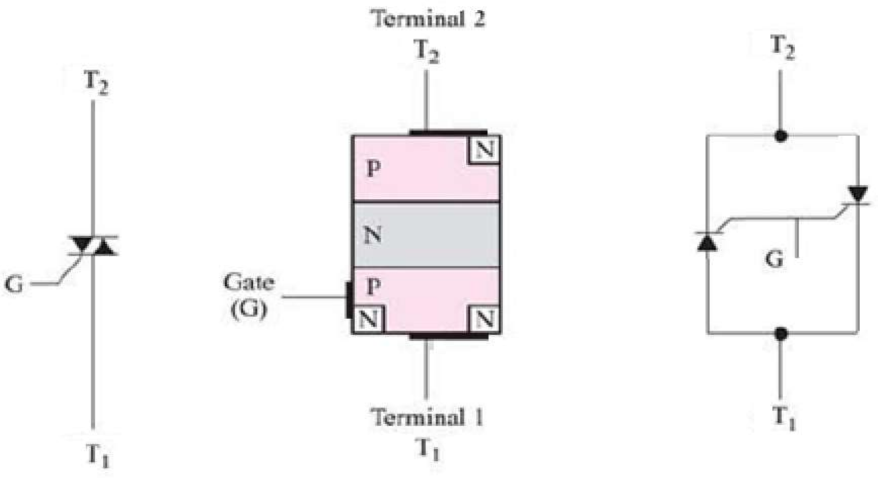
Fig(31) Diac (a) Structure (b) Symbol (c) charcteristics

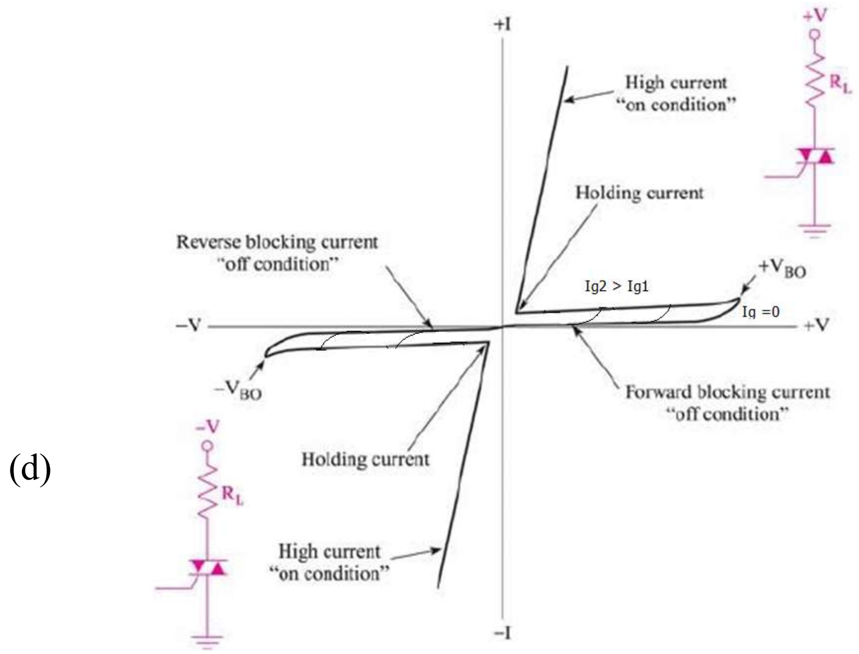
Diac appliactions

1) Counters, register and timing circuits computers,
2) Pulse generator,
3) Voltage sensors,
4) Oscillators

Triac

Triac operation similar to two SCRs back-to- back gate current trigger turns on Triac Terminals include, Gate, MT1 and MT2 Triac will remain off until the gate trigger, it on Triac conducts until current drops below holding current.





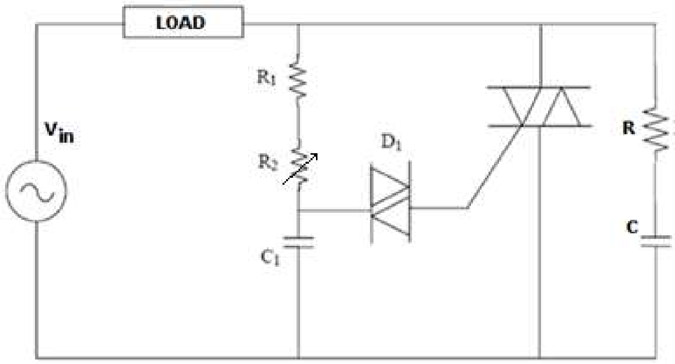
Fig(32) Triac (a) Symbol (b) Structure (c)equavilent circuit (d) charcteristics

Triac appliactions:

1) As a high power lamp switch.
2) Electronic changeover of transformer taps.
3) Light dimmer
4) Speed controls for electric fans and other electric motors
5) Modern computerized control circuits
6) For minimizing radio interference

Diac and traic application :

The diac is used in firing circuits for triac in ac power controllers as exmaple dimmer circuit.



Fig(33) Triac triggering circuit using diac

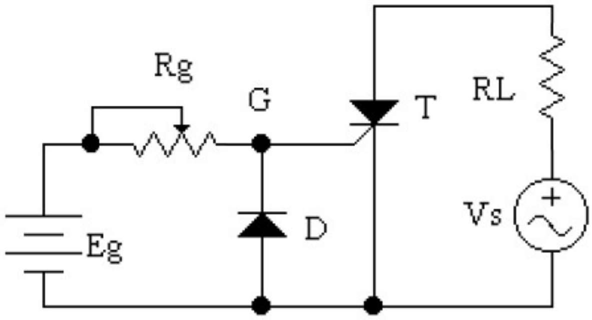
Thyristor triggering circuits

It is very important to study the triggering circuits of the thyristor and study both DC and AC triggering circuits.

1- DC triggering Circuits.
2- AC triggering circuits.
3- Pulse current triggering circuits.

1-DC triggering Circuits:

Resistor Rg limits the magnitude of the gate current and control the triggering angle between 0° and 90°. The diode is to prevent the reverse bias on the Gate.

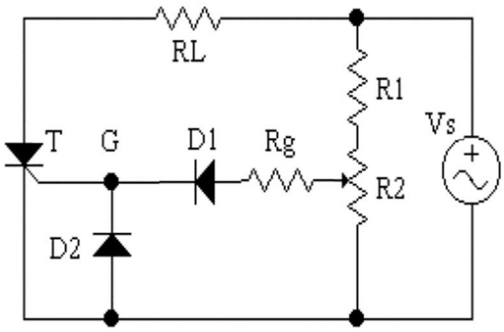


Fig(34) triggering circuit using resistor

2- AC triggering circuits: -

a- Using Resistor ($0 < \theta < 90°$):-

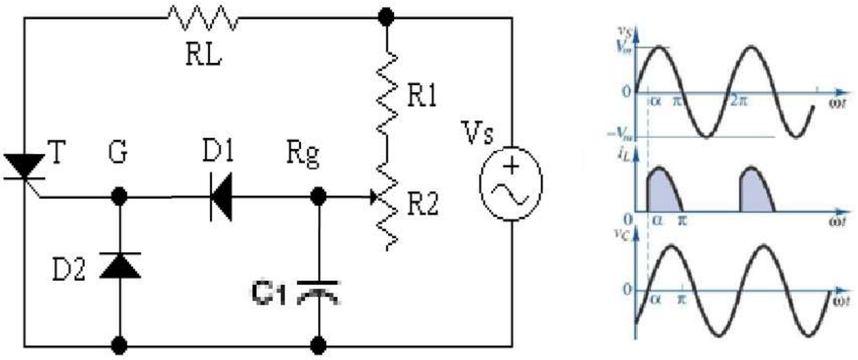
Resistor Rg limits the magnitude of the gate current and R_2 control the triggering angle between 0° and 90°. $\theta < 90°$.



Fig(35) triggering circuit using resistor

b-Using capacitor (0 < θ < 180°):-

In this circuit the capacitor current should be greater than the gate current. firing angle is greater than 90 degree. Part of the anode voltage is fed to the gate circuit. phase shift angle due to capacitor is given by $\theta=\tan^{-1}(X_C/R)$. θ > 90°.

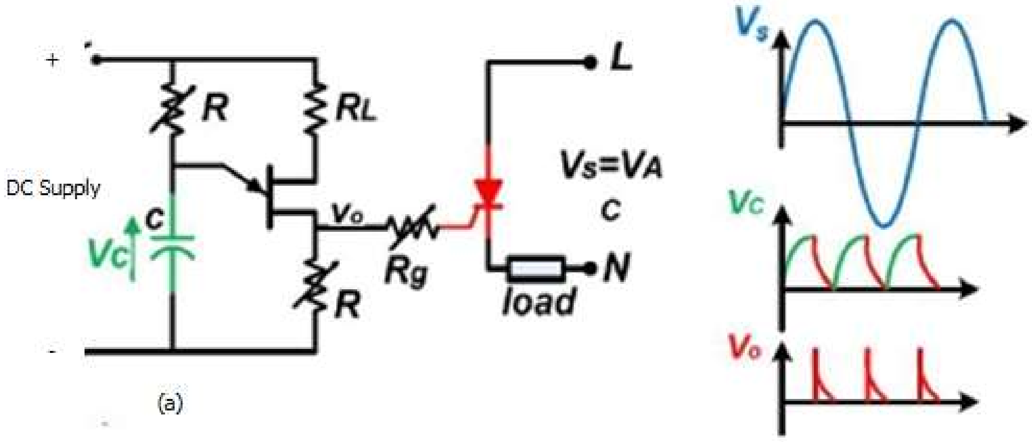


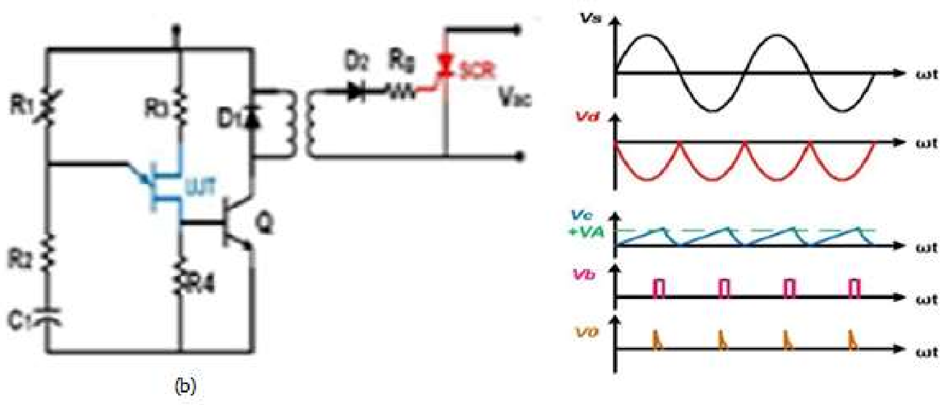
Fig(36) triggering circuit using capacitor

3- Pulse current triggering circuits: -

This the best method to trigger the thyristor by applying pulses to the gate terminal. these pulses may be narrow width or series of pulses with sufficient amplitude. There are many ways to generate the firing pulses.

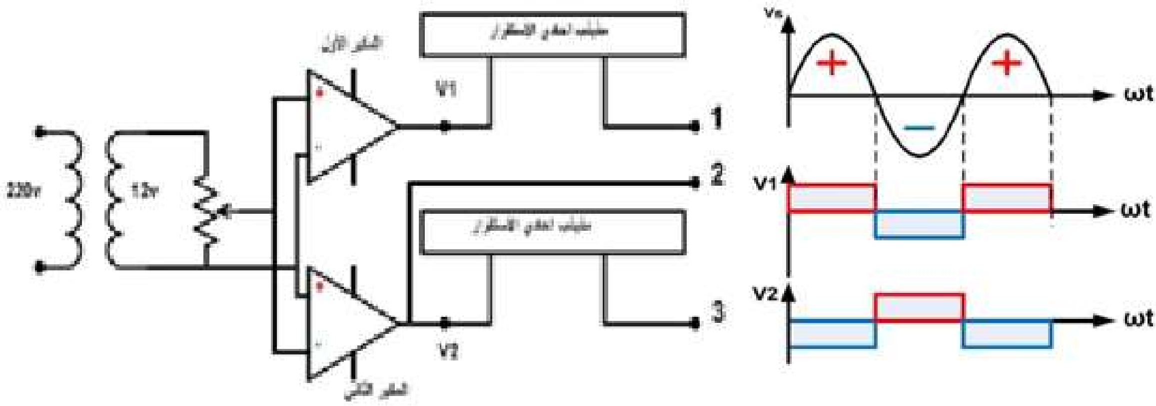
Relaxation oscillator: - In fig (37-b) the switching is used to amplify the gate current; the pulse transformer is used for isolation.





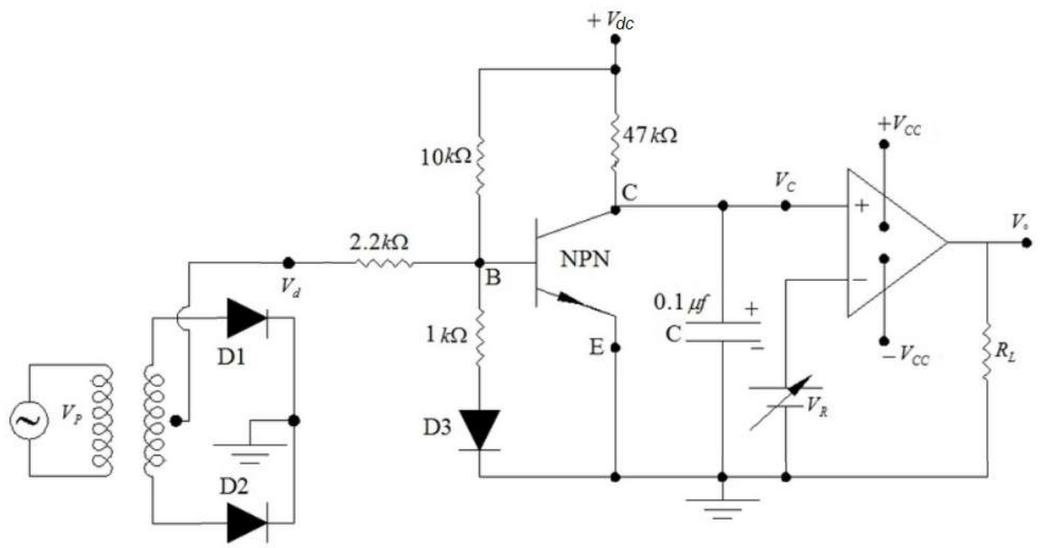
Fig(37) triggering circuit using relaxation oscillator (a) and(b)

b) Zero-crossing detector: -

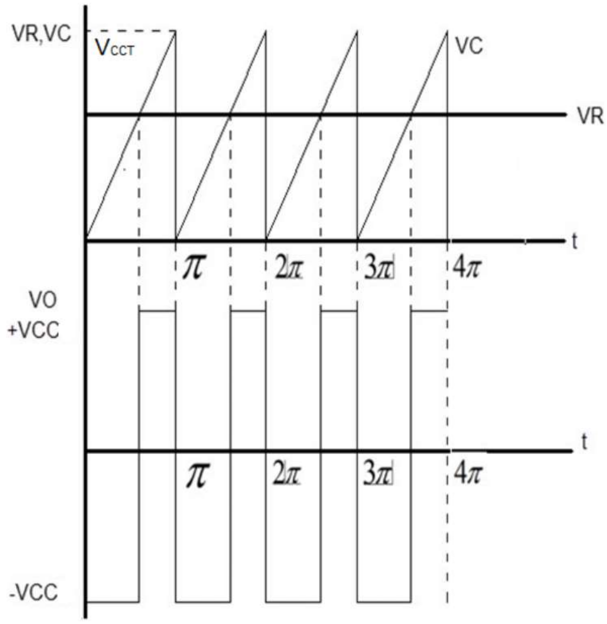


Fig(38) triggering circuit using zero-crossing detector

c) Comparator:-



(a)



(b)

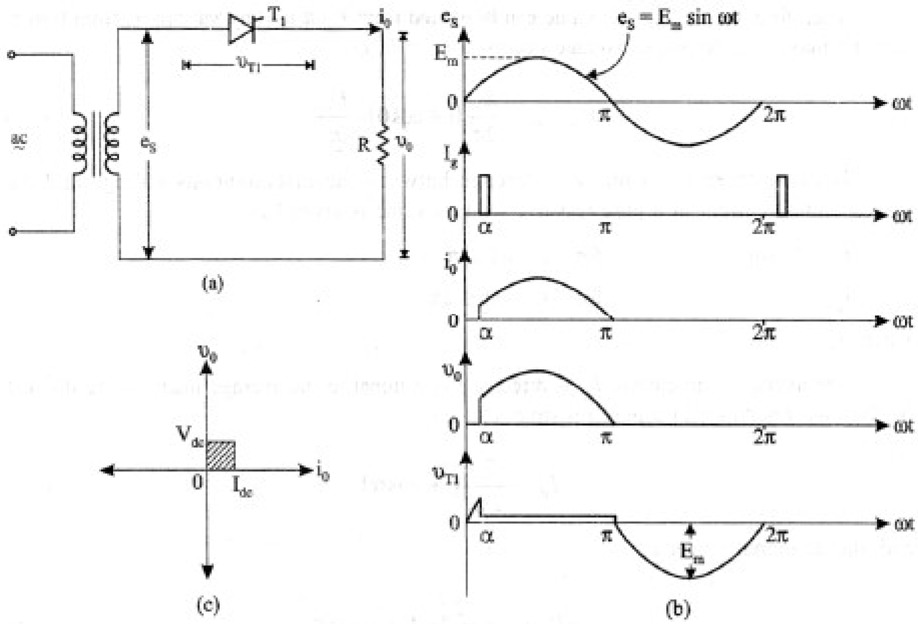
Fig(39) (a) Triggering circuit using comparator (b) Waveforms

Single Phase Controlled Rectifier

Rectification is a process of converting an alternating current or voltage into a direct current or voltage.

(1) Single Phase Half Wave Controlled Rectifiers with Resistive Load:

Single-phase half wave controlled rectifier means that the single SCR is used to convert the ac to dc. During the positive half cycle of the input voltage, thyristor T1 is forward biased and current flows through the load when the thyristor is fired, at ωt = α. The thyristor conducts only when the anode is positive with respect to cathode and a positive gate signal is applied, otherwise, it remains in the forward blocking state and blocks the flow of the load current. In the negative half cycle, i. e. , at ωt = π, the thyristor is in the reverse biased condition and no current flows through the load. Thus, varying the firing angle at which the thyristor starts conducting in positive half controls the average dc output voltage – cycle. The waveforms of the above circuit are shown in fig the output load voltage and current is positive, i. e. , they are one quadrant; it is called a half –wave semi converter.



Fig(40) Single Phase Half Wave Controlled Rectifiers with Resistive Load

The average dc output voltage across load is given by

$$Vdc = \frac{1}{2\pi}\int_{\propto}^{\pi} Vin\ dwt = \frac{1}{2\pi}\int_{\propto}^{\pi} Vm\sin(wt)\ dwt$$

$$= \frac{Vm}{2\pi}(1 + \cos(\propto))$$

Average current is given by

$$\mathbf{Idc = \frac{Vdc}{Rl}}$$

$$Vorms = \sqrt{\frac{1}{2\pi}\int_{\propto}^{\pi}(Vin)^2\, dwt} = \sqrt{\frac{1}{2\pi}\int_{\propto}^{\pi}(Vm\sin(wt))^2\, dwt}$$

$$= \frac{Vm}{2}\sqrt{\frac{\{\pi-\propto+\frac{1}{2}\sin(2\propto)\}}{\pi}}$$

$$\mathbf{Iorms = \frac{Vorms}{Rl}}$$

$$Porms = Vorms \times Iorms$$

$$Pin = \frac{Vm}{\sqrt{2}} \times Iorms$$

Power factor (p.f.) $= \frac{Porms}{Pin}$

Voltage across thyristor (V_{SCR})

$$Vdc = \frac{1}{2\pi}\int_0^{\propto} Vin\, dwt = \frac{1}{2\pi}\int_0^{\propto} Vm\sin(wt)\, dwt = \frac{Vm}{2\pi}(1-cos(\propto))$$

Example :- A heater of 10 Ω resistance (constant with temperature if it is used with a half wave rectifier, the input voltage source is (V = 240 v) calculate at (α = π/3).

1- Vdc of the heater.

2- The power of the load.

3- The power factor.

4- The voltage across the thyristor (SCR).

5- Draw the wave forms.

$$\mathbf{Vdc = \frac{Vm}{2\pi}(1+cos(\propto) = \frac{\sqrt{2}\times 240}{2\pi}(1+cos(60) = 81v}$$

$$Vorms = \frac{Vm}{2}\sqrt{\frac{\{\pi-\propto+\frac{1}{2}\sin(2\propto)\}}{\pi}} = \frac{\sqrt{2}\times 240}{2}\sqrt{\frac{\{\pi-\frac{\pi}{3}+\frac{1}{2}\sin(2\times 60)\}}{\pi}} = 152v$$

$$\mathbf{Iorms = \frac{Vorms}{Rl} = \frac{152}{10} = 15.2A}$$

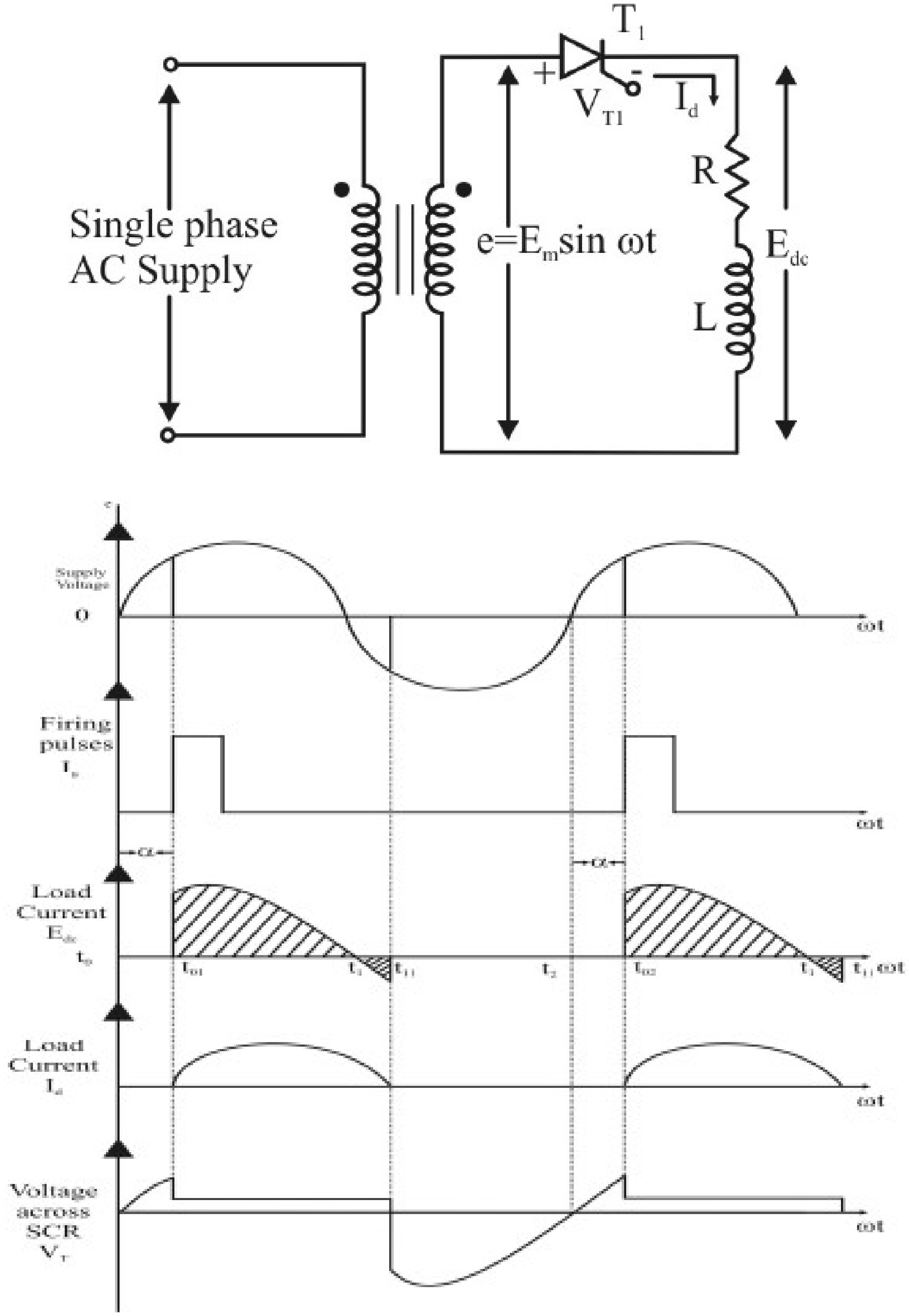
$$Porms = Vorms \times Iorms = 152 \times 15.2 = 2310KW$$

$$Pin = \frac{Vm}{\sqrt{2}} \times Iorms = 240 \times 15.2 = 3648KW$$

Power factor (p.f.) $= \frac{Porms}{Pin} = \frac{2310}{3648} = 0.633$

$$Vdc = \frac{Vm}{2\pi}\left(1-cos(\propto)\right) = \frac{\sqrt{2}\times 240}{2\pi}\left(1-cos(60)\right) = 27v$$

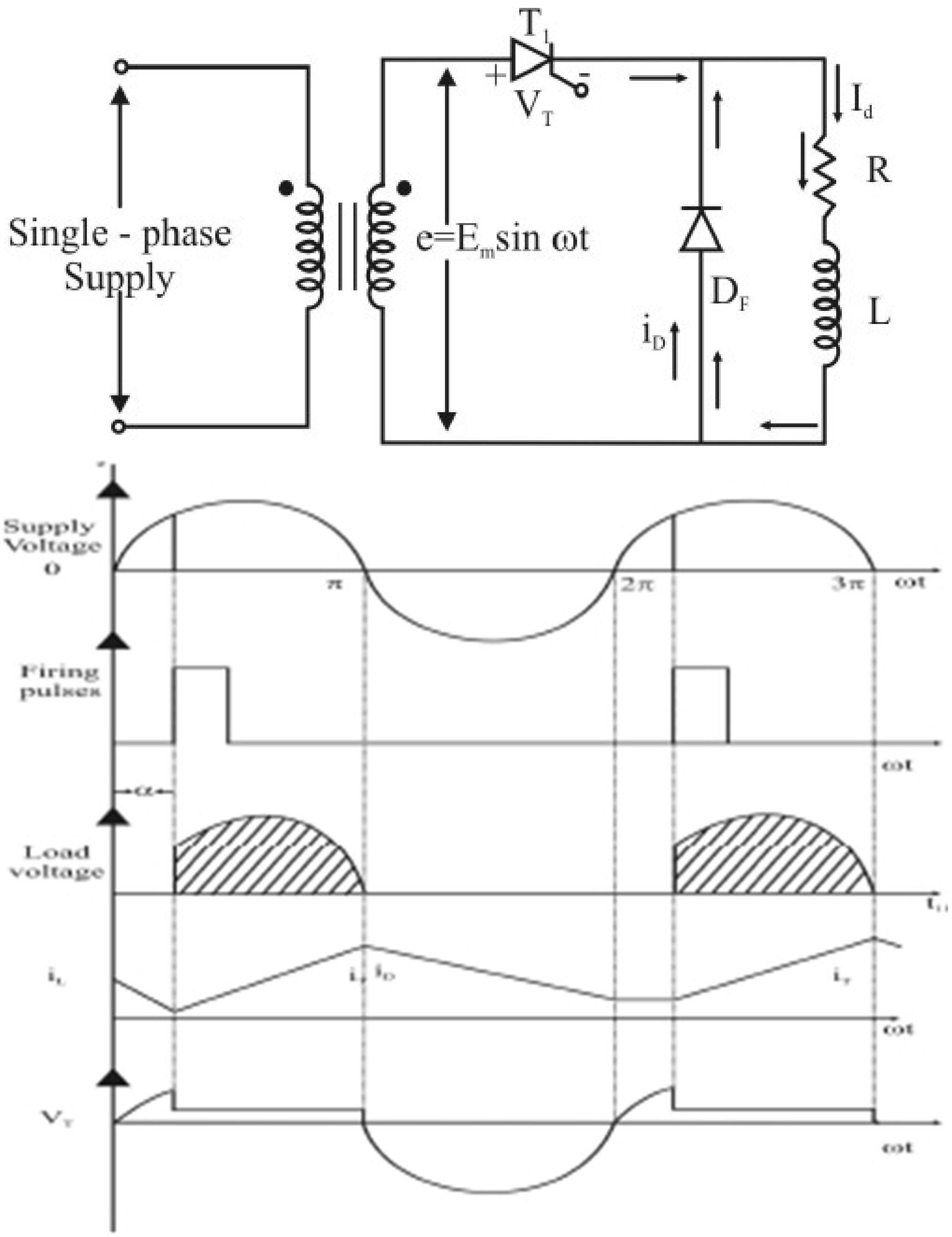
(2) Single Phase Half Wave Controlled Rectifiers with RL Load: The single phase half wave controlled rectifier with inductive load is as shown in the following figure due to energy stored in the inductor the current continues to flow during the negative half cycle , till the load current is zero & due to negative supply voltage thyristor turns OFF.



Fig(41) Single Phase Half Wave Controlled Rectifiers with RL Load

(3) Single Phase Half Wave Controlled Rectifiers with RL- Load & Freewheeling diode:

As we know that due to the inductance, the current continues to flow during the negative half cycle. To avoid this unwanted flow of current through the load a diode is connected in parallel with the load to commutate the current away from the rectifier whenever goes into the reverse state. Circuit & waveform of single phase half wave controlled rectifier with L-load & freewheeling diode.



Fig(42) Single Phase Half Wave Controlled Rectifiers with RL- Load & Freewheeling diode

Single Phase Bridge type Full Wave Rectifier:

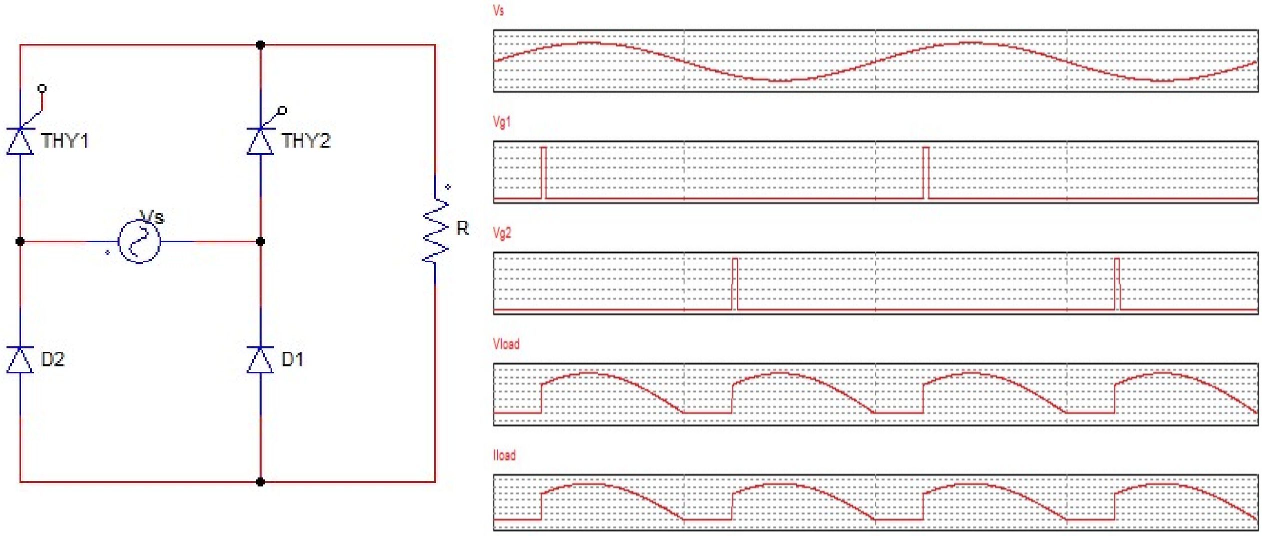
There are two types of bridge configuration full wave rectifier:

1-Half controlled bridge rectifier
2- Fully controlled bridge rectifier

1-Half controlled bridge rectifier:

(a) With resistive load

In this configuration two thyristors and two power diodes are connected in either arm of the bridge During the positive half cycle, TH1 is forward bias and when thyristor is triggered, the load currents flows through TH1 and the diode D1 in the circuit shown in figure. During the negative half –cycle, TH2 is forward bias, the thyristor TH2 and the diode D2 constitute the load current. The waveforms of the voltage and current in relation to the input voltage are shown in figure.



FIG(43)Half controlled bridge rectifier With resistive load

The average dc voltage across load is,

$$Vdc = \frac{Vm}{\pi}(1 + \cos\alpha)$$

The average load current is,

$$\mathbf{Idc} = \frac{\mathbf{Vdc}}{\mathbf{Rl}}$$

Therefore, the dc output power is, Pdc = Vdc * Idc

$$\text{Vorms} = \sqrt{\frac{1}{\pi}\int_{\propto}^{\pi}(\text{Vin})^2\,\text{dwt}} = \sqrt{\frac{1}{\pi}\int_{\propto}^{\pi}(\text{Vm}\sin(\text{wt}))^2\,\text{dwt}}$$

$$= \frac{\text{Vm}}{\sqrt{2}}\sqrt{\frac{\{\pi-\propto+\frac{1}{2}\sin(2\propto)\}}{\pi}}$$

$$\mathbf{Iorms} = \frac{\mathbf{Vorms}}{\mathbf{Rl}}$$

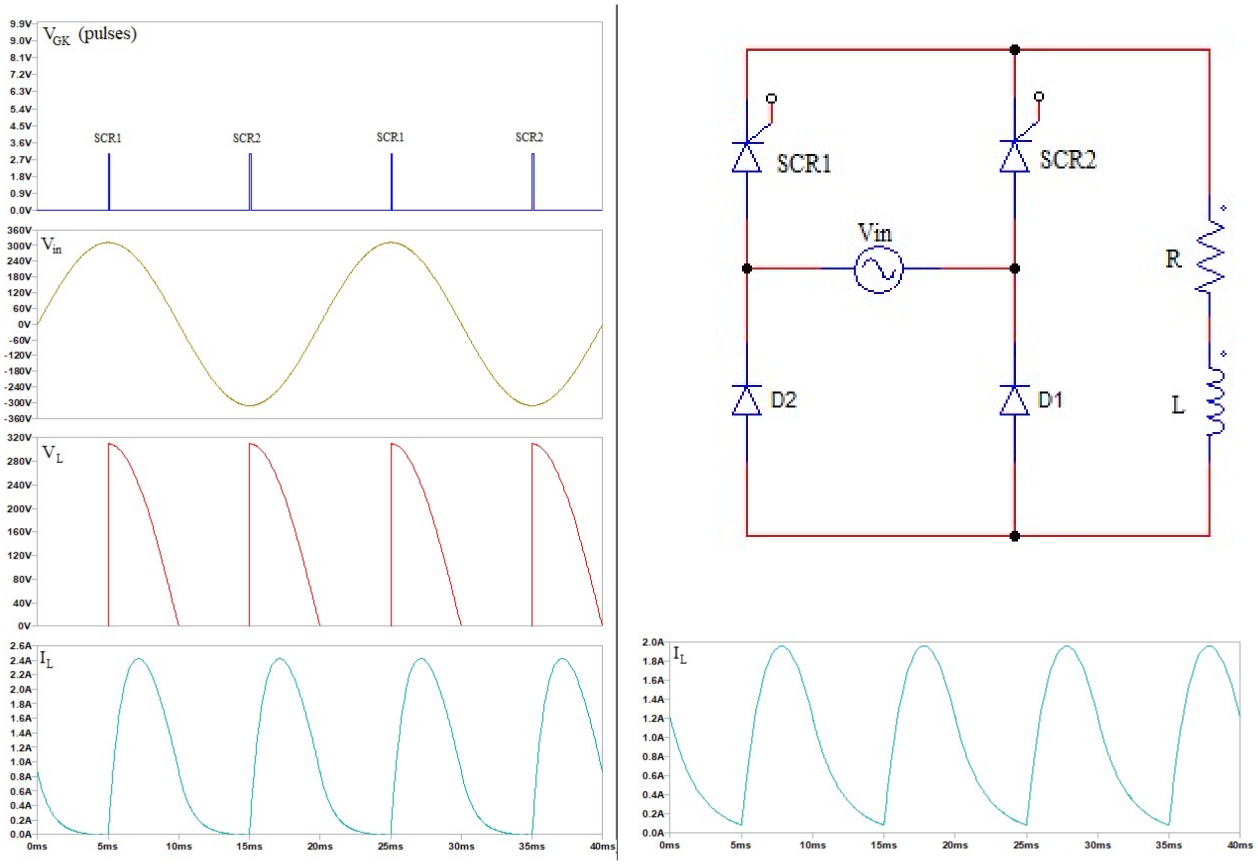
$$\text{Porms} = \text{Vorms} \times \text{Iorms}$$

$$\text{Pin} = \frac{\text{Vm}}{\sqrt{2}} \times \text{Iorms}$$

$$\text{Power factor (p.f.)} = \frac{\text{Porms}}{\text{Pin}}$$

(b)with inductive load

The single phase full wave half controlled rectifier with inductive load is as shown in figure. During the positive half cycle, SCR1 & D1 are forward bias and when thyristor is triggered, the load currents flows through SCR1 and the diode D1, due to energy stored in the inductor the current continues to flow during part of the negative half cycle through SCR1 and the diode D2 , till the load current is less than I_H. or SCR2 is triggered and turns ON which applies reverse bias on SCR1 and turns it OFF. SCR1 and the diode D2 act as a free wheeling diode for the load and thus there is no negative voltage appears in the output. The same relationships of load voltage (not current) of a single-phase half controlled bridge with resistive load will be applied here also

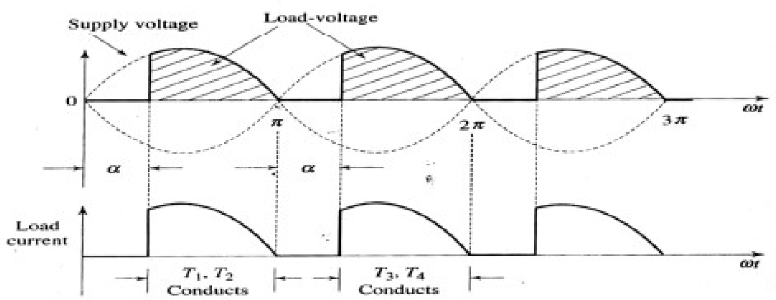


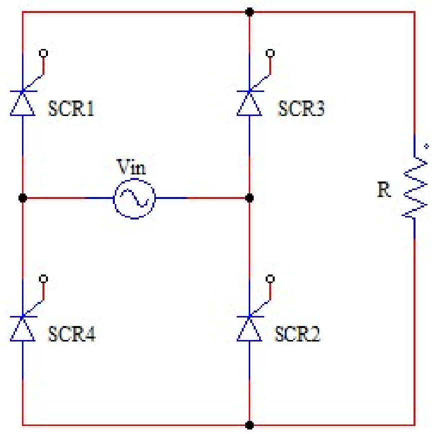
FIG(44) Half controlled bridge rectifier With inductive load. Left low inductance & I_L reaches zero ampere. Right: high inductance & I_L doesn't reach zero ampere.

2- Fully controlled bridge rectifier

a-with resistive load

A single-phase fully controlled bridge circuit consists of four thyristors as shown in figure, with a resistive load. During the positive half cycle thyristors SCR1and SCR2 are in the forward bias and when these thyristors fire simultaneously at ωt = α, the load is connected to the input through SCR1 and SCR2. When ωt = π the thyristors current drops under holding current I_H and conducting thyristors SCR1 and SCR2 turns OFF.
This process will be repeated during the negative half cycle after triggering simultaneously thyristor SCR3 and SCR4 at ωt = π + α.
are in the forward bias, and simultaneous firing of these thyristors reverse biases the previously conducting thyristors SCR1 and SCR2. These reverse biased thyristors turn off due to line or natural ommutation and the load current transfers from SCR1and SCR2 to SCR3 and SCR4. The voltage and current waveforms are shown in figure.
The same relationships of a single-phase half controlled bridge with resistive load will be applied here also.





FIG(45)full controlled bridge rectifier With resistive load

(b)with inductive load

The single phase full wave full. controlled rectifier with inductive load is as shown in figure fig(46) due to energy stored in the inductor the current continues to flow during the negative half cycle.

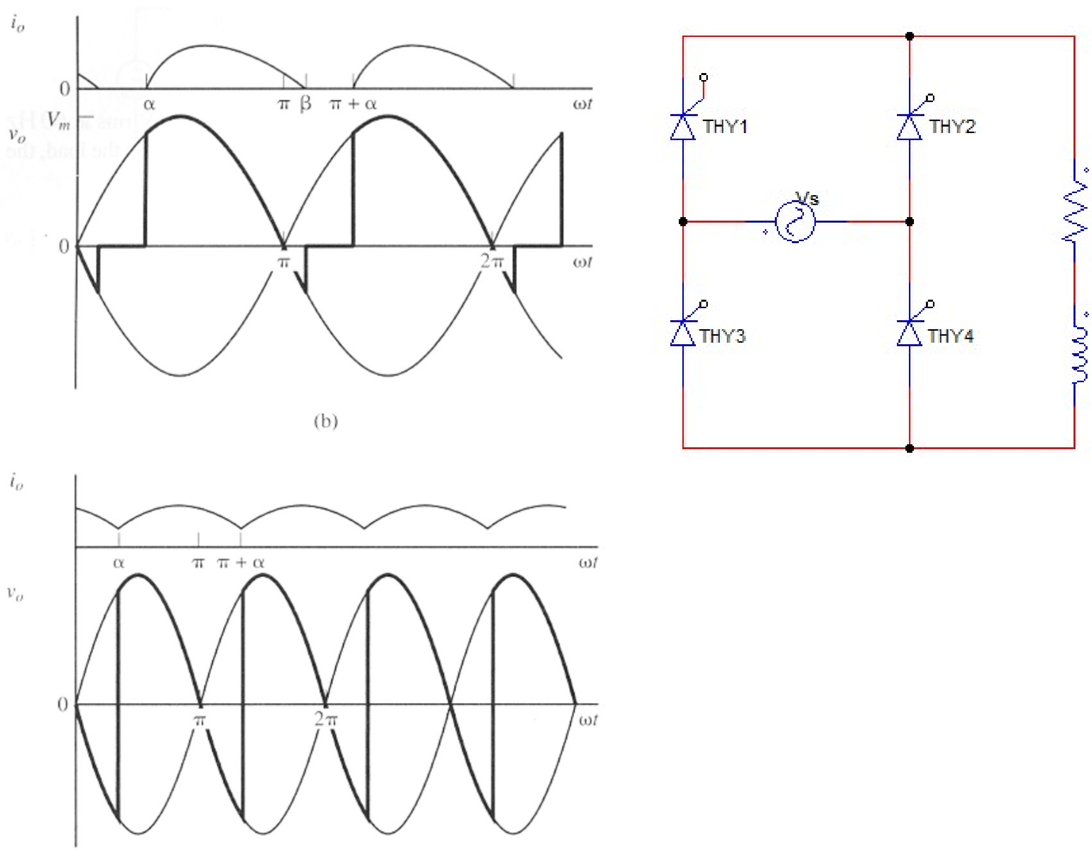
load angle $\phi=\tan^{-1} \omega L/R$

if the inductance is large the load current will be continous $\phi>\alpha$

the load dc voltage

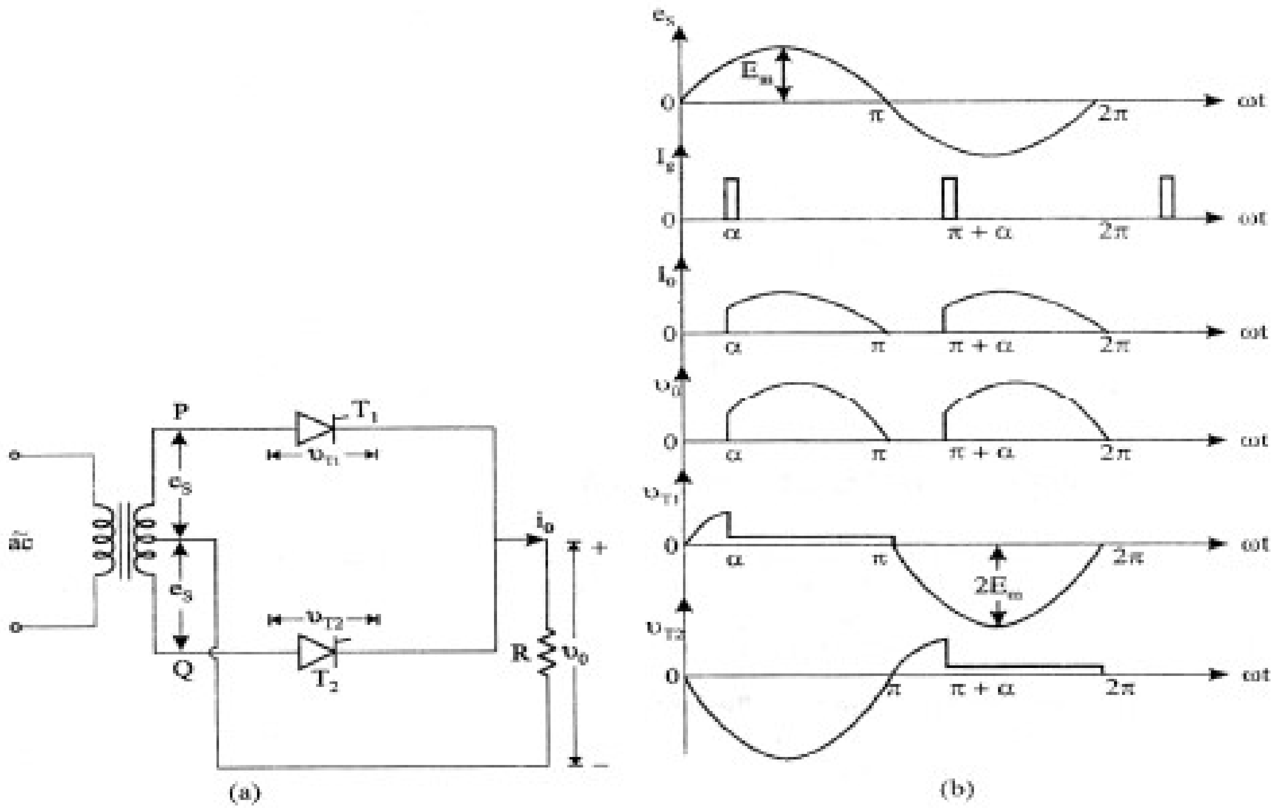
$V_{dc} = 2V_m \cos \alpha / \pi$

But if the inductance is small the load current will be discontinous $\phi<\alpha$



FIG(46)full controlled bridge rectifier With inductive load discontinuous and continuous current

Single Phase center tap Full Wave Rectifier with R Load: The circuit diagram of a single-phase full-wave converter using center- tapped transformer is shown in figure

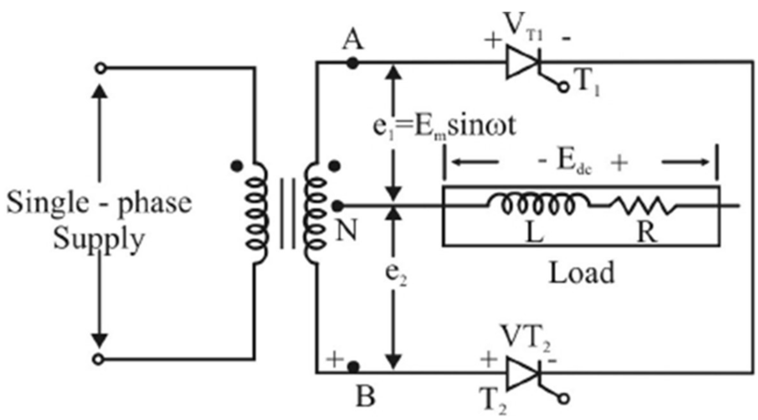


FIG(47)full controlled center- tapped transformer rectifier With resistive load

The same relationships of a single-phase half controlled bridge will be applied here also.

Single Phase center tap Full Wave Rectifier with R L Load:

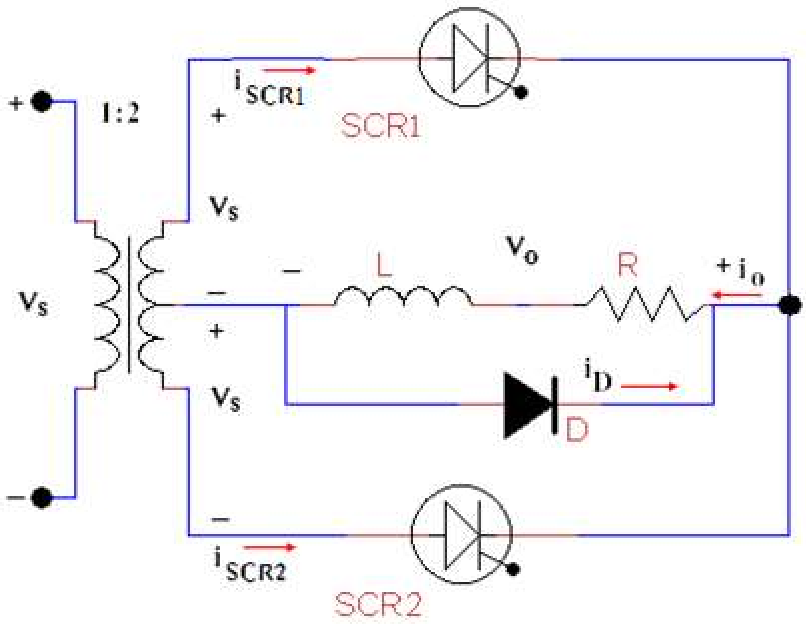
The circuit diagram of a single-phase full-wave converter using center-tapped transformer is shown in figure



FIG(48)full controlled center- tapped transformer rectifier With inductive load.

The voltage and current waveform and the load average voltage in a full wave rectifier with highly inductive load are the same as full wave full controlled bridge rectifier with inductive load.

Single Phase center tap Full Wave Rectifier with R L Load and free wheeling diode : The circuit diagram of a single-phase full-wave converter using center - tapped transformer is shown in figure



FIG(49)full controlled center- tapped transformer rectifier With inductive load and free wheeling diode.

The voltage waveform is the same as in full wave full controlled bridge rectifier with **resistive** load and current waveform is the same as in full wave full controlled bridge rectifier with **inductive** load.

Example1: A resistive load (30Ω) is supplied from single phase half controlled full wave rectifier, calculate the rms and dc voltage and current at firing angle (30^0) the rms power dissipated in the load and the power factor, the supply voltage 230 V.

$V_{dc} = V_m (1+\cos\alpha) / \pi = \sqrt{2}x230(1+\cos 30) / 3.14 = 194$ v

$I_{dc} = V_{dc} / R = 194/30 = 6.5$A

$$Vorms = \frac{Vm}{\sqrt{2}}\sqrt{\frac{\{\pi-\propto+\frac{1}{2}\sin(2\propto)\}}{\pi}} = \frac{\sqrt{2}x230}{\sqrt{2}}\sqrt{\frac{\{3.14-\propto+\frac{1}{2}\sin(2x30)\}}{3.14}} = 226 \text{ v}$$

$$\mathbf{Iorms} = \frac{\mathbf{Vorms}}{\mathbf{Rl}} = \frac{\mathbf{226.6}}{\mathbf{30}} = \mathbf{7.55}\ \text{A}$$

$$Porms = Vorms \times Iorms = 226.6 \times 7.55 = 1710.83 \text{ watt}$$

$$\text{Power factor (p.f.)} = \frac{Porms}{Pin} = \frac{Vorms}{V} = \frac{226.6}{230} = 0.9$$

Example2: For full controlled bridge rectifier L=50mH, R=10Ω, $\alpha=30^0$, Vin=325*sin(100 πt) calculate:

1-load angle

2-is the load current continous or discontinous

3-average load voltage

$\phi = \tan^{-1} \omega L/R = \tan^{-1} (100 \times 3.14 \times 50 \times 10^{-3}/10) = 57.5^0$

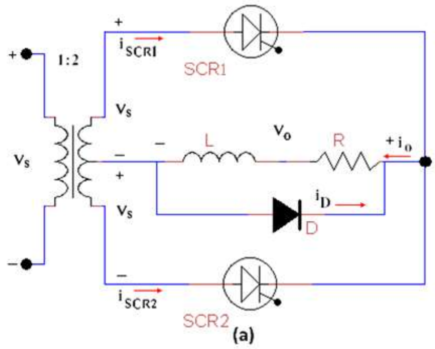
$\phi > \alpha$ the load current is continous

Vdc = 2Vm cos α / π = 2x325 cos 30 / 3. 14 =179. 2 V

Example3: For full controlled center-tapped transformer rectifier with highly inductive load The transformer turns ratio 2:1, the supply voltage 240v calculate:

1- the dc load voltage with and without freewheeling diode for firing angle 45^0
2- discuss the results

1- the dc load voltage



$\frac{V1}{V2} = \frac{N1}{N2}$

$V_2 = \frac{240}{2} = 120$ v

$V_a = \frac{120}{2} = 60$ v

A-without freewheeling diode

$V_{dc} = 2V_m \cos \alpha / \pi = 2*\sqrt{2} * 60*\cos 45 / 3.14 = 37.8$v

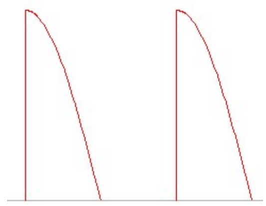
B-with freewheeling diode

$V_{dc} = V_m (1+\cos \alpha) / \pi = \sqrt{2}$ x60 (1+cos 45) / 3. 14=45. 66 v

2-: Vdc with freewheeling diode > Vdc without freewheeling diode because there is a negative part in the load voltage without freewheeling diode.

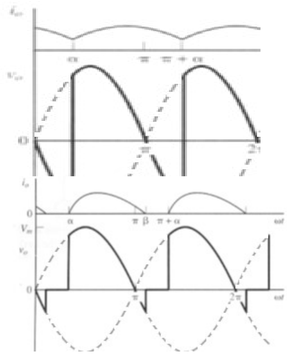
Summary:

$$Vdc = \frac{Vm}{\pi}(1+\cos\alpha), \quad \text{and } Idc = \frac{Vdc}{Rl}$$



$$Vorms = \frac{Vm}{\sqrt{2}}\sqrt{\frac{\{\pi - \propto + \frac{1}{2}\sin(2\propto)\}}{\pi}}, \text{and } Iorms = \frac{Vorms}{Rl}$$

==



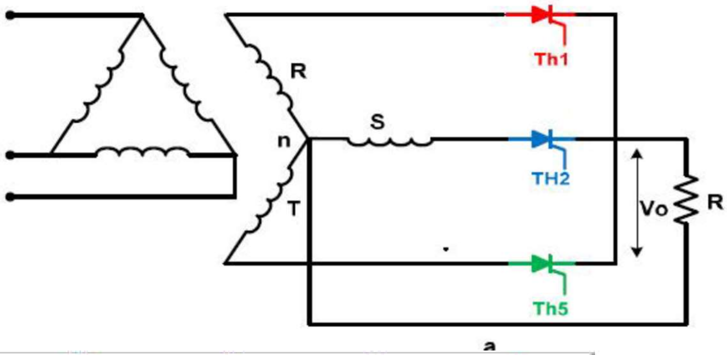
$$Vdc = \frac{2Vm * \cos\alpha}{\pi}$$

==

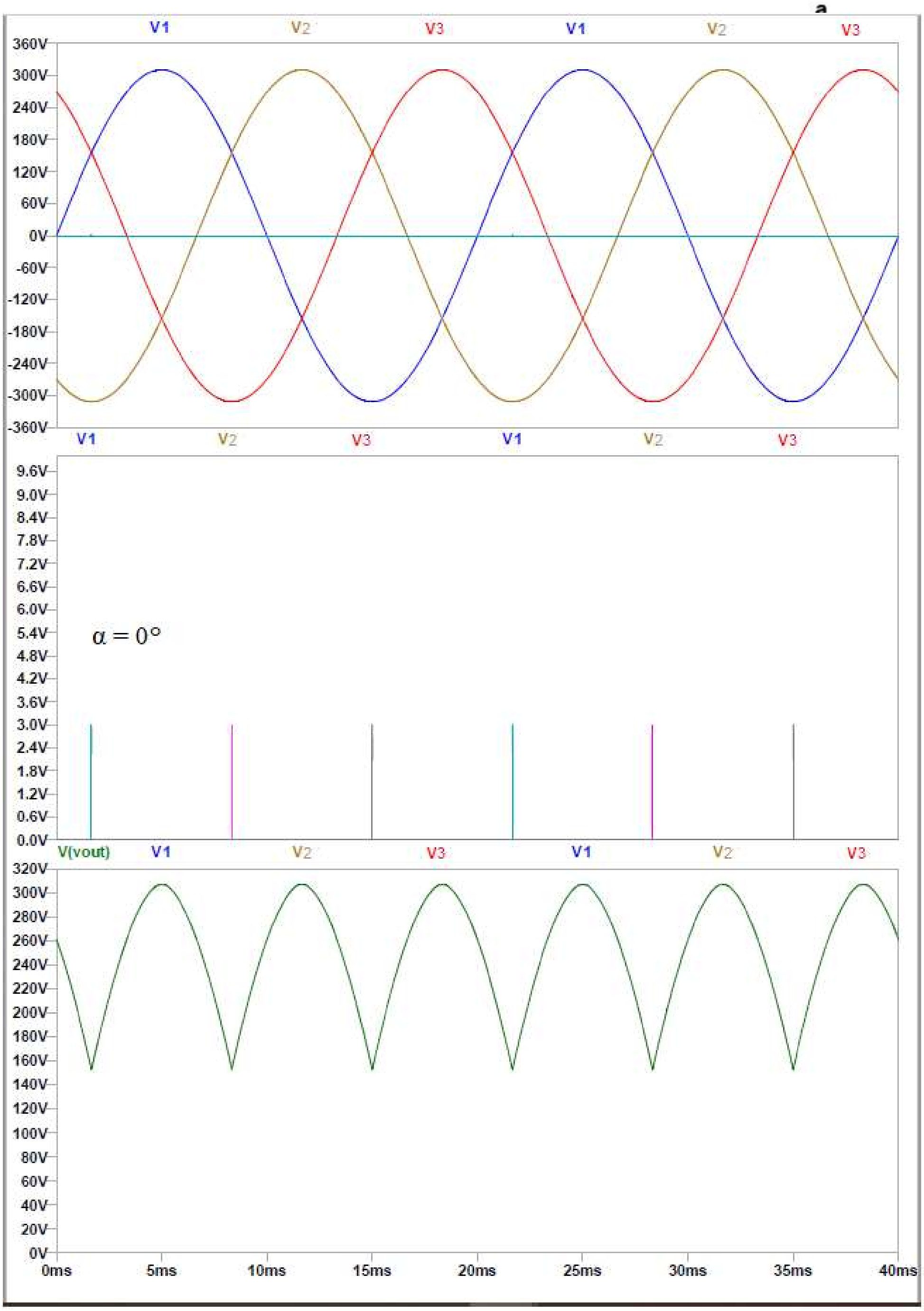
No relationships

Three phase controlled converters

a) Three phase half-wave converter with resistive load



We use here phase voltage where



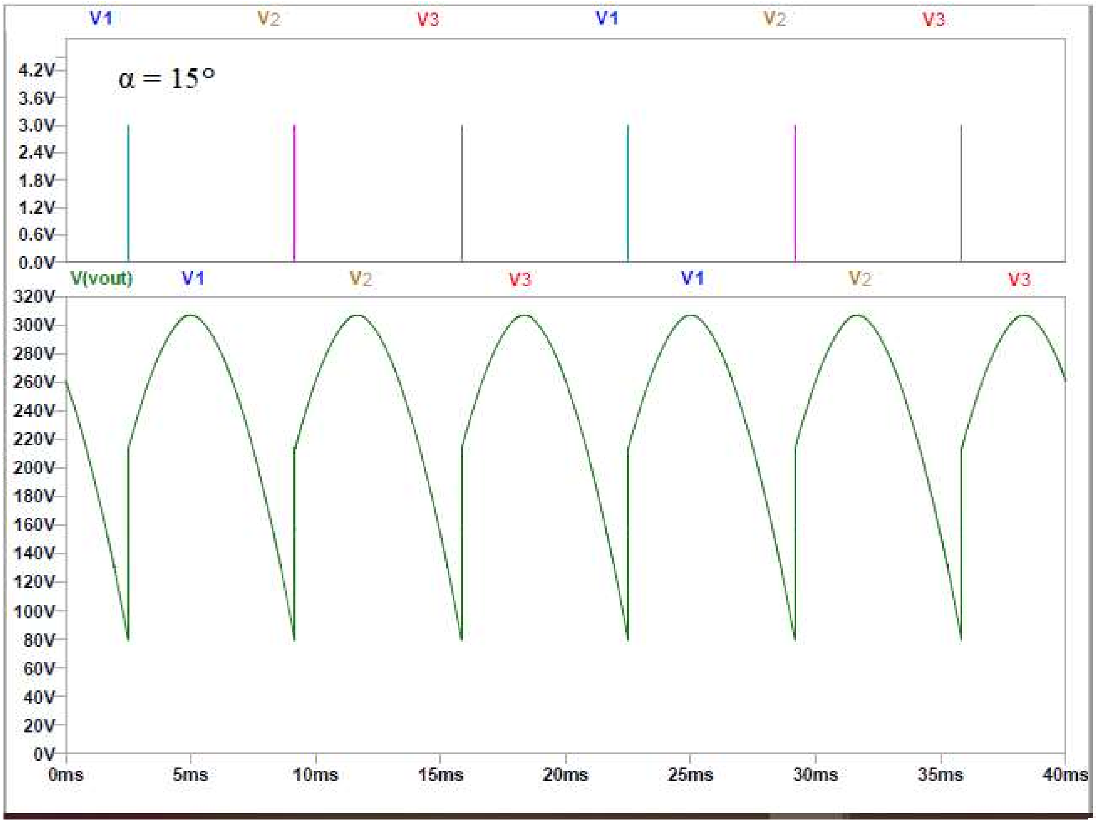
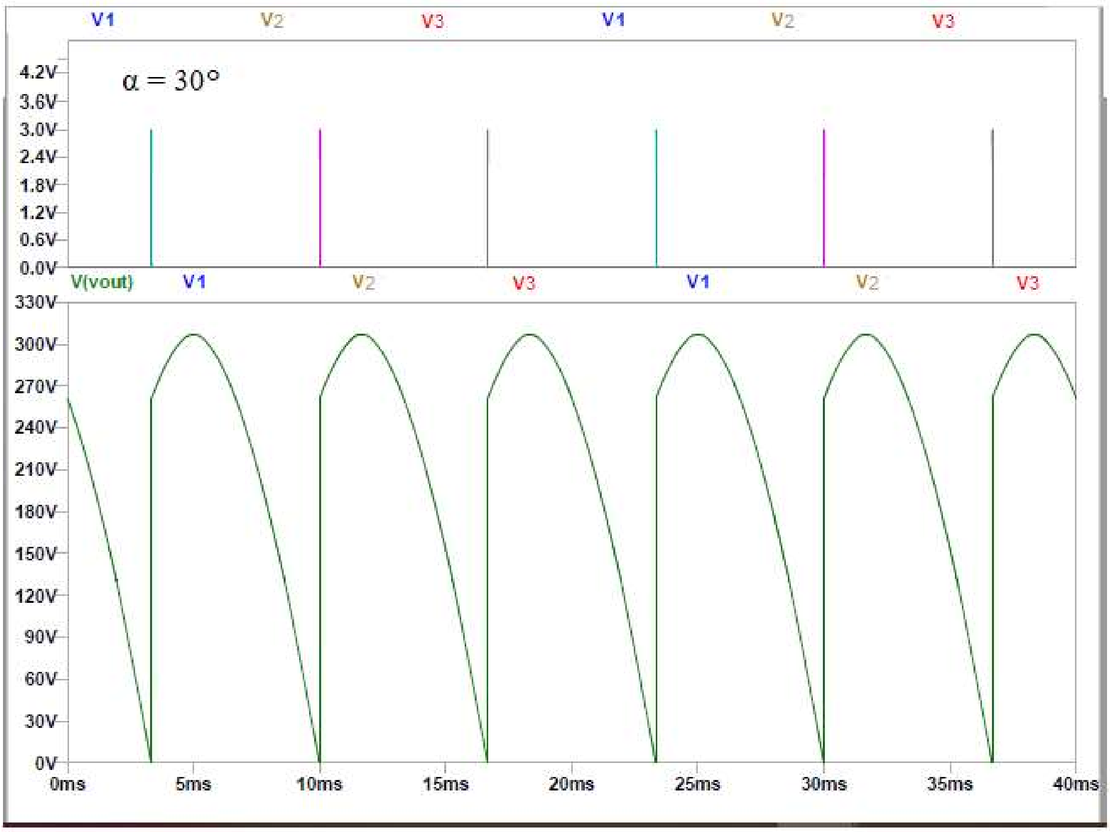
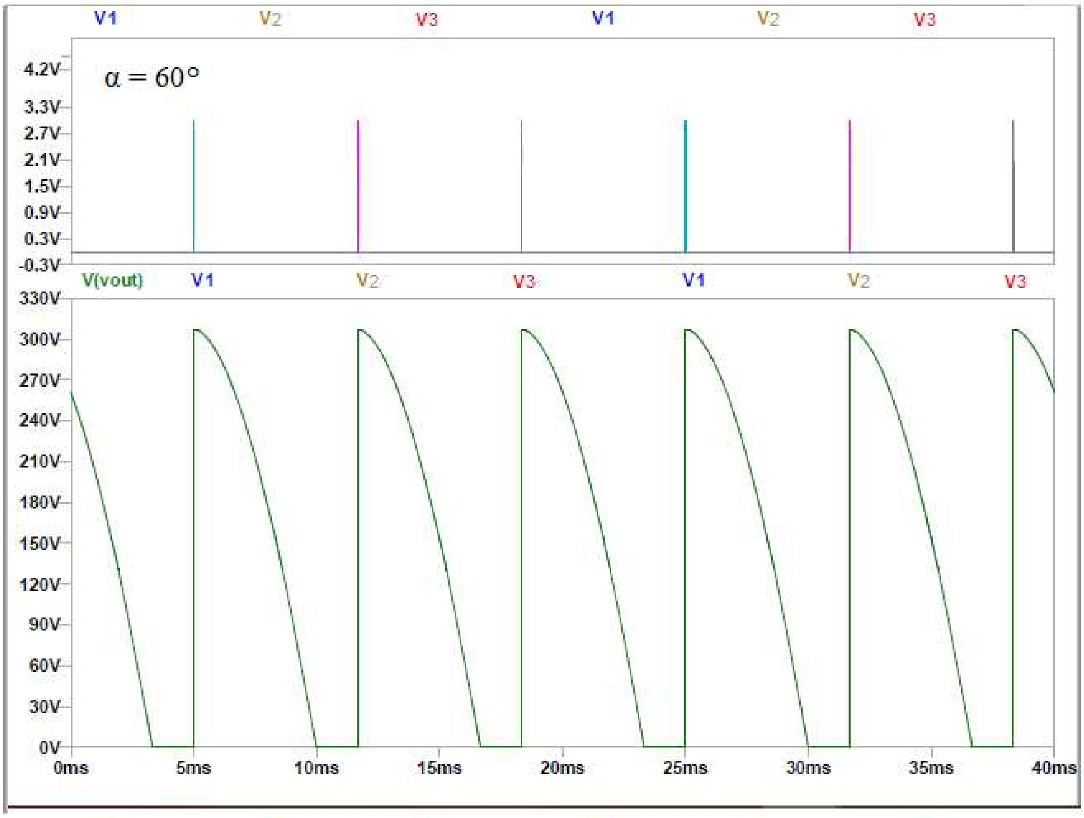
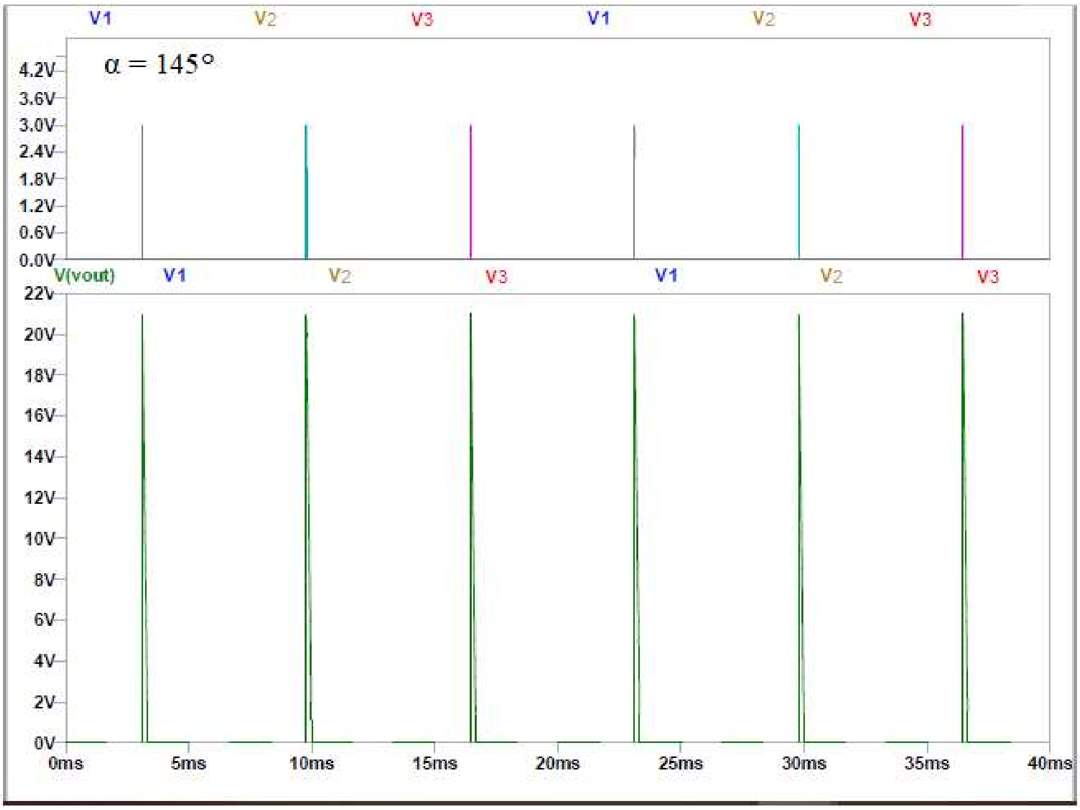


Fig (50) Three phase half-wave converter continuous conduction with α=0⁰ and α=15⁰




α = 60°
V1
V2
V3
V(vout)
4.2V
3.3V
2.7V
2.1V
1.5V
0.9V
0.3V
-0.3V
330V
300V
270V
240V
210V
180V
150V
120V
90V
60V
30V
0V
0ms
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms


α = 145°
V1
V2
V3
V(vout)
4.2V
3.6V
3.0V
2.4V
1.8V
1.2V
0.6V
0.0V
22V
20V
18V
16V
14V
12V
10V
8V
6V
4V
2V
0V
0ms
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms

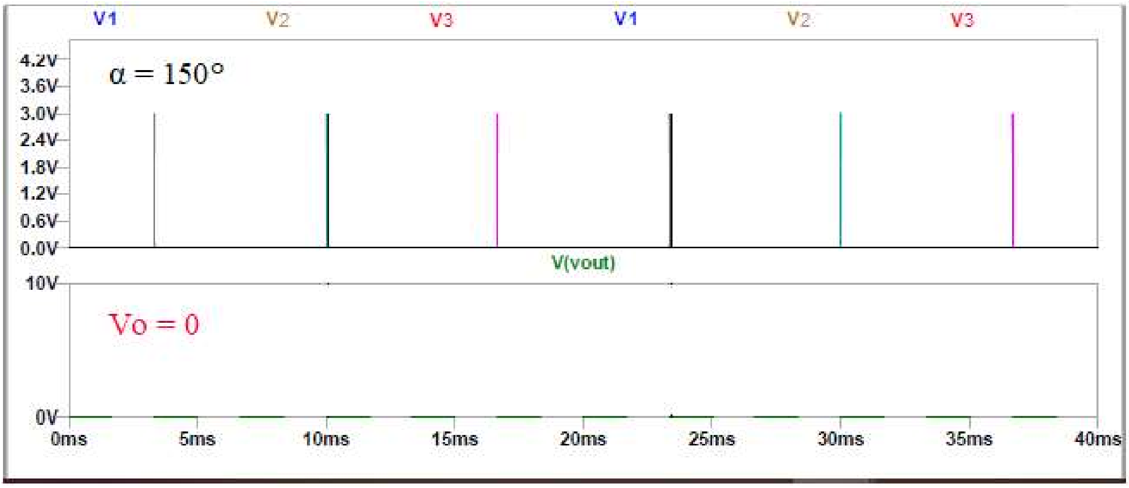


Fig (51) Three phase half-wave converter discontinuous conduction with α=30°, α=60°, α=145° and α=150°

V1 = Vm sinωt
V2 = Vm sin(ωt-120°)
V3 = Vm sin(ωt +120°)

1- Continuous control:-

When $0 < \alpha < 30°$

$$Vdc = \frac{3\sqrt{3}Vm}{2\pi} Cos(\propto)$$

2- Discontinuous control:-

When $30° \leq \alpha < 150°$

$$Vdc = \frac{3Vm}{2\pi}(1 + Cos(30{+}\propto))$$

Example:

A resistive load is supplied from three phase half-wave rectifier, if the supply voltage is 230V calculate the dc load voltage at firing angle 0^0, 15^0, 30^0, 60^0, 90^0, 120^0 and 150^0.

At $\alpha=0^0$ continuous conduction

$$Vdc = \frac{3\sqrt{3}Vm}{2\pi} Cos(\propto) = \frac{3\sqrt{3}x\sqrt{2}x230}{2x3.14} cos(0) = 269\ V$$

At $\alpha=15^0$ continuous conduction

$$Vdc = \frac{3\sqrt{3}Vm}{2\pi} Cos(\propto) = \frac{3\sqrt{3}x\sqrt{2}x230}{2x3.14} cos(15) = 261.5\ V$$

At $\alpha=30^0$ continuous conduction

$$Vdc = \frac{3\sqrt{3}Vm}{2\pi} Cos(\propto) = \frac{3\sqrt{3}x\sqrt{2}x230}{2x3.14} cos(30) = 233\ V$$

At $\alpha=30^0$ discontinuous conduction

$$Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30+\propto)) = Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30 + 30))$$

$$Vdc = 233\ V$$

At $\alpha=60^0$ discontinuous conduction

$$Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30+\propto)) = Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30 + 60))$$

$$Vdc = 155.3\ V$$

At $\alpha=90^0$ discontinuous conduction

$$Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30+\propto)) = Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30 + 90))$$

$$Vdc = 77.7\ V$$

At $\alpha=120^0$ discontinuous conduction

$$Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30+\propto)) = Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30 + 120))$$

$$Vdc = 20.8\ V$$

At $\alpha=150^0$ discontinuous conduction

$$Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30+\propto)) = Vdc = \frac{3x\sqrt{2}x230}{2x3.14}(1 + Cos(30 + 150))$$

$$Vdc = 0\ V$$

1- Three phase full-wave converter

We use here line voltage where

$\text{VLine} = \sqrt{3}\ Vphase \quad OR \quad VL = \sqrt{3}\,Vph$

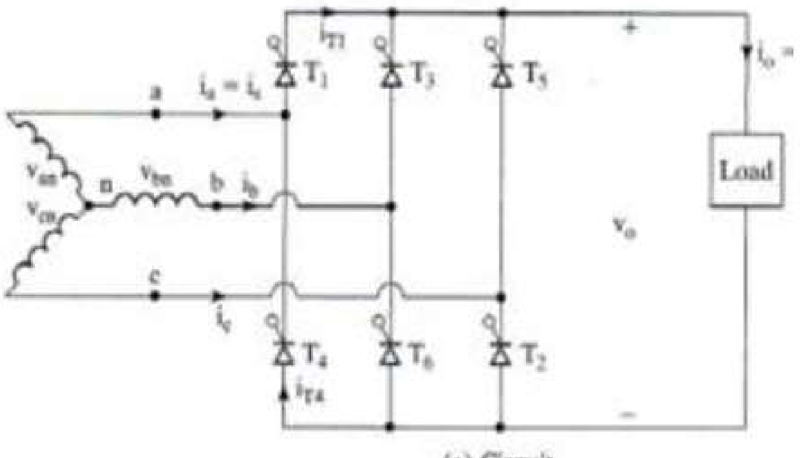
1- Continuous control:-

When $0 < \alpha < 60°$

$$\text{Vdc} = \frac{3\sqrt{3}\text{Vm}}{\pi}\cos(\propto)$$

2- Discontinuous control:-

When $60° \leq \alpha < 120°$



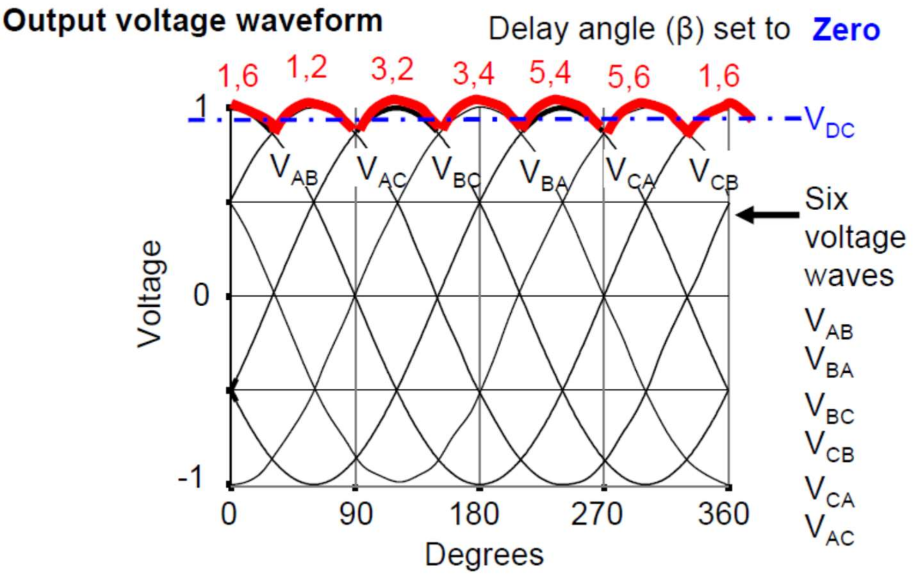


Fig (52) Three phase full-wave converter

Thyristor Commutation

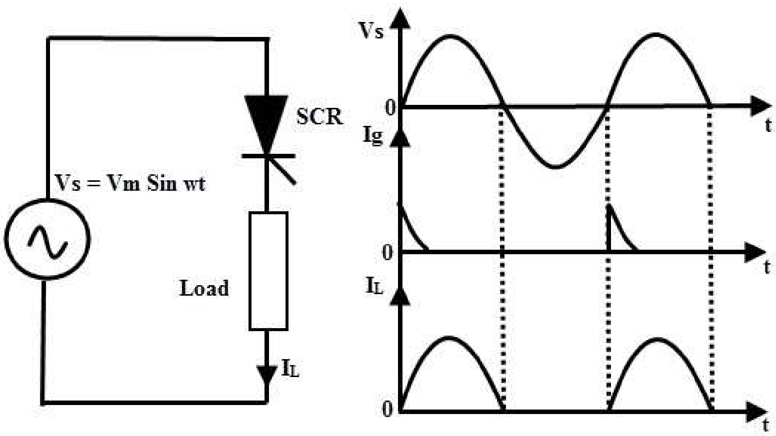
To turn OFF the conducting SCR the below conditions must be satisfied.

- The anode or forward current of SCR must be reduced to zero or below the level of holding current and then,
- A sufficient reverse voltage must be applied across the SCR to regain its forward blocking state.

Methods of thyristor commutation:-

1- Natural commutation. (line commutation)

Natural Commutation of thyristors takes place in AC circuits, at every end of the positive half cycle the anode current goes through the natural current zero and also immediately a reverse voltage is applied across the SCR. These are the conditions to turn OFF the SCR.



Fig(53) Natural Commutation circuit

2- Forced commutation.

This commutation is mainly used in **chopper** and **inverter** circuits. It is a technique used to force the thyristor to be in reverse bias or the anode current to decrease to zero by using an external device connected to the thyristor.

Types of forced commutation:-

a- Load commutation

This is also known as resonant commutation, or self-commutation. In this commutation, the source of commutation voltage is in the load. The commutating components L and C are connected either parallel or series with the load resistance R as shown. This load must be an under damped R-L-C supplied with a DC supply so that natural zero is obtained. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.

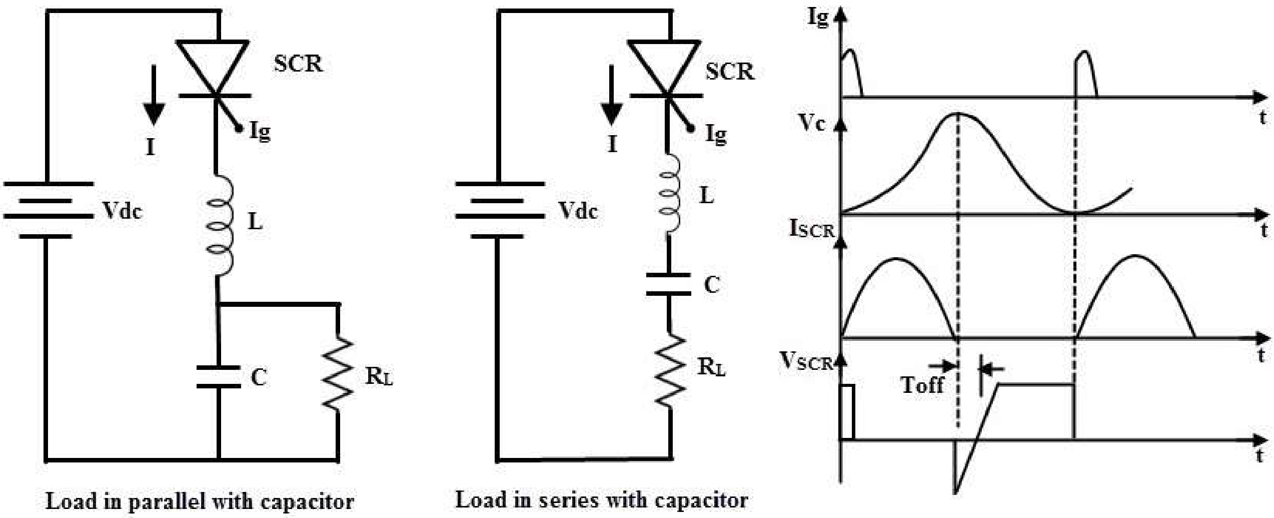
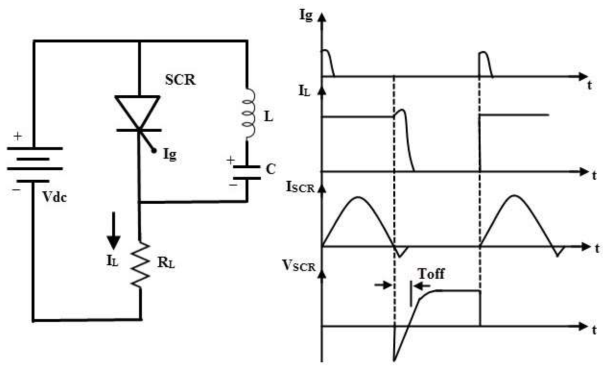


Fig (54 a) Load commutation circuit

b- Self commutation

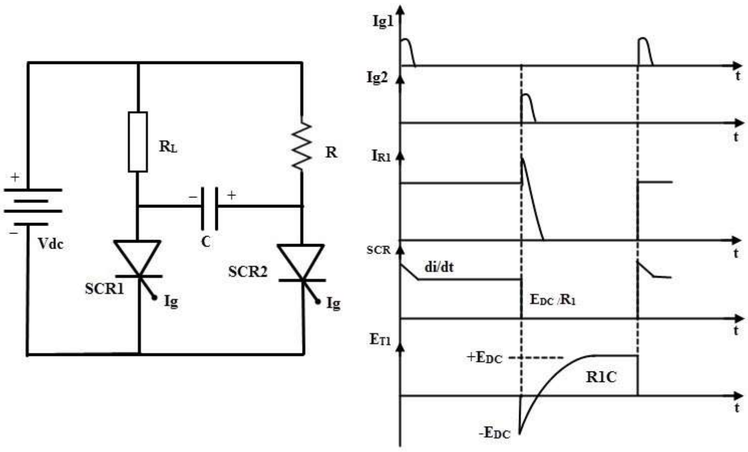
the LC resonant circuit is connected across the SCR but not in series with load as in case of class (a) commutation and hence the L and C components do not carry the load current.



Fig(54 b) Self commutation circuit

c- Complementary commutation:-

In this commutation method, the main SCR is to be commutated is connected in vparallel with main SCR. In this, SCR turns OFF with a reverse voltage of a charged capacitor.



Fig(55) Complementary commutation circuit

d- Auxiliary commutation

In this, the main SCR is commutated by the auxiliary SCR. The main SCR with load resistance forms the power circuit while the diode D, inductor L and SCR2 forms the commutation circuit.

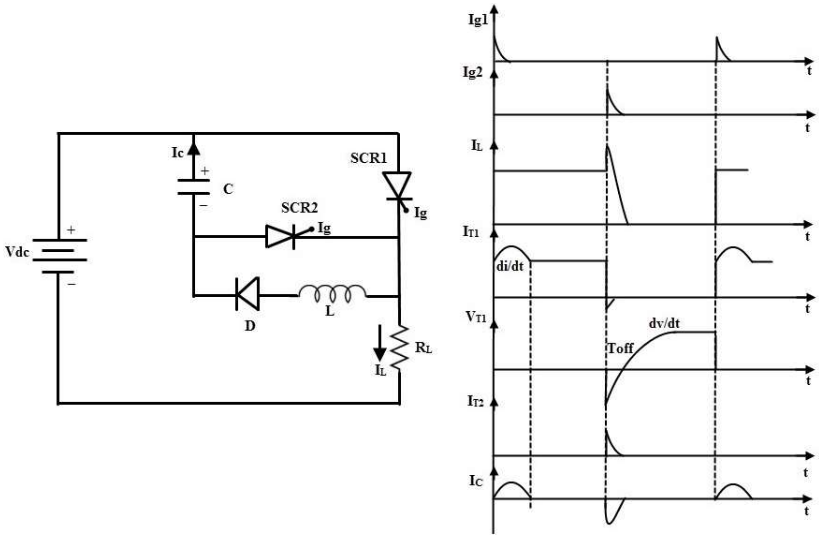


Fig (56) auxiliary commutation circuit

e- External pulse commutation

An external pulse source is used to produce the reverse voltage across the SCR. It uses a pulse transformer to produce the commutating pulse.

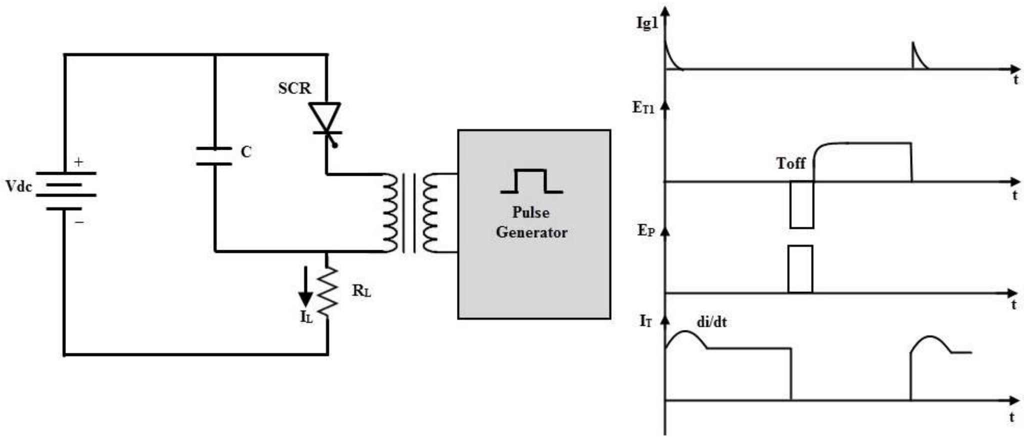


Fig (57) External pulse commutation circuit

DC to DC Converters (Choppers)

Many DC operated applications need different levels of DC voltage from a fixed DC source. Such as subway cars, DC traction systems, control of large DC motors, battery operated vehicles, trolley buses, etc. They require variable DC to produce variable speed. The output voltage is controlled by adjusting ON time of the thyristor (or switch) which turn changes the width of DC voltage pulse at the output. This method of switching is called as pulse width modulation (PWM) control. The output of the chopper can be less or greater than the input and also it can be fixed or variable. DC choppers are classified into three basic types based on input and output voltage levels and are discussed below.

Methods of Control

The output dc voltage can be varied by the following methods.

- Pulse width modulation control or constant frequency operation.
- Variable frequency control

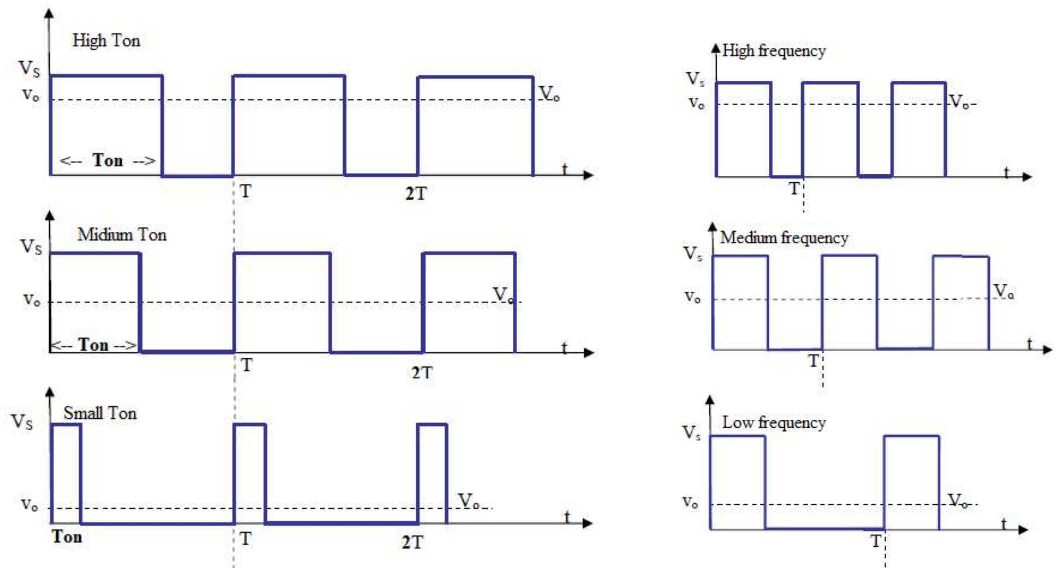


Fig (62) PWM and Frequency control

1- Step-down Chopper or Buck converter:

It produces an average output voltage lower than the input DC voltage.

a) with resistive load

Figure (62) shows a step-down chopper with resistive load. The thyristor in the circuit acts as a switch. When thyristor is ON, supply voltage appears across the load and when thyristor is OFF, the voltage across the load will be zero. The output voltage waveform is as shown in Fig. (63).

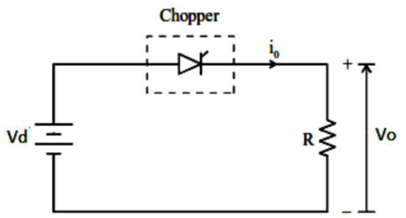


Fig.(63a) step-down chopper

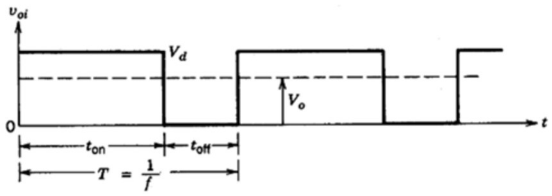


Fig.(63b) The output voltage waveform.

Pulse Width Modulation (PWM)

t_{ON} is varied keeping chopping frequency F & chopping period T constant.

Output voltage is varied by varying the ON time t_{ON}

$$V_o = \frac{t_{on}}{T} V_d = D\,V_d$$

Where, Vd *is supply voltage*

V_o *is load voltage*

$D = \frac{t_{on}}{T}$ *is duty cycle*

$T = ton + toff$ *is control period*

$F = \frac{1}{\mathrm{T}}$ *is Frequency*

Example 1: - A step-down d.c chopper, fed from Supply of (60 V), the waveform of the load voltage formed of rectangular pulses each of width (2 ms) and the periodic time of (5msec), Draw the waveform of the load voltage, then calculate the average output voltage.

$$V_o = \frac{t_{on}}{T} V_d = \frac{2}{5} \times 60 = 24\mathrm{V}$$

b) with inductive load: -

chopper circuit with R-L load as shown in Fig. (64). This is a step-down chopper**.**

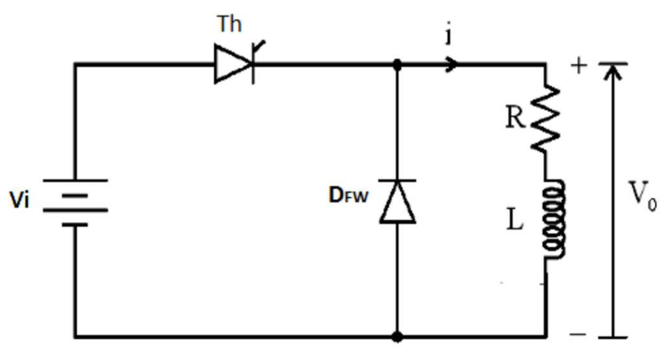


Fig (64) step-down chopper with inductive load

In case of large inductive load, the current is continuous as shown in Fig. (65).

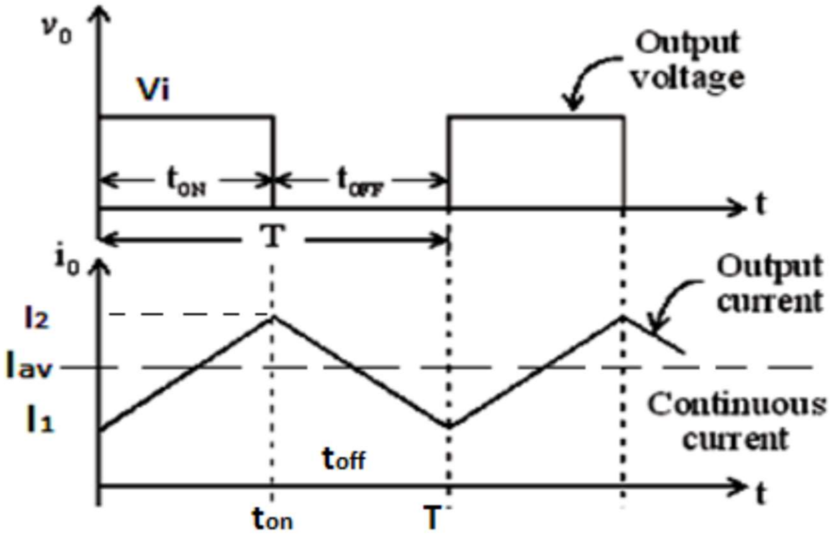


Fig. (65) The output voltage waveform.

2- Step-up Chopper or Boost converter:

When the thyristor is turned OFF, the load gets the voltage from input as well as from inductor. So the voltage appearing at the output will be more than the input.

$$V_o = \frac{T}{t_{off}} V_d = \frac{T}{T - t_{on}} V_d = \frac{1}{1 - \frac{t_{on}}{T}} V_d = \frac{1}{1 - D} V_d$$

By varying this duty ratio, the output voltage will be varied till the load gets desired voltage. Figure (66) shows a step-up chopper

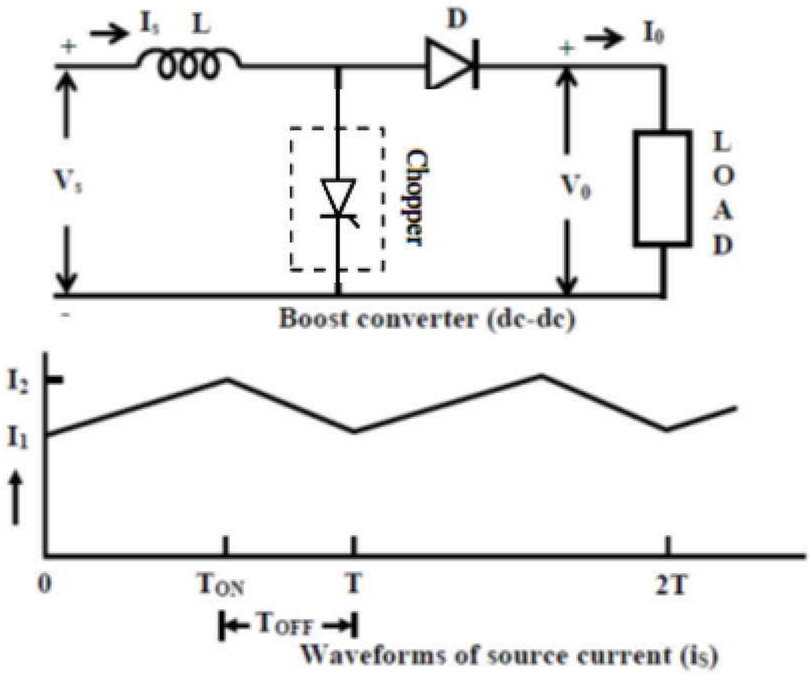


Figure (66) shows a step-up chopper

When chopper SCR is ON, the path is closed and inductor store energy during this period. When SCR is OFF, as the inductor current cannot die down instantaneously, this current is forced to flow through the diode and load for time t_{off}.

Example 2: - A step-up dc chopper, fed from Supply of (100 v), the waveform of the load voltage formed of rectangular pulses each of width (2 ms) on time and The periodic time of (5msec), Draw the waveform of the load voltage, then calculate the average output voltage.

$$D = \frac{t_{on}}{T} = \frac{2}{5} = 0.4$$

$$V_o = \frac{1}{1-0.4} \times 100 = 166.6 \text{ v}$$

3- Step up-down Chopper or Buck-Boost converter:

This makes it possible to increase or reduce the voltage input level. Fig (67) shows a step up-down chopper.

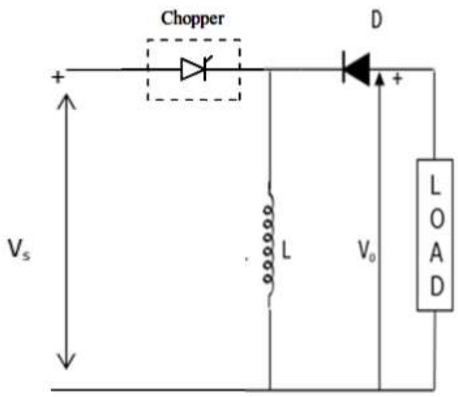


Fig (67) step up-down chopper.

When the SCR is switched ON, the inductor L becomes charged by the source voltage Vs.

When the SCR is switched OFF, the inductor's polarity reverses and this causes it to discharge through the diode and the load.

The output voltage Vo is

$$V_o = \frac{t_{on}}{T-t_{on}} V_d = \frac{D}{1-D} V_d$$

$D = \frac{t_{on}}{T}$ duty cycle

When D = 0.5, $V_O = V_S$

Hence, in the interval $0 \leq D \leq 0.5$, output voltage varies in the range $0 \leq Vo \leq Vs$ and we get step down operation. Whereas, in the interval $0.5 \leq D \leq 1$, output voltage varies in the range $Vs \leq Vo$ and we get step up operation.

Example 3:- A step up-down d. c chopper, fed from Supply of (120 v), The periodic time of (5msec), calculate the average output voltage for:-

1- on time pulses width (2 ms)
2- on time pulses width (4 ms)

1- ton = 2 ms

duty cycle $D = \frac{t_{on}}{T} = \frac{2}{5} = 0.4$

output voltage $V_o = \frac{\mathrm{D}}{1-\mathrm{D}} V_d = \frac{0.4}{1-0.4} \times 120 = 80$ V

2- ton = 4 ms

duty cycle $D = \frac{t_{on}}{T} = \frac{\mathbf{4}}{\mathbf{5}} = 0.8$

output voltage $V_o = \frac{\mathrm{D}}{1-\mathrm{D}} V_d = \frac{0.8}{1-0.8} \times 120 = 480$V

AC to AC Converters

AC/AC converters connect an AC source to AC loads by controlling amount of power supplied to the load. This converter converts the AC voltage at one level to the other by varying its magnitude as well as frequency of the supply voltage.

These are used in different types of applications including uninterrupted power supplies, high power AC to AC transmission, adjustable speed drives, renewable energy conversion systems and aircraft converter systems.

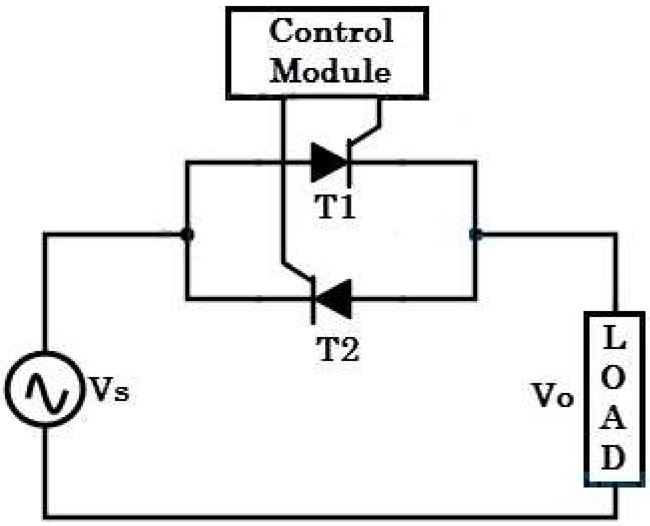
The types of AC to AC converters are discussed below.

AC/AC Voltage Converters

These converters control the rms value of output voltage at a constant frequency. The common application of these converters includes starting of AC motors and controlling power to heaters.

A single-phase AC/AC voltage converter consists of a pair of anti-parallel thyristors along with a control circuit as shown in figure below.

The other names of this controller are single phase full wave converter and AC voltage controller.

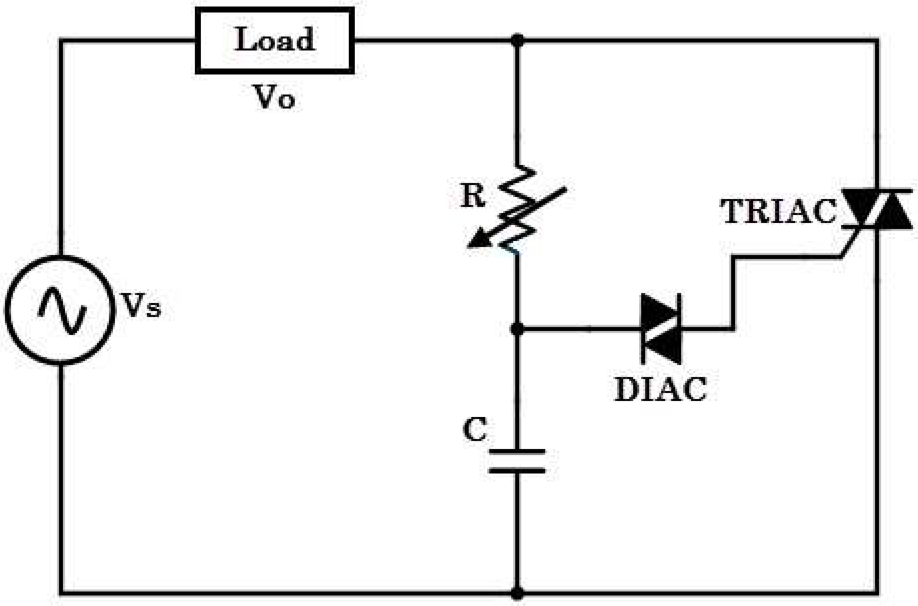


During positive half cycle of the input signal, thyristor-1 is forward biased and in negative half cycle of the input, thyristor-2 is forward biased.

By varying the triggering or conduction angel of each thyristor during each half-cycle, the magnitude of voltage appeared across the load is controlled.

The other popular form of AC voltage controller is the use of TRIAC in place of two anti-parallel thyristors. The figure below shows TRIAC based AC controller along with triggering control circuit.

Here diac controls the positive and negative triggering to the TRIAC so that average output voltage to the load is controlled.



AC/AC frequency Converters

These converters are mainly used for varying the frequency of the input source to desired level of the load. An AC/AC frequency converter changes the frequency of input voltage/current of the load compared to the frequency of the source.
Some of these converters may control magnitude of voltage besides the frequency control. These are mainly used for adjusting the speed of AC drives and also for induction heating.
The two major classes of these converters include

1. Cyclo converters, and
2. Matrix converters.

AC voltage controllers

The most important applications of AC voltage controllers is industrial heating circuits and lighting dimmers and Speed control of induction motors.

There are two types of control:

1- ON-OFF Control: The thyristor connects the power from the power source to the load for a number of cycles and separates this power during another number of cycles
2- Phase-Difference Control: The thyristor separates the supply power from the load during part of the cycle while connecting the power during the last part of the cycle

1- ON-OFF Control:

The working principle of these controllers can be explained from the circuit shown in the figure.

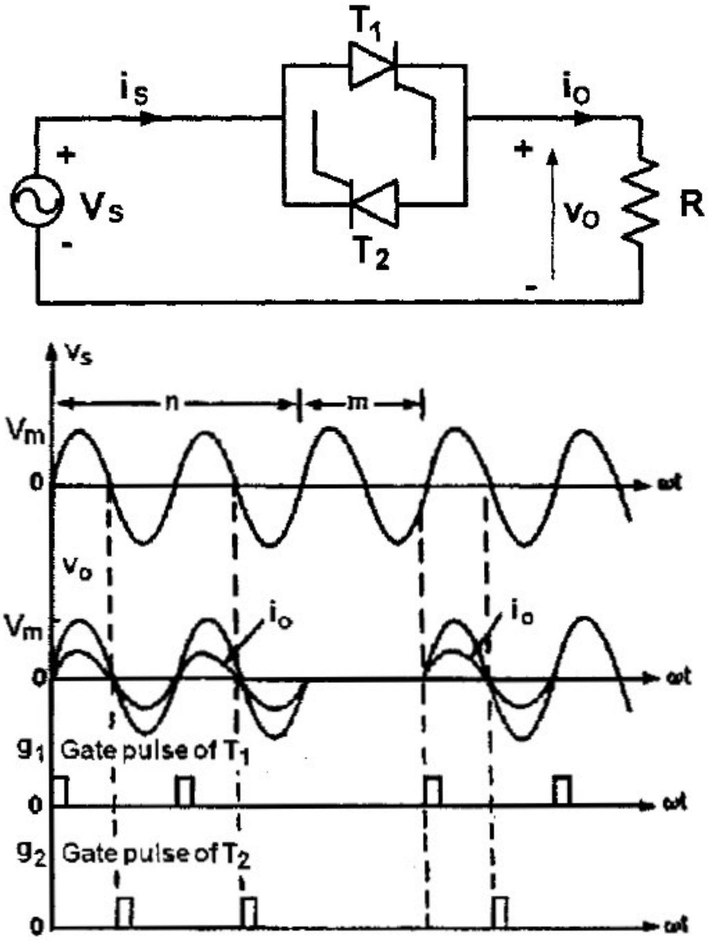


Fig. ON-OFF AC voltage controller

If the input is connected to the load for a number of cycles (n) and the load has been disconnected for a number of cycles (m), then the effective value of the output is given by the following relationship:

$$V_{orms} = V_{irms}\sqrt[2]{\frac{n}{n+m}} = V_{irms}\sqrt[2]{K}$$

Where $K = \frac{n}{n+m}$

Example 1: A single phase full wave ON-OFF AC controller connected With a 10Ω load, the effective value of the phase voltage is Vrms=120 volts, the frequency of f=60 hertz, the conduction period is n=25 turns and the connection period is m=75 cycles. Calculate

1- The effective value of the output voltage
2- The power factor of the input circuit

$K = \frac{n}{n+m} = \frac{25}{25+75} = 0.25$

$V_{im} = \sqrt{2}\, V_{irms} = 1.414 * 120 = 170$ v

$V_{orms} = V_{irms} \sqrt[2]{K} = V_{im} \sqrt[2]{K} = 120 \sqrt[2]{0.25} = 120 * 0.5 = 60v$

$I_{orms} = \frac{Vorms}{RL} = \frac{60}{10} = 6A$

$P_o = I^2_{orms} * R_L = 6^2 * 10 = 360Watt$

$P_i = Virms * Iirms = 120 * 6 = 720Watt$

$PF = \frac{Po}{Pi} = \frac{360}{720} = 0.5$

Or, $PF = \sqrt[2]{K} = \sqrt[2]{0.25} = 0.5$

2- Phase difference Control

2.1 Single phase AC voltage Controller

2.1.1 Half-wave Controller

Waveforms shows the principle of the circuit work

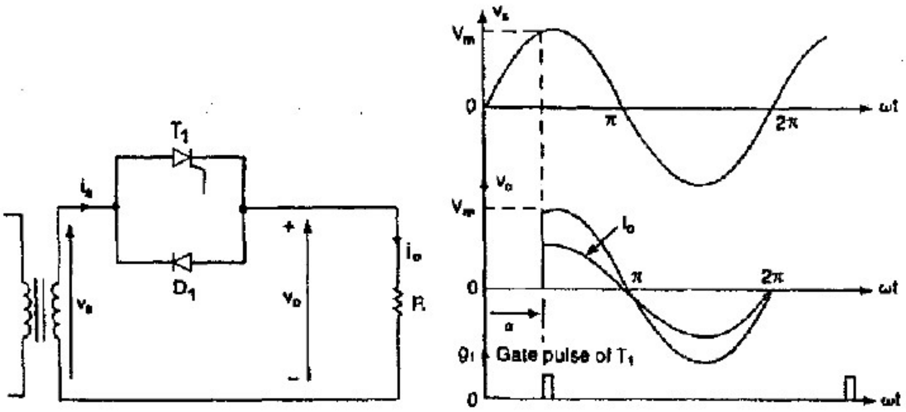


Fig. Phase difference Half-wave Controller

The equation for the average voltage and the effective value of the voltage in the output can be written as follows:

$$V_{dc} = \frac{\mathbf{Vm}}{\mathbf{2\pi}}(\mathbf{cos}(\propto) - \mathbf{1})$$

$$V_{orms} = V_{irms} * \sqrt{\frac{\{2\pi \quad \propto + \frac{1}{2}\sin(2\propto)\}}{2\pi}}$$

When α is changed from 0 to π then V_{orms} shall change from V_{irms} to $\frac{Virms}{\sqrt{2}}$ and Vdc from 0 to $(-\frac{\sqrt{2}\,Virms}{\pi})$

Example 2:

a single-phase voltage half-wave controller is connected with a 10Ω load, the supply voltage is V_{irms} =120 volts and the frequency is f=50 Hz if the triggering angle was $\frac{\pi}{2}$. Find the following:

1- The effective value of the output voltage
2- The power factor of the input circuit
3- The average value of input current

$$V_{orms} = V_{irms} * \sqrt{\frac{\{2\pi - \propto + \frac{1}{2}\sin(2\propto)\}}{2\pi}} = V_{irms} * \sqrt{\frac{\{2\pi - \frac{\pi}{2} + \frac{1}{2}\sin(\pi)\}}{2\pi}} = 120 * \sqrt{\frac{3}{4}} = 104v$$

$$I_{orms} = \frac{Vorms}{RL} = \frac{104}{10} = 10.4A$$

$$P_o = I^2_{orms} * R_L = 10.4^2 * 10 = 1080Watt$$

$$P_i = V_{irms} * I_{irms} = 120 * 10.4 = 1248Watt$$

$$PF = \frac{Po}{Pi} = \frac{1080}{1248} = 0.866$$

$$\text{Or, } PF = \frac{Vor * Iorms}{Virm * Iirm} = \frac{Vorms}{Virms} = \sqrt{\frac{3}{4}} = \sqrt[2]{0.75} = 0.866$$

$$V_{dc} = \frac{\mathbf{Vm}}{\mathbf{2\pi}}(\mathbf{cos}(\propto) - \mathbf{1}) = \frac{\sqrt{2}\,\mathbf{Virms}}{\mathbf{2\pi}}\left(\mathbf{cos}\left(\frac{\pi}{2}\right) - \mathbf{1}\right) = \frac{\sqrt{2}*\mathbf{120}}{\mathbf{2\pi}}(\mathbf{0} - \mathbf{1}) = -27v$$

$$I_{dc} = \frac{Vdc}{RL} = \frac{-2}{10} = -2.7A$$

2.1.2 Full-wave Controller

There is a phase difference of 180 degrees between triggering angles of the thyristors T1 and T2. It is also possible to obtain a full wave single-phase voltage control circuit, using one thyristor and four diodes connected in a bridge as shown in the figure,

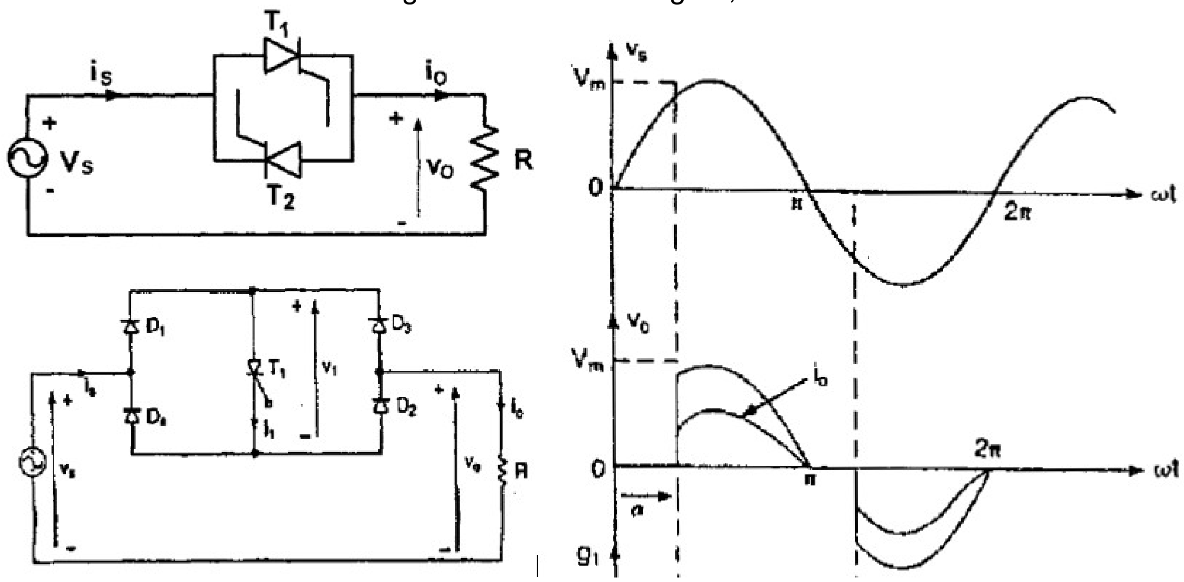


Fig. full wave single-phase voltage control circuits and waveforms

The equation for the average and effective value of the output voltage can be written as follows:

$$V_{dc} = \frac{\mathbf{Vm}}{\boldsymbol{\pi}}(\mathbf{cos}(\propto) + \mathbf{1})$$

$$V_{orms} = V_{irms} * \sqrt{\frac{\{\pi - \propto + \frac{1}{2}\sin(2\propto)\}}{\pi}}$$

When α is changed from 0 to π then V_{orms} shall change from V_{irms} to 0 and Vdc from $\frac{2Vm}{\pi}$ to 0

Example 3:

a single-phase voltage full-wave controller is connected with a 10Ω load, the supply voltage is V_{irms} =120 volts and the frequency is f=50 Hz if the triggering angle was $\frac{\pi}{2}$. Find the following:

1- The effective value of the output voltage
2- The power factor of the input circuit
3- The average value of input current

$$V_{orms} = V_{irms} * \sqrt{\frac{\{\pi - \propto + \frac{1}{2}\sin(2\propto)\}}{\pi}} = V_{irms} * \sqrt{\frac{\{\pi - \frac{\pi}{2} + \frac{1}{2}\sin(\pi)\}}{\pi}} = 120 * \sqrt{\frac{1}{2}} = 85v$$

$$I_{orms} = \frac{Vorms}{RL} = \frac{85}{10} = 8.5A$$

$$P_o = I^2_{orms} * R_L = 8.5^2 * 10 = 720Watt$$

$$P_i = V_{irms} * I_{irms} = 120 * 10.4 = 1018Watt$$

$$PF = \frac{Po}{Pi} = \frac{720}{1018} = 0.707$$

$$Or, PF = \frac{Vorms * Iorms}{Vir \quad * Iirms} = \frac{Vorm}{Virms} = \sqrt{\frac{1}{2}} = \sqrt[2]{0.5} = 0.707$$

$$V_{dc} = \frac{\mathbf{Vm}}{\boldsymbol{\pi}}(\mathbf{cos}(\propto) + \mathbf{1}) = \frac{\sqrt{2}\,\mathbf{Virms}}{\boldsymbol{\pi}}\left(\mathbf{cos}\left(\frac{\pi}{2}\right) + \mathbf{1}\right) = \frac{\sqrt{2} * \mathbf{120}}{\boldsymbol{\pi}}(\mathbf{0} + \mathbf{1}) = 54v$$

$$I_{dc} = \frac{Vdc}{RL} = \frac{54}{10} = 5.4A$$

2.2 Three phase AC voltage controllers:

2.2.1 Three phase Half wave voltage controllers

A Three phase Half wave voltage controller is shown in figure. The current passing through the load can be controlled by controlling the thyristors and the diodes provide the return of the current .

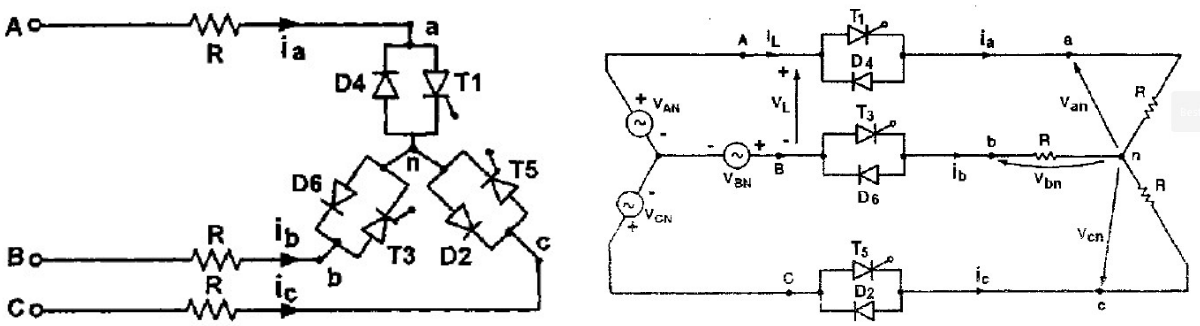
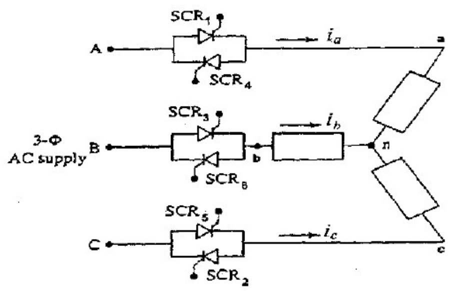
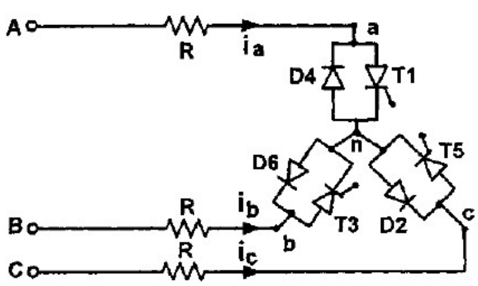


Fig. Half wave 3-phase voltage control circuits

2.2.2 Three phase Full wave voltage controllers (Delta and Star connections)

Triggering angle is $0° \leq \alpha < 150°$





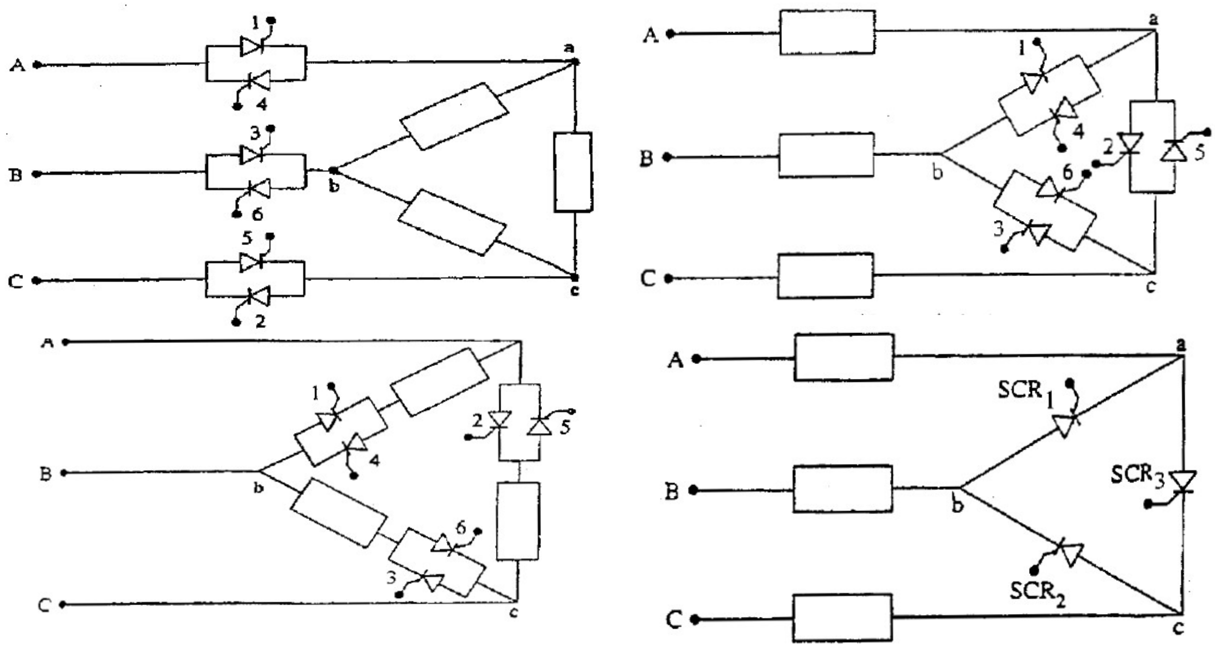


Fig. Full wave 3-phase voltage control circuits

The three-phase voltage controllers, the star and delta connection of the full wave .
Triggering angle is $0° \leq \alpha < 150°$

Cycloconverter:

To convert AC voltage into DC voltage, a rectifier is used and then converting the DC voltage into AC voltage with variable frequency by using an inverter. A two-stage converter is used.
A cycloconverter is a converter that converts an AC voltage of a certain frequency into an AC voltage at a different frequency without the use of another converter. The commutation is mostly natural or line commutation and the output frequency is a partial of the frequency of the input. These cycloconverters are used to control the speed of the AC motors with a frequency from zero to 20 hertz.

Types of cycloconverter

1-single phase/ single phase cycloconverter:

it consists of two bridges. The first bridge gives the load positive half wave, while the second bridge supplies the load with negative half wave. A center tapped transformer can also be used to build a cycloconverter as shown in Figure

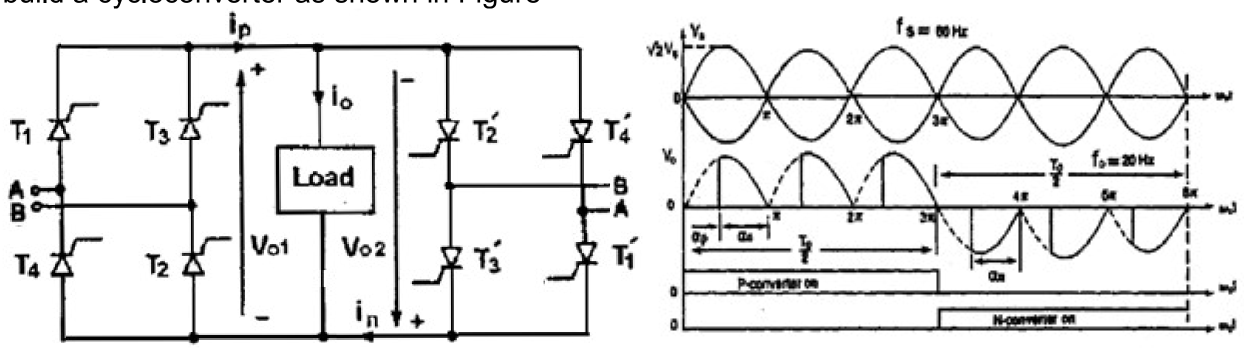


Fig. cycloconverter consists of two bridges

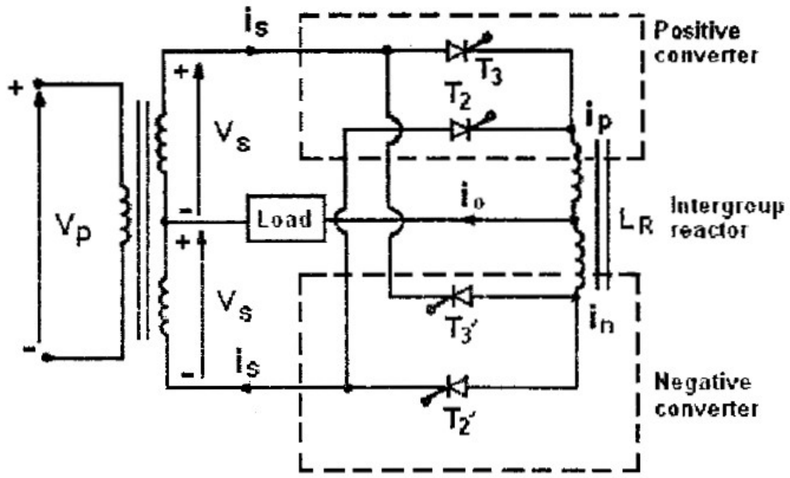


Fig. cycloconverter consists of center tapped transformer

2-Three phase/ single phase cycloconverter:

Three-phase source while the load is a single phase as in Figure

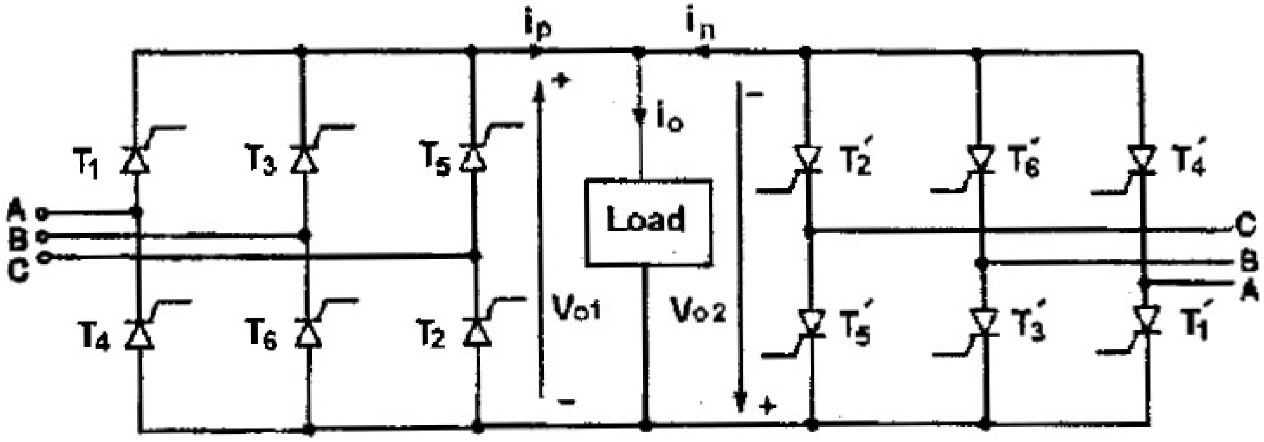
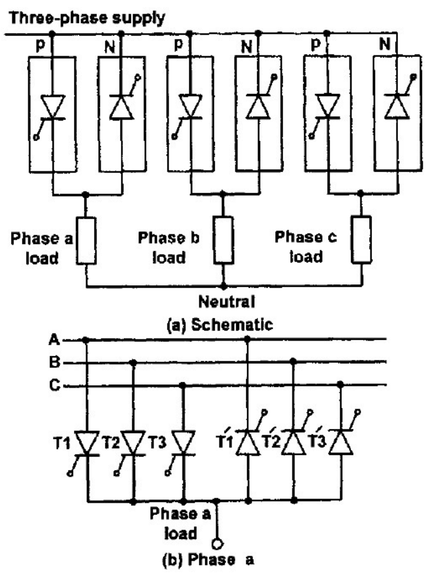


Fig. Three phase/ single phase cycloconverter consists of of two 3-phase bridges

3-Three phase/ Three phase cycloconverter:

There are 3 P-N pairs in schematic figure (a). Each pair consists of 6 thyristors and is represented by the underneath figure (b)



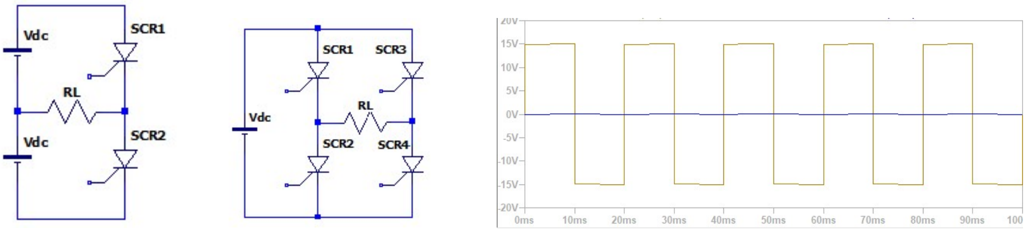
Inverters (DC to AC Converters)

The output of the inverter can be variable/ fixed AC voltage with variable/fixed frequency.
These can be single phase or three phase inverter depending on the supply voltage. These converters are mainly divided into two groups. One is PWM based inverters and other multilevel inverters.
Inverter applications:-

1- Driving AC instalations from a dc supply such as a sun panels or battary dc voltage.
2- DC to AC with AC to DC convertor in transmission line.

1- Half Bridge Inverter:

It uses two power supplies. When thyristor 1 is conducting then the load voltage is Vdc and when thyristor 2 is conducting then the load voltage is -Vdc.



Fig(58) (a) Half Bridge Inverter, (b) Bridge Inverter and (c) Output waveforms.

2- Bridge Inverter

The bridge inverter functions similar to half bridge inverter but it uses a single power supply.

Single phase bridge inverter with inductive load:
Four freewheeling diodes are required to handle the induced emf of the inductive load.

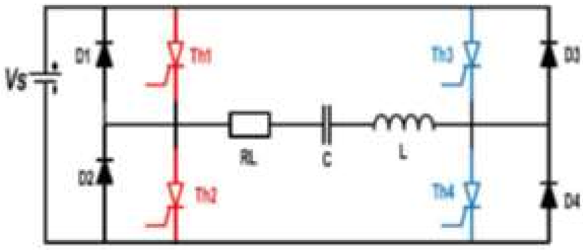


Fig (59) single phase bridge rectifier

3- Parallel Inverter:-

A center-tapped transformer is used. When Th1 is ON then the current flows in the load in one direction and when Th2 is ON then the current flows in the opposite direction. Th1 and Th2 should not conduct similtaniously.

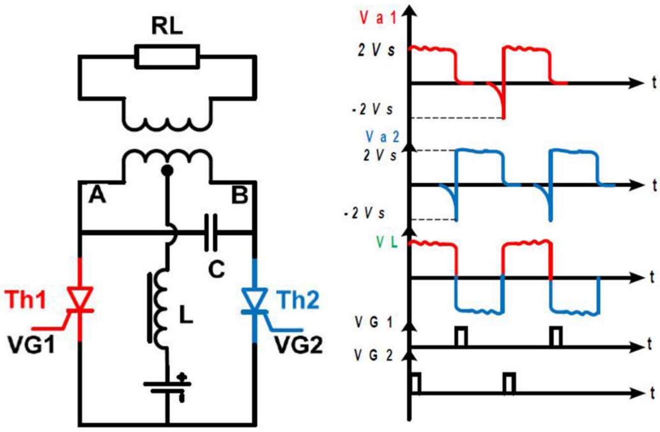


Fig (60) parallel inverter

$$Fm = \frac{n^2}{48\ x\ C\ x\ R_L}$$

$$0.25 < \frac{t_{on}}{t_{off}} < 3.34$$

$$t_{on} = \frac{4\ x\ C\ x\ R_L}{n^2}$$

$$t_{off} = \frac{L\ x\ n^2}{R_L}$$

$t_{on} > 2*t_q$

Where,

F_m = maximum frequency

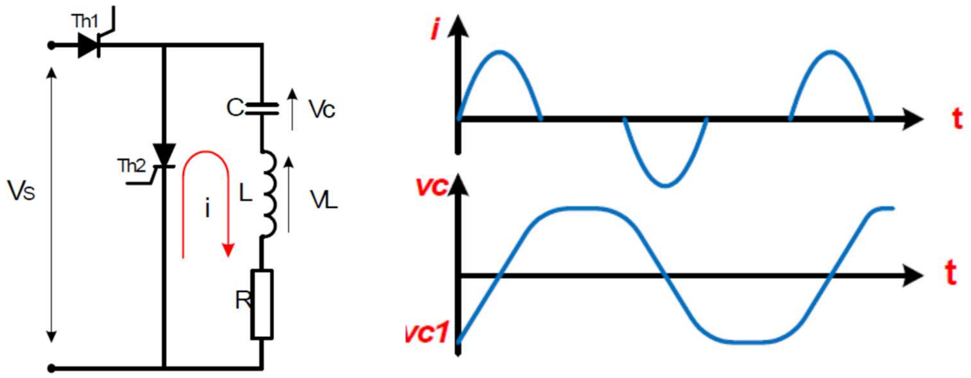
n = transformation ratio $n = \frac{V_2}{V_1} = \frac{N_2}{N_1}$

t_{on} = on time
t_{off} = off time
t_q = thyristor commutation time.

Example1. Design a parallel inverter to generate square wave with frequency of (f = 400Hz) to feed a resistive load of (120W) and voltage of (240V). the battery voltage 12V.

$$P = \frac{V^2}{R_L}$$
$$R_L = \frac{V^2}{P} = \frac{(240)^2}{120} = 480\Omega$$
$$n = \frac{V2}{V1} = \frac{240}{12} = 20$$
$$Fm = \frac{n^2}{48\,x\,C\,x\,R_L}$$
$$C = \frac{n^2}{48\,x\,F_m\,x\,R_L} = \frac{(20)^2}{48\,x\,400\,x\,480} = 43\mu F \approx 47\mu F$$
$$t_{on} = \frac{4\,x\,C\,x\,R_L}{n^2} = \frac{4\,x\,47\,x\,10^{-6}\,x\,480}{(20)^2} = 225.6\mu sec$$
$$\text{Choose } \frac{t_{on}}{t_{off}} = 3$$
$$t_{off} = \frac{t_{on}}{3} = \frac{225.6}{3} = 75.2\ \mu sec$$
$$t_{off} = \frac{L\,x\,n^2}{R_L}$$
$$L = \frac{t_{off}\,x\,R_L}{n^2} = \frac{75.2\,x\,10^{-6}\,x\,480}{(20)^2} = 90.24\mu H$$
$$t_q = \frac{t_{on}}{2} = \frac{225.6}{2} = 112.8\ \mu sec$$

4- series inverter:-



Fig(61) Series inverter

$$L = \frac{R}{2}\,x\,\frac{\pi}{\omega_d} \qquad (\mu H)$$
$$C = \frac{4\,L}{4L^2\omega_d{}^2 + R^2} \qquad (\mu F)$$
$$V_s = \frac{\pi}{3} I_m\,R$$
$$\frac{T}{2} = \frac{\pi}{\omega_d} + t_q$$
Where,
$\omega_d = 2\pi f_d$ = resonance frequency

$I_m = maximum\ current$
$V_s = dc\ supply\ voltage$

Example 2: Design a series inverter which supplies maximum current (1A) to a resistive load of (150Ω) and frequency (f=400Hz) the thyristor turns off time t_q=25 μsec

$$T = \frac{1}{F} = \frac{1}{400} = 2.5msec$$
$$\frac{T}{2} = \frac{\pi}{\omega_d} + t_q$$
$$\frac{\pi}{\omega_d} = \frac{T}{2} - tq = \frac{2500}{2} - 25 = 1225\mu sec$$
$$\omega_d = \frac{\pi}{1225\ x\ 10^{-6}} = \frac{3.14}{1225\ x\ 10^{-6}} = 2.56\ x\ 10^3 rad/sec$$
$$L = \frac{R}{2}\ x\ \frac{\pi}{\omega_d} = \frac{150}{2}\ x\ \frac{3.14}{2.56\ x\ 10^3} = 92mH$$
$$C = \frac{4\ L}{4L^2{\omega_d}^2 + R^2} = \frac{4\ x\ 92\ x\ 10^{-3}}{4\ x\ (92\ x\ 10^{-3})^2\ x\ (2.56\ x\ 10^3)^2 + (150)^2}$$
$$C = 15.7\ \mu F \cong 16\mu F$$
$$V_s = \frac{\pi}{3} I_m\ R =$$
$$V_s = \frac{3.14}{3}\ x\ 1\ x\ 150 = 157V$$

Three phase bridge inverter:

The load is a three-phase load connected as star or delta. Six freewheeling diodes are required for inductive load to handle the induced emf of the inductive load.

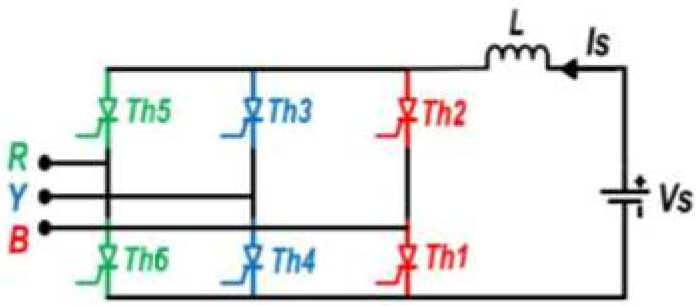


Fig (62) Three phase bridge inverter

Speed control of DC motor

We will study some practical and industrial applications of controlled rectifiers, DC choppers and .inverters such as speed control of DC motors and induction motors
The controlling of the speed of DC motors with separate feeding is in the primary practical applications in the use of controlled single or three phases rectifiers. The importance of using this kind of motors comes because of their ease of control and the wide range of this control in addition to the ease of writing linear mathematical models for them, and as it is known that the easiest and fastest way to control the speed of the DC motor is to control the value of the armature voltage and that requires feeding the motor from DC generator with variable field supply to obtain a variable DC voltage, but in the past thirty years and with the advancement and development of these controlled rectifiers, the expensive DC generators can be replaced by these rectifiers that operate on single and three phase alternating current from which the DC voltage can be obtained with variable value depending on the angle of ignition alpha
.

Speed control of a DC motor using 1-phase controlled rectifiers

Figure (62) shows a separately excited DC motor that is fed from a single-phase alternating current source with the use of a single-phase controlled rectifier. Figure (63) shows the waveforms of voltage at the motor terminals and the current passing through it. As a result of the presence of a high inductance in the armature of the motor, the armature current shall be continuous and the commutation angle $\beta = \pi + \alpha$. Therefore, the average value of the voltage on the armature of the :motor, considering continuous current, will be as follows

$$V_a(\alpha) = \frac{2\sqrt{2}}{\pi} Vs * cos(\alpha) \qquad \text{-----------1}$$

From this equation we find the value of average voltage is a function of the triggering angle α. where triggering angle α is changed from 0º to 180º,

V_a (α) is positive and the motor in Forward rotation direction when α < 90º,

V_a (α) = 0 and Motor speed =0 if α = 90º

V_a (α) is negative and reversed rotation direction when α > 90º.
If the freewheel diodes are used or a half-controlled rectifier is used then the negative output voltage is omitted and the reverse rotation of the motor is no longer exist.

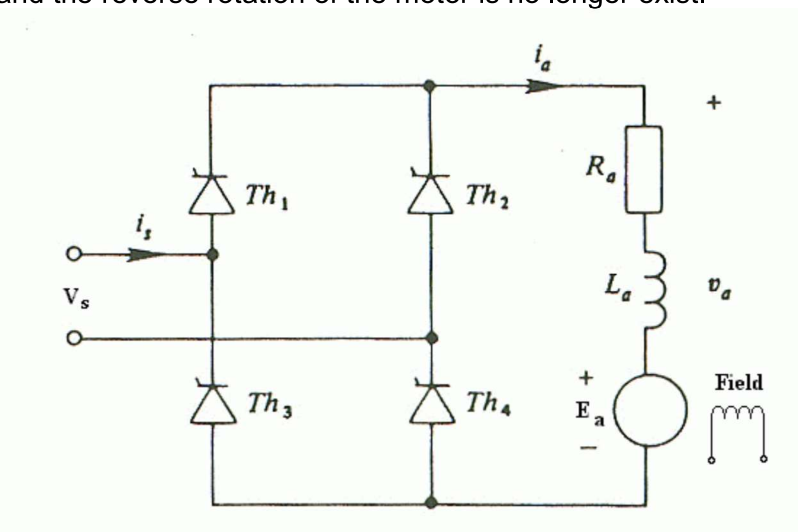


Fig.(62) Separately excited DC motor with a single-phase controlled rectifier

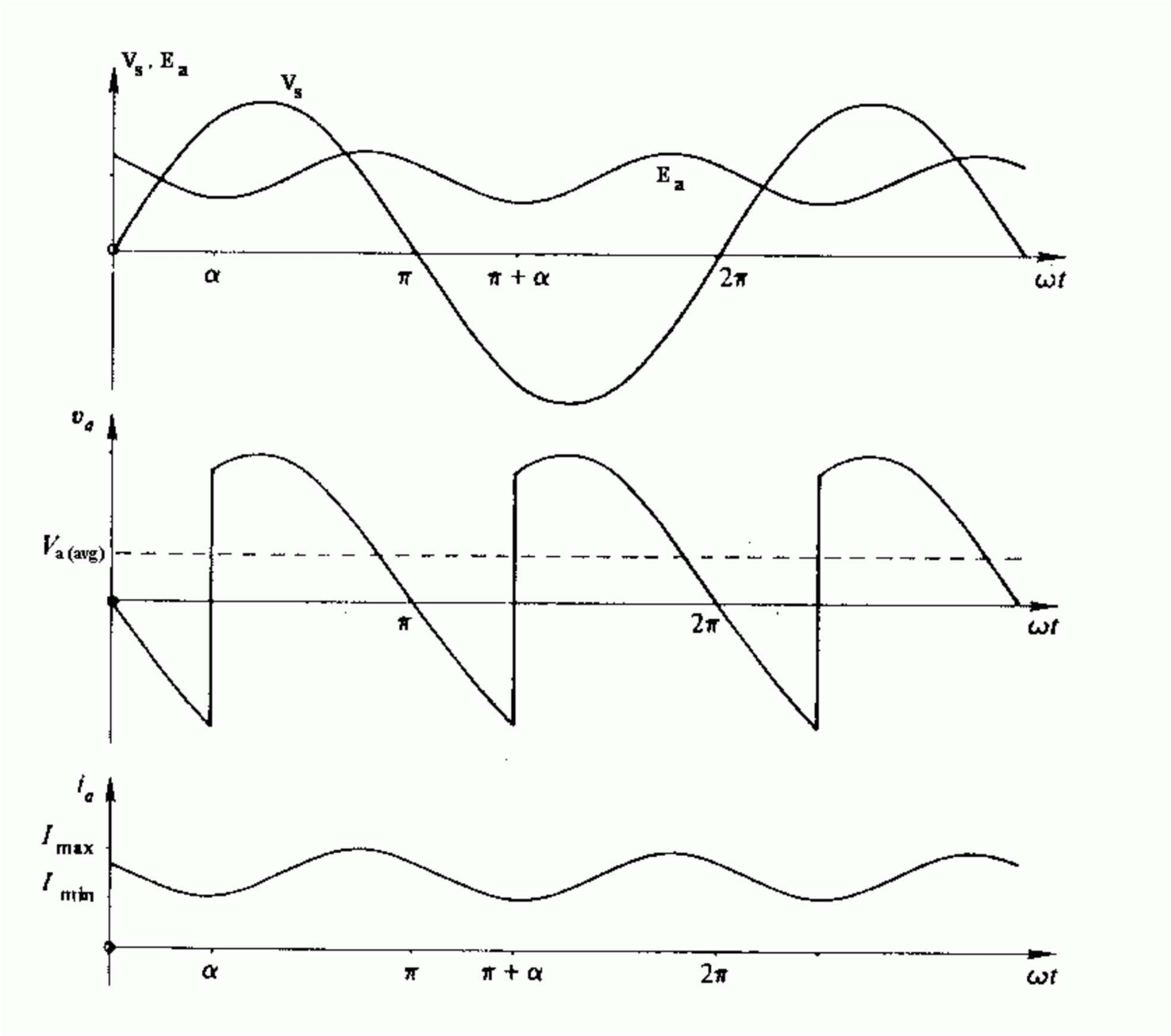


Fig.(63) Input and output voltage waveform

The relationships of a dc motor are the following:

$$\omega = \frac{2\pi N}{60} \quad \text{-------------2}$$

where ω and N are the angular velocity in radians/second or (rad/sec) and rotation velocity in revolutions/minute or (rev/min) or (RPM)

$E_a = K.\Phi.\omega = K_b.\ \omega$ -------------3

$T_a = K.\Phi.I_a = K_T.\ I_a$

$I_a = T_a / K_T$ -------------4

$V_a = E_a + R_a.I_a$

$E_a = V_a - R_a.I_a$ -------------5

Where V_a, I_a, T_a and R_a are the armature voltage in (v), current in (A), Torque in (N.m) and winding's resistance in (Ω).

E_a is the armature back emf in (v),

Φ is the magnetic flux from the field windings which is constant due to the separately field fed,

K, K_b and K_T are constants.

Substituting equation 3 & equation 4 in equation 5 results

$K_b.\ \omega = V_a - R_a.T_a / K_T$

$\omega = \frac{Va}{Kb} - \frac{Ra}{Kb.KT}.Ta$ -------------6

The values of (K_T) and (K_b) are equal and depend on the number of poles (P), magnetic flux (Φ), number of conductors in armature winding(Z) and number of parallel paths (a)

$K_T = K_b = \frac{PZ\Phi}{2\pi a}$ ---------------7

The relation between the speed of motor and the triggering angle can be obtained from substituting equation 1 & equation 6 which results as follows:

$\omega = \frac{2\sqrt{2}}{\pi.Kb} Vs * cos(\alpha) - \frac{Ra}{Kb.KT}.Ta$ -------------8

On no-load Ta = 0 and ω = ωo

$\omega o = \frac{2\sqrt{2}}{\pi.Kb} Vs * cos(\alpha)$

Then eq. 8 can be rewritten as

$\omega = \omega o - \frac{Ra}{Kb.KT}.Ta$ -------------9

Example 1

A separately excited DC motor of nominal speed of 1200 rpm can be controlled by a single-phase controlled rectifier as shown in Figure 62. The full load current is I_a = 38 A and its armature resistance R_a = 0.3 Ω and supply voltage Vs = 260v. The motor constants for voltage and torque are $K_b = K_T$ = 1.74 and considering that the reluctance of the motor is sufficient for the current to be continuous, find at a triggering angle of 30 degrees the following:

- The motor torque at full load
- The motor speed at the full load
- The power factor of the source

Solution

a- The motor torque at full load can be found using the equation 4 as follows.

$T_a = K_T.\ I_a = 1.74 * 38 = 66.121$ N.m

b- The motor speed at the full load can be found using the equation 8 as follows.

$\omega = \frac{2\sqrt{2}}{\pi.Kb} Vs * cos(\alpha) - \frac{Ra}{Kb.KT}.Ta = \frac{2\sqrt{2}}{\pi*1.74} 260 * cos(30) - \frac{0.3}{1.74*1.74}.66.121$

$\omega = 116.56 - 6.55 = 110$ rad / sec

The motor speed at the full load can be found using the equation 2 as follows

$N = \frac{60\omega}{2\pi} = \frac{60*110}{2\pi} = 1051$ rpm

c- The power factor of the source can be found using the following equation.

$PF = \frac{Va.Ia}{Vs.Is}$

since the average value of the motor current I_a is approximately equal to the effective value of the supply current I_s as the motor current is almost constant and continuous and thus can be seen the power factor value as follows

$I_a = I_s$

$PF = \frac{Va}{Vs}$

From eq. 1

$Va(\alpha) = \frac{2\sqrt{2}}{\pi} Vs * cos(\alpha)$

$PF = \frac{Va}{Vs} = \frac{2\sqrt{2}}{\pi} * cos(\alpha) = \frac{2\sqrt{2}}{\pi} * cos(30) = 0.78$

Speed control of a DC motor using DC choppers

The speed of a DC motor can also be controlled using a complete DC chopper shown in Figure (63) where the motor is fed from the output of the chopper, the output voltage of the chopper can be controlled by controlling the operating cycle of the chopper. The output voltage in the chopper can be calculated from the following relationship:

$Va = D\ Vs$

where D is the operating cycle.
The motor current can be either continuous or discontinuous depending on the operating cycle value.

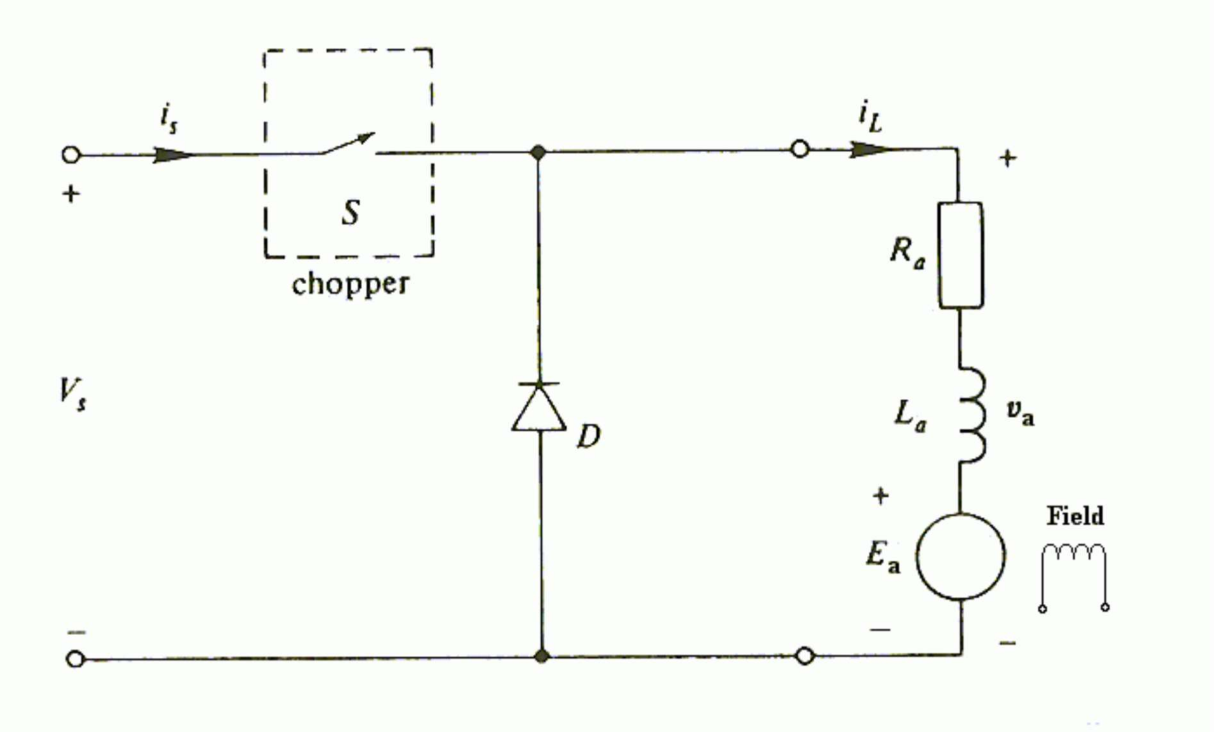


Fig.(64) DC motor drive with separate feeding with DC

Example 2

A DC chopper is fed from 150 volt and supply a separately excited DC motor. If the constant factors of the DC motor are as follows:

R_a = 0.5Ω, L_a = 10 mH and K_b =0.05 v/rpm

Find the frequency of the chopper when conduction time (T_a=1.6 ms) at a revolution speed of (N = 2000rpm) if the armature current was constant (I_a = 40A)

Solution:

The output voltage of the chopper can be calculated from eq 3 and eq. 5

$E_a = K.\Phi.\omega = K_b.\ \omega$ -------------3

$V_a = E_a + R_a.I_a = K_b.\ \omega + R_a.I_a$ -------------5

$V_a = 0.05\ v/rpm * 2000\ rpm + 0.5\Omega * 40A = 100v + 20v = 120v$

The duty cycle can be calculated as follows:

$$D = \frac{Va}{Vs} = \frac{120}{150} = 0.8$$

The frequency of the chopper can be calculated as follows:

$$D = \frac{Ton}{T}$$

$$F = \frac{1}{T} = \frac{D}{Ton} = \frac{0.8}{0.0016} = 500\ Hz$$

Speed Control of Three Phase Induction Motor

In the three-phase induction motor, three coils are disposed in positions displaced 120 electrical degrees of the phase difference.

When a three-phase AC power supply is connected here, the current flowing in each coil has a 120-degree phase difference one another. This generates a rotating magnetic field to rotate the rotor with synchronous speed Ns.

At this time, the rotor rotates at a speed N, slightly slower than that of the rotating magnetic field. This ratio of the rotor's speed to the rotating magnetic field's speed is called 'slip'.

Before discussing the methods to control the speed of three phase induction motor one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas.

Synchronous Speed

$$Ns = \frac{120f}{P}$$

Where,

f = frequency, P is the number of poles and Ns is the synchronous speed.

The speed of induction motor is given by,

$N = N_s(1-s)$, $s = \frac{Ns-N}{Ns}$

Where,

N is the running speed of the rotor of an induction motor an s is the slip.

The torque produced by three phase induction motor is given by,

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2R_2}{R_2^2+(sX_2)^2}$$

When the rotor is at standstill slip, $s = 1$. So the equation of torque at $s = 1$ is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2R_2}{R_2^2+X_2^2}$$

Output Power(Watt) = ω (rad/sec) x Torque (N.m)

$$\omega = \frac{2\pi N}{60}$$

HP= 746 Watts

Where,

E_2 is the rotor emf, R_2 is the rotor resistance and X_2 is the rotor inductive reactance.

The speed control of three phase Induction Motor is changed from Both Stator and Rotor Side.

1. Speed Control from Stator Side: they are further classified as :

1.1. *Controlling Supply Voltage*

Since rotor resistance, R_2 and inductance, X_2 are constant so the torque produced by running three phase induction motor is given by

$T \propto sE_2^2$
We know that rotor induced emf $E_2 \propto V$. So,

$T \propto sV^2$
The equation above clears that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same, and it is only possible if we increase the slip and reduce speed of the motor. This method of speed control is rarely used because a decreasing the speed requires a reduction in voltage, and hence the ***current*** drawn by motor increases, which cause ***overheating*** of the induction motor.

1.2. *Controlling Supply Frequency*

Ns depends on supply frequency. However, this method is not widely used. It may be used where; the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance ($X_L=2\pi fL$). And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

1.3. *Voltage and frequency (V/f) control.*

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

$$N_s = \frac{120f}{P}$$

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E\ or\ V = 4.44\, \Phi . K . T . f \quad or \quad \Phi = \frac{V}{4.44\, K . T . f} \quad or \quad \Phi \propto \frac{V}{f}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor. In another words with decrease in frequency X_L will decrease and this change further cause increase in no load current of the motor. So, it is important to maintain flux, φ constant and it is only possible if we change voltage and frequency simultaneously causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using ***converter*** and ***inverter*** set. It is called Variable Frequency Drive method or VFD methode.

1.3.1. Inverter Drive Method:

Figure 2-2 shows a configuration diagram of the three-phase induction motor driven by an inverter. Three-phase output pins of the inverter are connected to the coils of the motor.

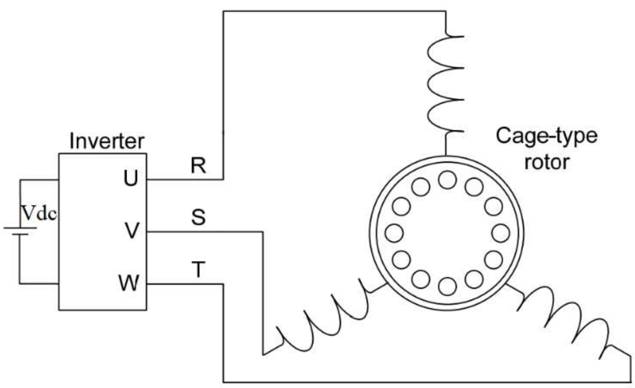


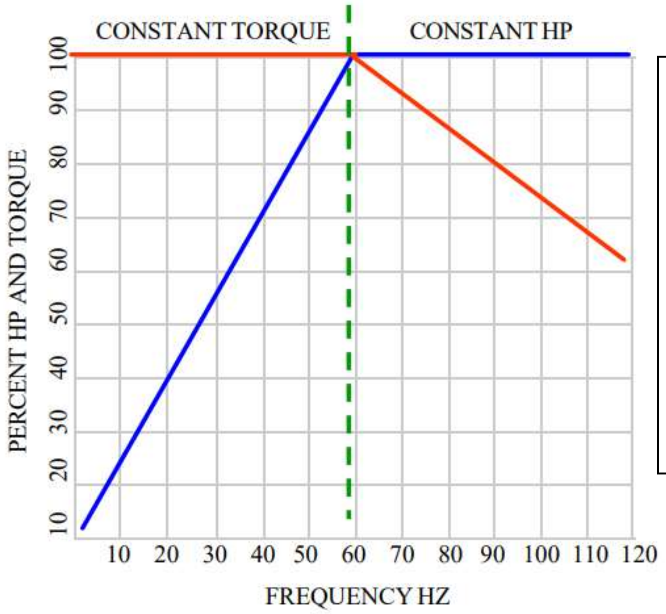
Figure 2-2 Configuration Diagram of Inverter Drive

1.3.2. PWM Drive Characteristics

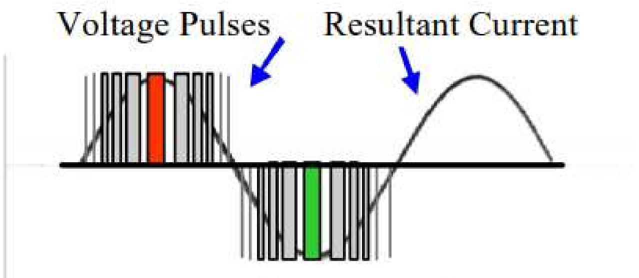
- VFD supply Vdc is constant. ·
- Pulse amplitude is constant over entire frequency range and equal to the Vdc.
- Lower resultant voltage is created by more and narrower pulses.
- Higher resultant voltage is created by fewer and wider pulses.
- Alternating current (AC) output is created by reversing the polarity of the voltage pulses. - Even though the voltage consists of a series of square-wave pulses, the motor current will very closely

approximate a sine wave. The inductance of the motor acts to filter the pulses into a smooth AC current waveform.

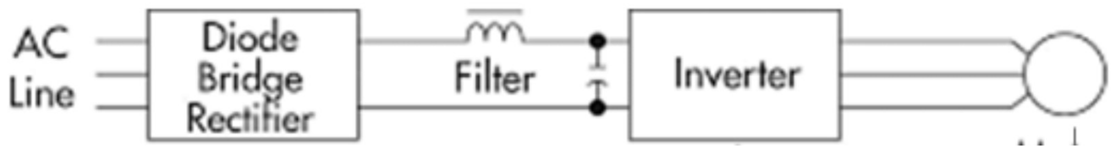
- Voltage to frequency ratio remains constant from 0 - 60 Hertz. For a 460v motor this ratio is 7.6 volts/Hz. To calculate this ratio, divide the motor voltage 460v by 60 Hz. At low frequencies the voltage will be low, as the frequency increases the voltage will increase. (Note: this ratio may be varied somewhat to alter the motor performance characteristics such as providing a low-end boost to improve starting torque.)
- For frequencies above 60 Hz the voltage remains constant. Some AC drives switch from a PWM waveform to a six-step waveform for 60 Hz and above. On most AC variable speed drives the voltage is held constant above the 60 hertz frequency. The diagram below illustrates this voltage/frequency relationship.

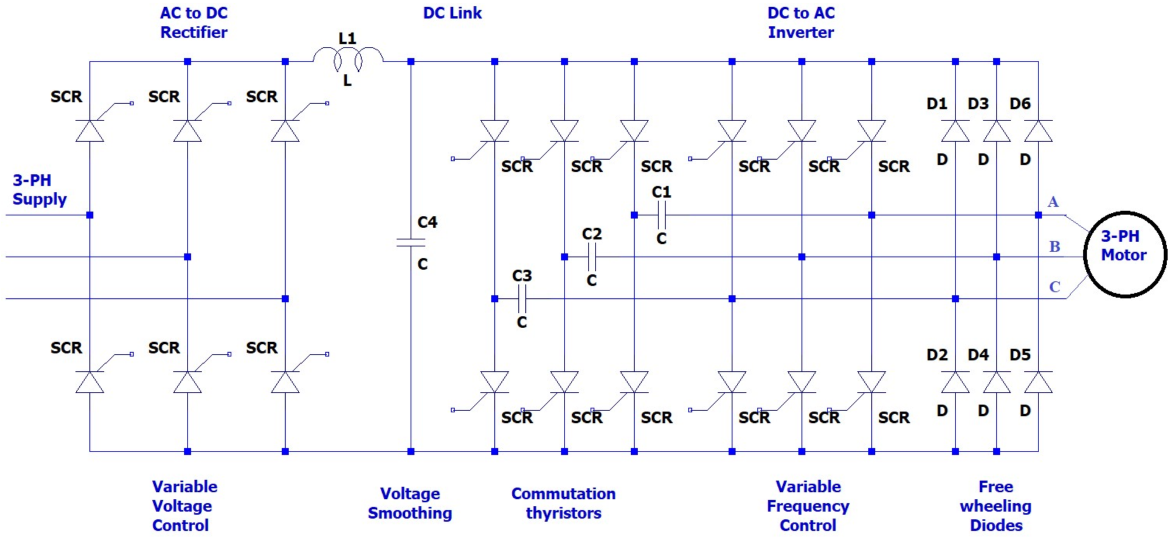


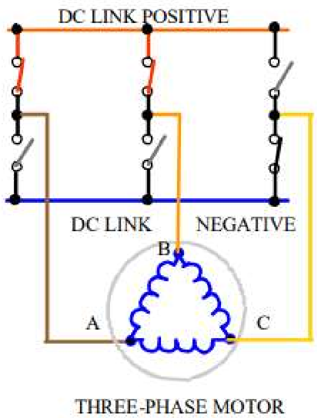
Blue = Horsepower
Red = Torque
Green = Motor Nameplate Frequency (60 Hz)
In Constant Torque Area - VFD supplies rated motor nameplate voltage and motor develops full horsepower at 60 hertz base frequency. In Constant Horsepower Area - VFD delivers motor nameplate rated voltage from 60 Hertz to 120 hertz (or drive maximum). Motor horsepower is constant in this range but motor torque is reduced as frequency increases.



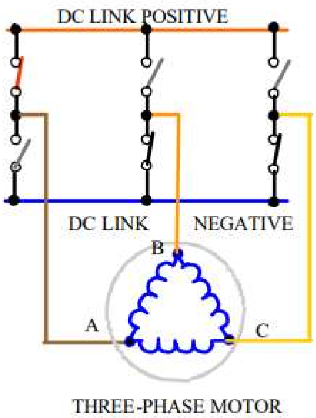
PWM Waveform Phase A to B



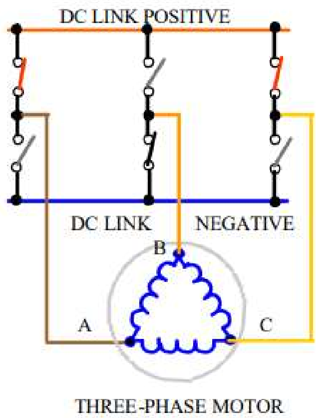




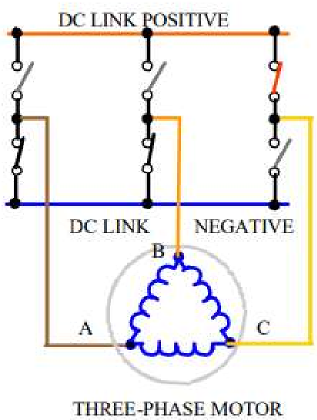
0 - 60 DEG
$V_{AB} = 0$
$V_{BC} = +E$
$V_{CA} = -E$



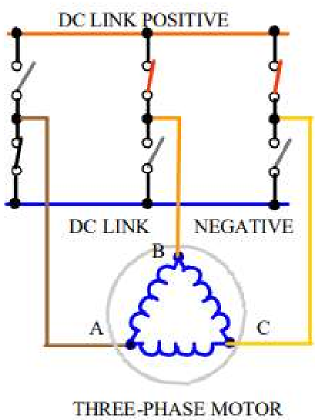
60 - 120 DEG
$V_{AB} = +E$
$V_{BC} = 0$
$V_{CA} = -E$



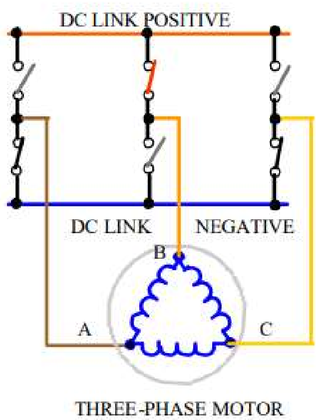
120 - 180 DEG
$V_{AB} = +E$
$V_{BC} = -E$
$V_{CA} = 0$



180 - 240 DEG
$V_{AB} = 0$
$V_{BC} = -E$
$V_{CA} = +E$

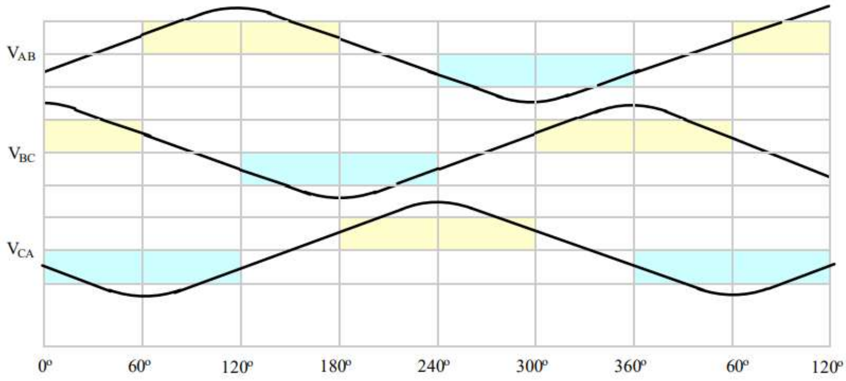


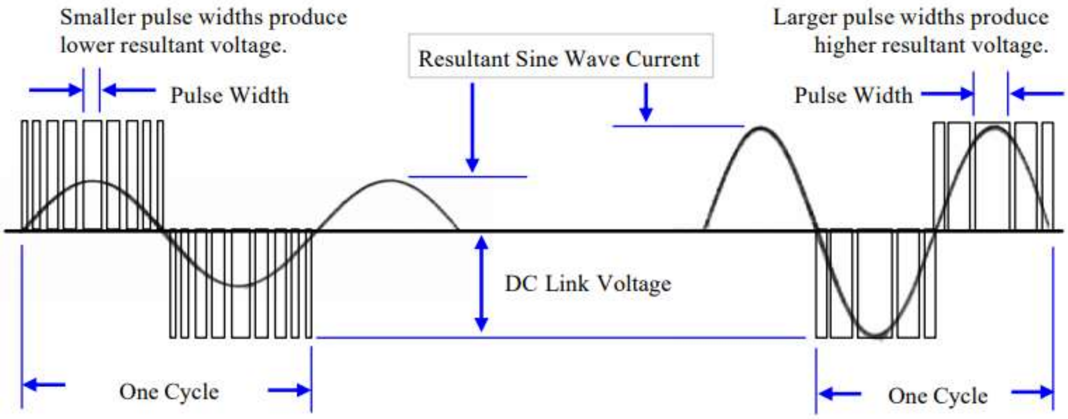
240 - 300 DEG
$V_{AB} = -E$
$V_{BC} = 0$
$V_{CA} = +E$



300 - 360 DEG
$V_{AB} = -E$
$V_{BC} = +E$
$V_{CA} = 0$

The development of a variable frequency drive three-phase waveform is shown below. Refer to the previous page to see the switching sequences that produce a particular portion of the waveform





1.4. Changing the number of stator poles:

Rotating magnetic field rotates at synchronous speed

$$N_s = \frac{120f}{P}$$

The motor rotates with a lower speed than Ns. The stator poles can be changed by two methods

1.4.1. Multiple stator winding method.

In this method of speed control of three phase induction motor, we provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. Disadvantages of this method are that the smooth speed control is not possible. This method is costlier and less efficient as two different stator windings are required. This method of speed control can only be applied to squirrel cage motor.

For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles. for supply frequency of 50 Hz. Calculate synchronous speed?

i) Ns when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM

ii) Ns when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

1.4.2. Pole Amplitude Modulation Method (PAM)

In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

Therefore the resultant mmf wave will have two different number of poles

$i.e\ P_{11} = P_1 - P_2\ and\ P_{12} = P_1 + P_2$

Therefore by changing the number of poles we can easily change the speed of three phase induction motor.

1.5. Adding Rheostat in Stator Circuit

In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped. In case of three phase induction motor torque produced is given by $T \propto sV_2^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

2. Speed Control from Rotor Side: they are further classified as:

2.1.Adding External Resistance on Rotor Side

In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The three-phase induction motor operates in a low slip region. In low slip region term $(sX)^2$ becomes very small as compared to R_2. So, it can be neglected. and also, E_2 is constant. So, the equation of torque after simplification becomes,

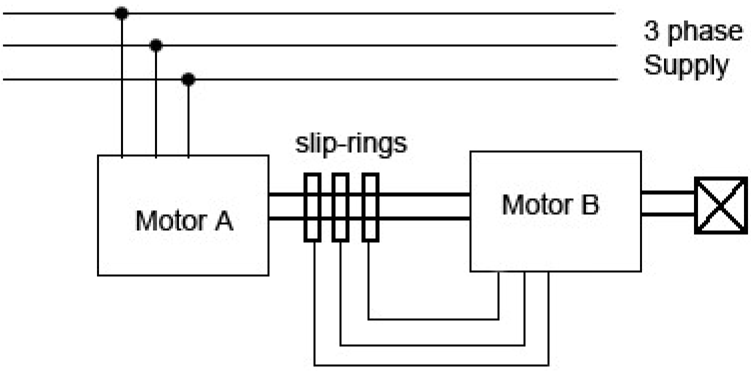
$$T \propto \frac{s}{R_2}$$

Now if we increase rotor resistance R_2, torque must remain constant to supply the same load. So, slip increases, which will further result in the decrease in rotor speed. Thus, by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

- The speed above the normal value is not possible.
- Presence of resistance causes more losses.
- Large speed change requires a large value of resistance, and it will cause large copper loss and hence reduction in efficiency.
- This method cannot be used for squirrel cage induction motor.

2.2. Cascade Control Method

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure.



Motor A is called the main motor and motor B is called the auxiliary motor.

Let, N_{SA} = synchronous speed of motor A
N_{SB} = synchronous speed of motor B
P_A = number of poles stator of motor A
P_B = number of stator poles of motor B
N = speed of the set and same for both motors
f = frequency of the supply

Now, slip of motor A, $S_A = (N_{SA} - N) / N_{SA}$.
frequency of the rotor induced emf in motor A, $f_A = S_A f$
Now, auxiliary motor B is supplied with the rotor induce emf

therefore, $N_{SA} = (120*f_A)/P_A = (120*f)/P_A$ and $\boldsymbol{P_A = (120f_A)/ N_{SA}}$

$N_{SA} = \frac{120*f}{P_A}$ And $P_A = \frac{120*f}{N_{SA}}$

$N_{SB} = \frac{120*f_B}{P_B} = \frac{120*S_A*f}{P_B}$ And $P_B = \frac{120*S_A*f}{N_{SB}}$

now putting the value of $S_A = \frac{N_{SA}-N}{N_{SA}}$ Hence $P_B = \frac{120*f(N_{SA}-N)}{N_{SB}*N_{SA}} = \frac{120*f*N_{SA}}{N_{SB}*N_{SA}} - \frac{120*f*N}{N_{SB}*N_{SA}}$

$$P_B = \frac{120*f}{N_{SB}} - \frac{120*f*N}{N_{SB}*N_{SA}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.
i.e. $N = N_{SB}$.

$$P_B = \frac{120*f}{N} - \frac{120*f}{N_{SA}}$$

from the above equations, it can be obtained that

$$P_A + P_B = \frac{120*f}{N_{SA}} + \frac{120*f}{N} - \frac{120*f}{N_{SA}} = \frac{120*f}{N}$$

$$N = \frac{120*f}{P_A + P_B}$$

With this method, four different speeds can be obtained

1. when only motor A works, corresponding speed = N_{SA} = 120f / P_A
2. when only motor B works, corresponding speed = N_{SB} = 120f / P_B
3. if cumulative cascading is done, speed of the set = N = 120f / (P_A + P_B)
4. if differential cascading is done, speed of the set = N = 120f (P_A – P_B)

2.3.Injecting Slip Frequency EMF into Rotor Side

In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of the slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with the rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled. The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved.

SCR Protection

For satisfactory and reliable operation, the specified ratings of an SCR should not be exceeded. Otherwise, there is a chance of damage permanently to the SCR.

SCR may face different types of threats during its operation like:

1. Over voltage.
2. Over current.
3. High dv/dt.
4. High di/dt.
5. High temperature.

Over Voltage Protection

Over voltages are the greatest causes of failure of SCRs. These transient over voltages often lead to unscheduled turn ON of the SCR. Also, may lead to the permanent destruction of the SCR if the reverse transient voltage is more than the V_{BR} across the SCR. Over voltages Due to:

- a high voltage transient of the supply.
- Lightning surges.
- high inductive load.
- a sudden operation of switches produces arc voltages.

To protect the SCR against the transient over voltages, a parallel R-C snubber network is provided for each SCR in a circuit.

Over Current Protection

During the short circuit conditions, over current flows through the SCR. a circuit breaker and/or fuse are used for protecting the SCR.

High dv/dt Protection

if the rate of forward voltage applied is very high across the SCR, then it causes to turn ON the SCR even without any gate signal. This is called as dv/dt triggering of the SCR which is generally not employed as it is false triggering process. Hence, the rate of rise of anode to cathode voltage, dv/dt must be in specified limit to protect the SCR against false triggering. This can be achieved by using RC snubber network across the SCR.

High di/dt Protection

If the rate of rise of anode current (di/dt) is high results a non-uniform spreading of current over the junction. Due to the high current density, this further leads to form local hot spots near the gate-cathode junction. This effect may damage the SCR due to overheating.

To prevent the high rate of change of current, an inductor is connected in series with thyristor. Typical SCR di/dt ratings are in range between 20- 500 ampere per microseconds.

High Temperature Protection

With the increase in the temperature of the junction, insulation may get failed. So we have to take proper measures to limit the temperature rise.
Protective Measure: We can achieve this by mounting the thyristor on heat sink which is mainly made by high thermal conductivity metals like aluminum (Al), Copper (Cu) etc. Mainly aluminum (Al) is used due to its low cost. There are several types of mounting techniques for SCR such as – Lead-mounting, stud-mounting, Bolt-down mounting, press-fit mounting, press-pack mounting etc.

Gate Protection of Thyristor

Gate circuit should also be protected from overvoltage and overcurrent.
Overvoltage: in the gate circuit can cause overcurrent and gate protection is achieved by using a Zener diode
Overcurrent: can cause high junction temperature and a resistor can be used to protect the gate circuit from overcurrent.
Noise: in gate circuit can also cause false triggering which can be avoided by using a resistor and a capacitor in parallel.
high reverse voltage: A diode (D) may be connected in series or in parallel with the gate to protect it.