Thirteen-seventeen weeks

Power transistor

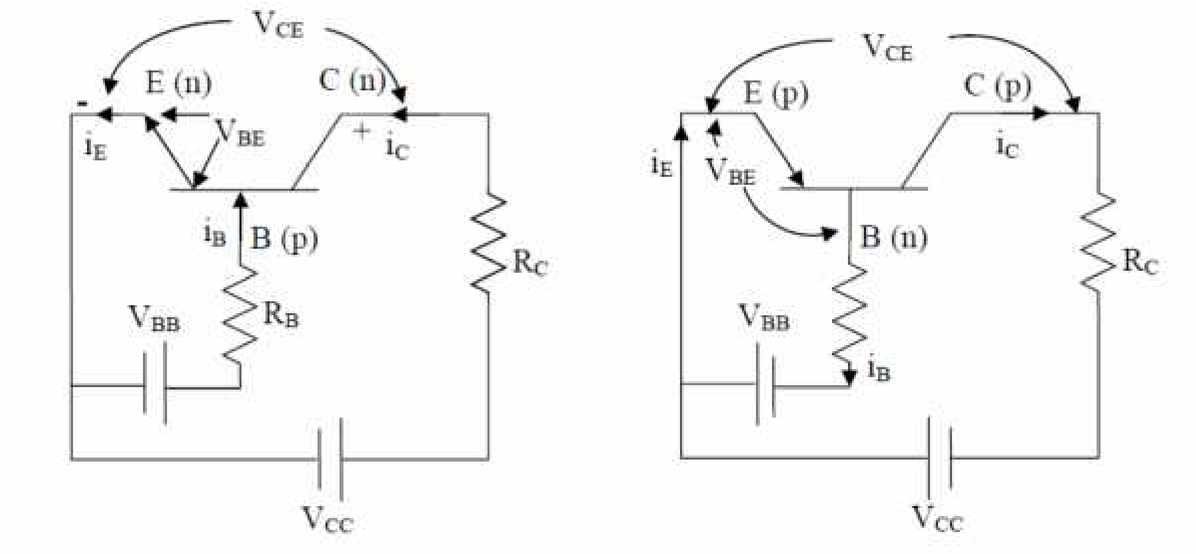
Power transistor has controlled characteristics, it turn on when the current signal given to the control terminal and stay at this case as signal found.

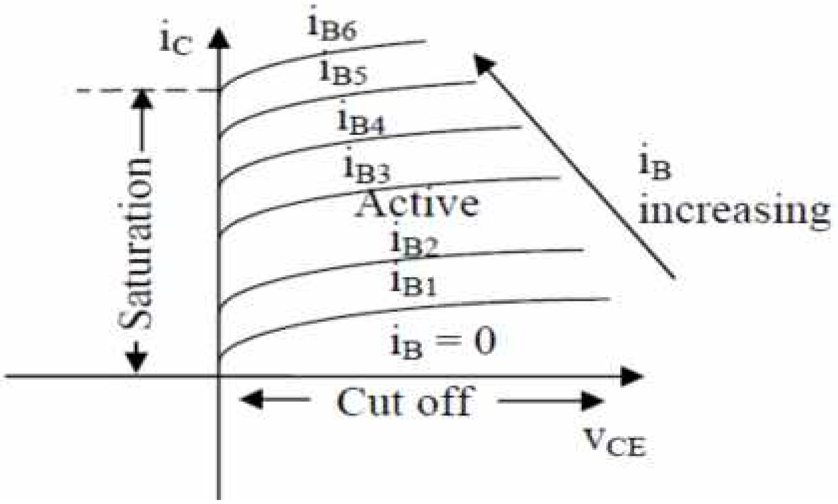
It has four types:

1- Bipolar junction transistor
2- Metal oxide semiconductor field effect transistor.
3- Insulated gate bipolar transistor
4- Static induction transistor

Bipolar junction transistor

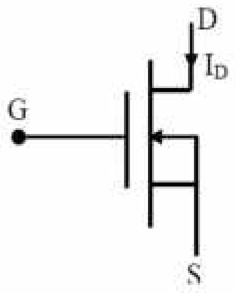
Power Bipolar Junction Transistor (BJT) is the first semiconductor device to allow full control over its Turn on and Turn off operations. It simplified the design of a large number of Power Electronic circuits that used forced commutated thyristors at that time and also helped realize a number of new circuits. It is three layers, two junctions pnp or npn, the term bipolar denotes that the current flow in the devices due to the movement the electrons and holes. It has three terminals, emitter, collector and base.



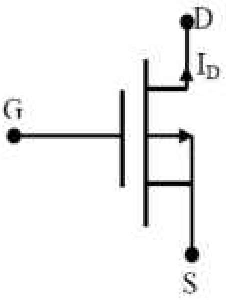


Metal oxide semiconductor field effect transistor.

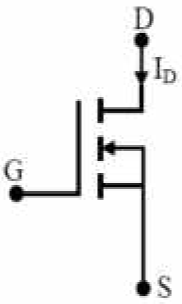
The operating principle a MOSFET is a voltage controlled majority carrier device. The movement of majority carriers in a MOSFET is controlled by the voltage applied on the control electrode (called gate) which is insulated by a thin metal oxide layer from the bulk semiconductor body. The electric field produced by the gate voltage modulates the conductivity of the semiconductor material in the region between the main current carrying terminals called the Drain (D) and the Source (S). Power MOSFETs can be of two types (i) depletion type and (ii) enhancement type. Both of these can be either **n-** channel type or **p**-channel type depending on the nature of the bulk semiconductor. Figure below shows the circuit symbol of these four types of MOSFETs.



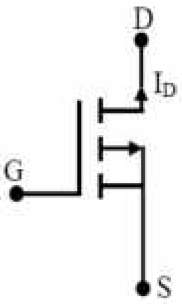
n-channel depletion type MOSFET



p-channel depletion type MOSFET

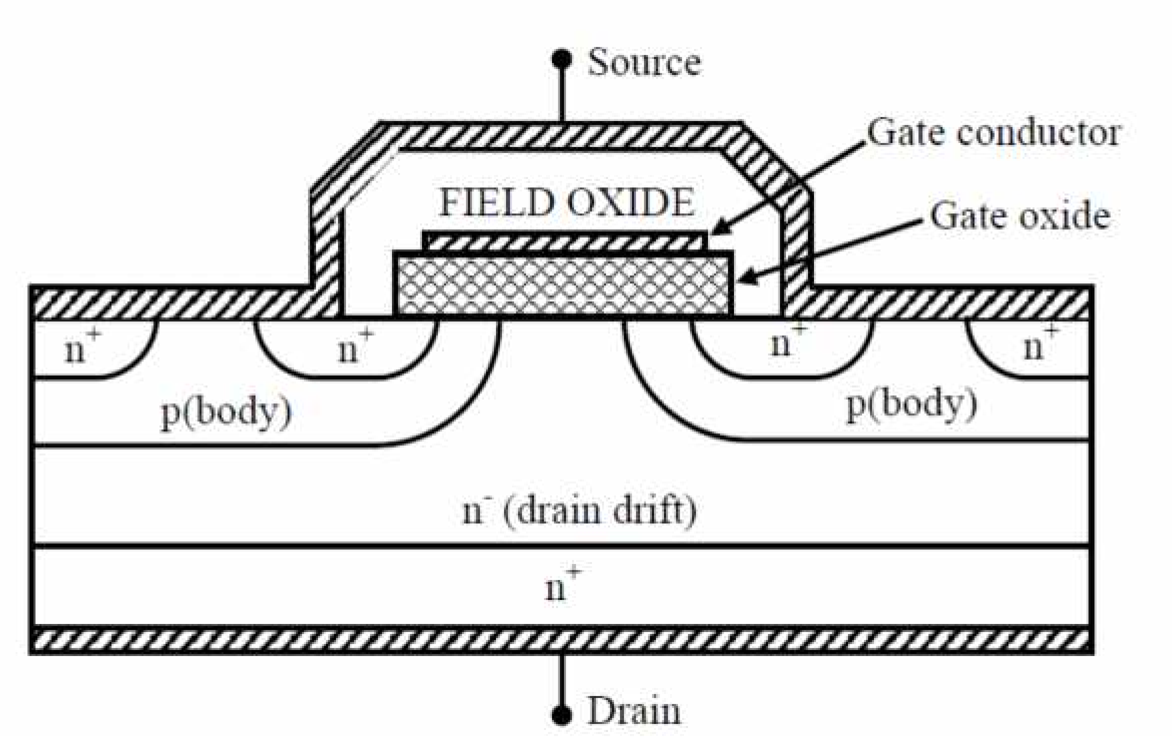


n-channel enhancement type MOSFET



p-channel enhancement type MOSFET

It can be concluded that depletion type MOSFETs are normally ON type switches, with the gate terminal open a nonzero drain current can flow in these devices. This is not convenient in many power electronic applications. Therefore, the enhancement type MOSFETs (particularly of the n-channel variety) is more popular for power electronics applications which shown in figure below

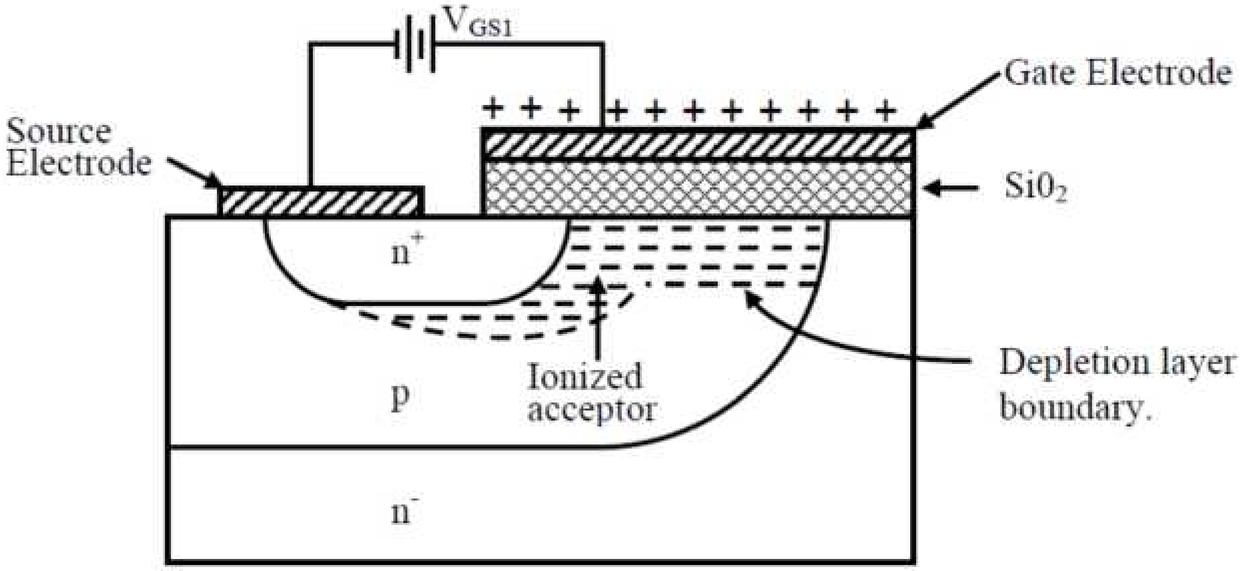


The two $\mathbf{n}^+$ end layers labeled "Source" and "Drain" are heavily doped to approximately the same level. The **p** type middle layer is termed the body (or substrate) and has moderate doping level. The $\mathbf{n}^-$ drain drift region has the lowest doping density. Thickness of this region determines the breakdown voltage of the device. The gate terminal is placed over the $\mathbf{n}^-$ and **p** type regions of the cell structure and is insulated from the semiconductor body be a thin layer of silicon dioxide (also called the gate oxide). The source and the drain region of all cells on a wafer are connected to the same metallic contacts to form the Source and the Drain terminals of the complete device

There is no path for any current to flow between the source and the drain terminals since at least one of the **p n** junctions (source – body and body-Drain) will be reverse biased for either polarity of the applied voltage between the source and the drain. The gate (silicon) oxide layer and the p-body silicon forms a high quality capacitor. When a small voltage is gate terminal positive with respect to the source, a depletion region forms at the interface between the SiO_2 and the silicon.

When gate is made positive with respect to source, an electric field is established and negative charge “electron” in p-substrate (below SiO_2) formed, and construct an n- channel and current can flow from drain to source. If V_{GS} increase will causes the depletion layer to grow in thickness. At the same time the electric field at the oxide-silicon interface gets larger and begins to attract free electrons. The source of electron is electron-hole generation by thermal ionization.

The disadvantage of n-channel : conducting between the source and drain give large ON-state resistance and high power dissipation. This planner MOSFET construction replace with vertical flow of electron from drain to source. Power MOSFET is very loss device at high current application, it could used in high switching application.



Comparison between PMOSFET and PBJT

1-MOSFET is unipolar, BJT is bipolar

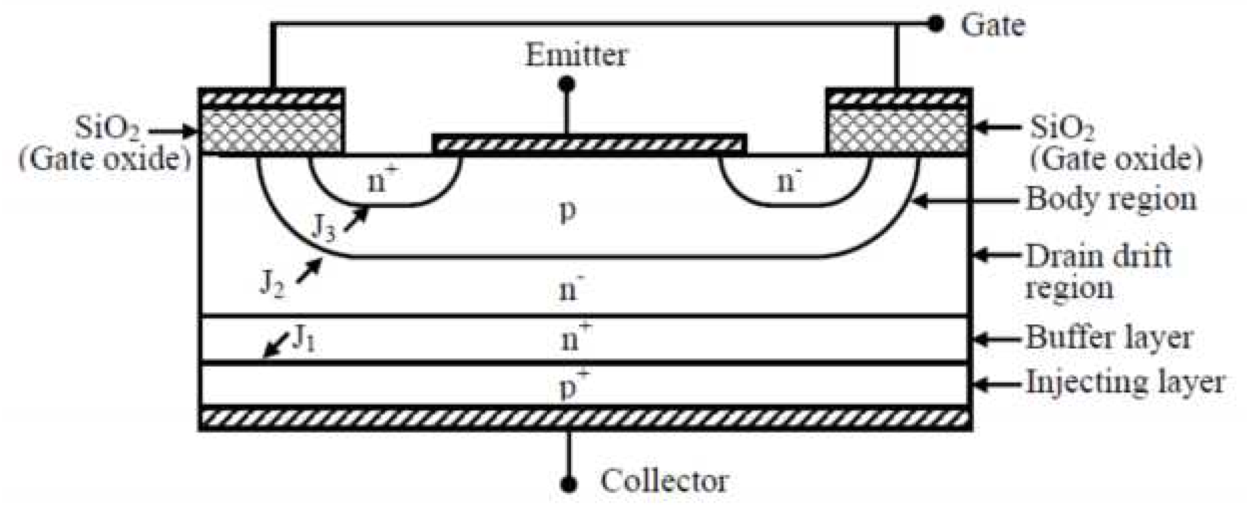
2-MOSFET has low switching losses but conduction losses is high, BJT has high switching losses but lower conduction losses

3-MOSFET has high input impedance, BJT has low input impedance.

4-MOSFET is voltage controlled, BJT is current controlled.

Insulated Gate Bipolar Transistor (IGBT)

The insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch and in newer devices is noted for combining high efficiency and fast switching. The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors. The IGBT combines an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. An IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor.



Static Induction Transistor (SIT)

Static induction transistor (SIT) is a high power, high frequency device. It is a vertical structure device with short multichannel. Being a vertical device, the SIT structure offers advantages in obtaining higher breakdown voltages than a Field-effect transistor (FET). For the SIT, it is not limited by the surface breakdown between gate and drain, and can operate at a very high current and voltage.

Characteristics of SIT

- short channel length
- low gate series resistance
- low gate-source capacitance
- small thermal resistance
- low noise
- low distortion
- high audio frequency power capability
- short turn-on and turn-off time, typically 0.25 μs

Rectifier circuits

One of the first and most widely used application of power electronic devices have been in rectification. Rectification refers to the process of converting an ac voltage or current source to dc voltage and current. Rectifiers specially refer to power electronic converters where the electrical power flows from the ac side to the dc side.

Rectifier circuit is divided to two groups:

1- Half wave rectifier
2- Full wave rectifier

And according to control into:

1- Uncontrolled rectifier
2- Half controlled rectifier
3- Fully controlled rectifier

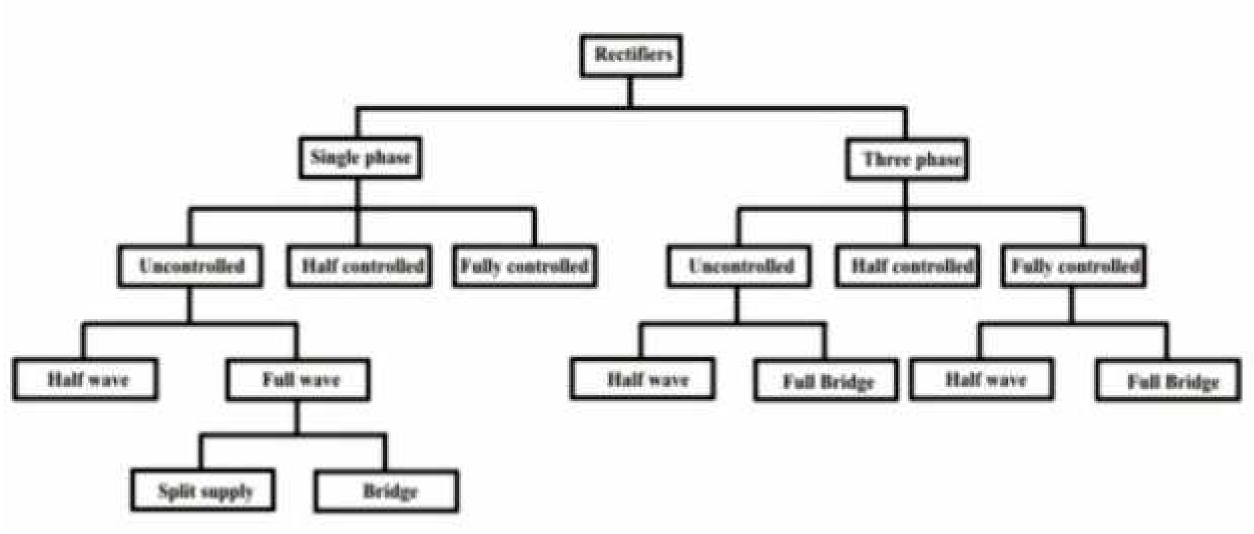
The uncontrolled rectifier circuit contains only diodes, which give a DC voltage fixed in magnitude relative to the AC power supply.

The half controlled rectifier circuit contains mixture of the thyristor and diodes which prevent several load voltage but allow adjustment of the direct mean voltage level.

Uncontrolled and half controlled called “unidirectional convertor”, permit power flow from AC supply to DC supply load only.

In fully controlled circuit al rectifier elements are thyristor or power transistor. In which a suitable control of the phase angle at which the thyristor are turned on so control the mean DC value. It also called bidirectional convertor permit power to flow in either direction between supply and load. The control does by phase of signal which simple, less expensive and efficient. It is used in many industrial application such variable speed derives, and this has two type

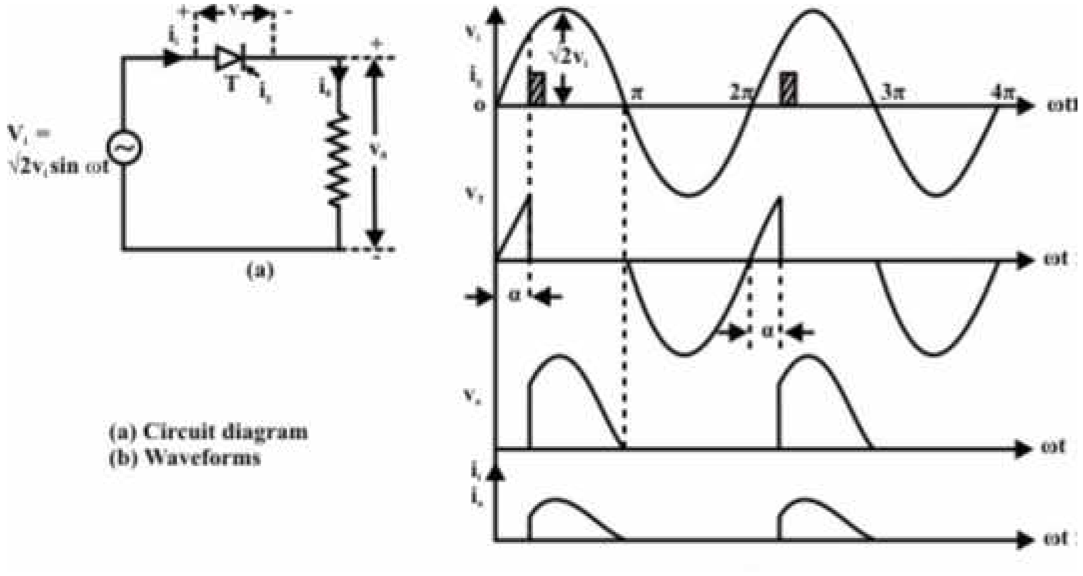
1- Single phase
2- Three phase



Single phase fully controlled half wave rectifier

Resistive load

In figure (a) below shows the circuit diagram of a single phase fully controlled half wave rectifier supplying a resistive load. At ωt = 0 when the input supply voltage becomes positive the thyristor T becomes forward biased. However, it does not turn ON till a gate pulse is applied at ωt = α. During the period $0 < \omega t \leq \alpha$, the thyristor blocks the supply voltage and the load voltage remains zero as shown in fig (b). Consequently, no load current flows during this interval. As soon as a gate pulse is applied to the thyristor at ωt = α it turns ON. The voltage across the thyristor collapses to almost zero and the full supply voltage appears across the load. From this point onwards the load voltage follows the supply voltage. At ωt = π as the supply voltage passes through the negative going zero crossing the load voltage and hence the load current becomes zero and tries to reverse direction. In the process the thyristor undergoes reverse recovery and starts blocking the negative supply voltage. Therefore, the load voltage and the load current remains clamped at zero till the thyristor is fired again at $\omega t = 2\pi + \alpha$. The same process repeats there after



(a) Circuit diagram
(b) Waveforms

The load average voltage is given by:

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

$$I_{dc} = \frac{V_{dc}}{R} = \frac{V_{max}}{2\pi R}(1 + cos \propto)$$

The maximum value of the average output voltage and current at (α=0)

$$V_{avmax} = \frac{V_{max}}{\pi}$$

$$I_{avmax} = \frac{V_{avmax}}{R} = \frac{V_{max}}{\pi R}$$

In some type of load like electric heating and incandescent lamps, the rms value is interesting

$$V_{rms=}\sqrt{\frac{1}{2\pi}\int_{\propto}^{\pi} V_m^2\, sin^2(wt)dwt}$$

$$V_{rms=}\frac{V_m}{2}\sqrt{\frac{1}{\pi}(\pi-\alpha+\frac{1}{2}sin2\alpha)}$$

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

$$I_{rms} = \frac{V_m}{2R}\sqrt{\frac{1}{\pi}(\pi - \alpha + \frac{1}{2}sin2\alpha)}$$

Power delivered to resistive load = (rms load voltage)× (rms load current)

$$= I_{rms} V_{rms} = (V_{rms})^2 / R = (I_{rms})^2 R$$

Input Volt Amperes = (source voltage)× (rms load current)

Power factor = power delivered to load / input Volt Amperes

$$pf = \frac{1}{\sqrt{2}}\sqrt{\frac{1}{\pi}(\pi - \alpha + \frac{1}{2}sin2\alpha)}$$

Rectification efficiency=P_{DC} / P_{AC}

Rectification iron efficiency (η) $= \frac{V_{dc} I_{dc}}{V_{rms} I_{rms}}$

Form factor (*F.F*)=$\frac{V_{rms}}{V_{dc}}$

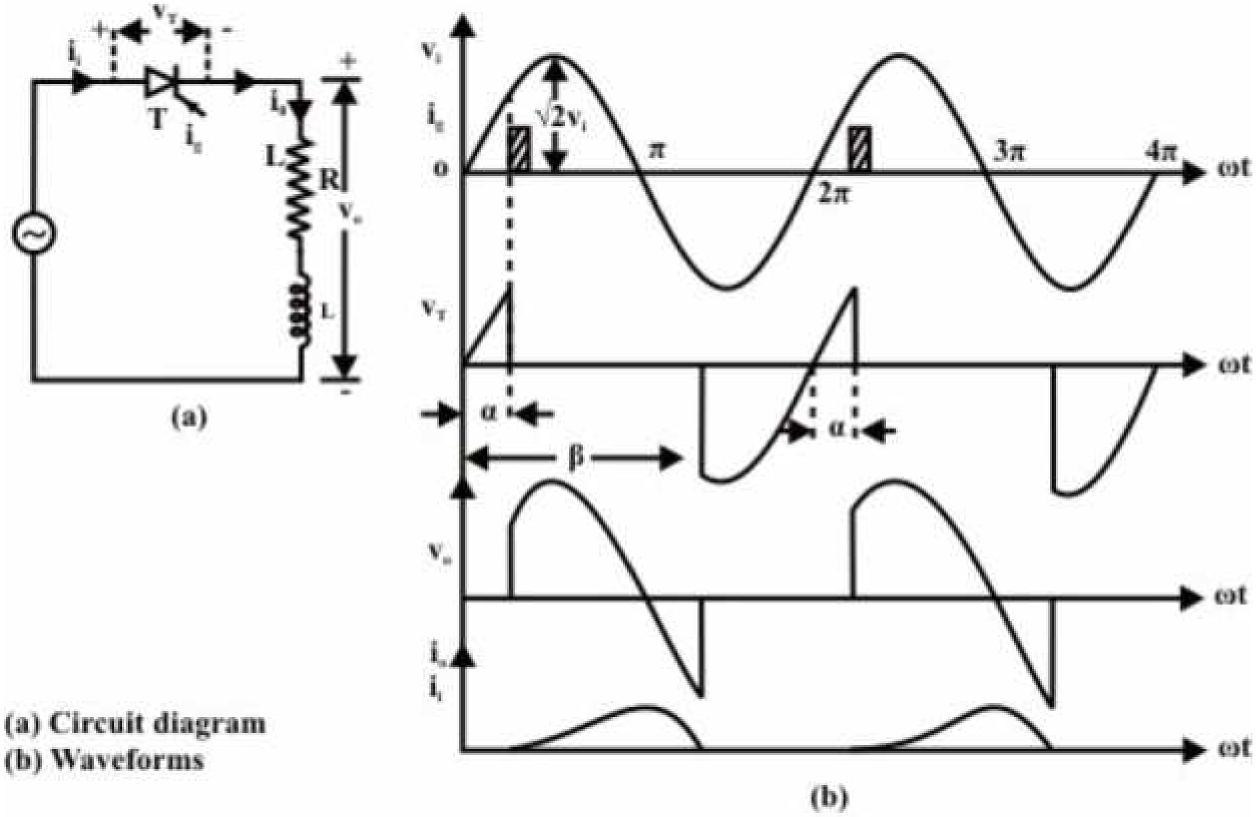
$$F.F = \frac{\pi\sqrt{(1 - \frac{\alpha}{\pi} + \frac{sin2\alpha}{2\pi})}}{(1 + cos\alpha)}$$

Ripple Factor (*RF*) =$\sqrt{F.F^2 - 1}$

Single phase fully controlled half wave rectifier

Resistive Inductive (RL) load

In figure below shows the circuit diagram and the waveforms of a single phase fully controlled half-wave rectifier supplying a resistive inductive load. The thyristor T becomes forward biased when the supply voltage becomes positive at ωt = 0. However, it does not start conduction until a gate pulse is applied at ωt = α. As the thyristor turns ON at ωt = α the input voltage appears across the load and the load current starts building up. The load current does not become zero at ωt = π, instead it continues to flow through the thyristor and the negative supply voltage appears across the load forcing the load current to decrease. Finally, at ωt = β (β > π) the load current becomes zero and the thyristor undergoes reverse recovery. From this point onwards the thyristor starts blocking the supply voltage and the load voltage remains zero until the thyristor is turned ON again in the next cycle. It is to be noted that the value of β depends on the load parameters.



(a) Circuit diagram
(b) Waveforms

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m\, sinwt\; dwt \;=\; \frac{V_m}{2\pi}\,(cos\alpha - cos\beta)$$

$$\beta = tan^{-1}(\frac{XL}{R}) \qquad\qquad XL = 2\pi f L$$

$$Z = \sqrt{(XL)^2 + (R)^2}$$

$$I_{dc} = \frac{V_{dc}}{Z}$$

$$V_{dcmax} = \frac{V_m}{2\pi}(1 - cos\beta) \quad when\ \alpha = 0$$

$$I_{dcmax} = \frac{V_{dcmax}}{Z}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} V_m\, sinwt\ dwt} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}(\beta - \alpha - \frac{1}{2}(\sin(2\beta) - \sin(2\alpha))}$$

$$I_{rms} = \frac{V_{rms}}{Z}$$

Single phase fully controlled half wave rectifier

Resistive Inductive (RL) load and freewheeling diode

With a RL load it was observed that the average output voltage reduces. This disadvantage can be overcome by connecting a diode across the load as shown in figure. The diode is called as a Free Wheeling Diode (FWD).

At $\omega t = \pi$, the source voltage v_S falls to zero and as v_S becomes negative, the freewheeling diode is forward biased. The stored energy in the inductance maintains the load current flow through R, L, and the FWD. Also, as soon as the FWD is forward biased, at $\omega t = \pi$, the SCR becomes reverse biased, the current through it becomes zero and the SCR turns off. During the period $\omega t = \pi \text{ to } \beta$, the load current flows through FWD (freewheeling load current) and decreases exponentially towards zero at $\omega t = \beta$.

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

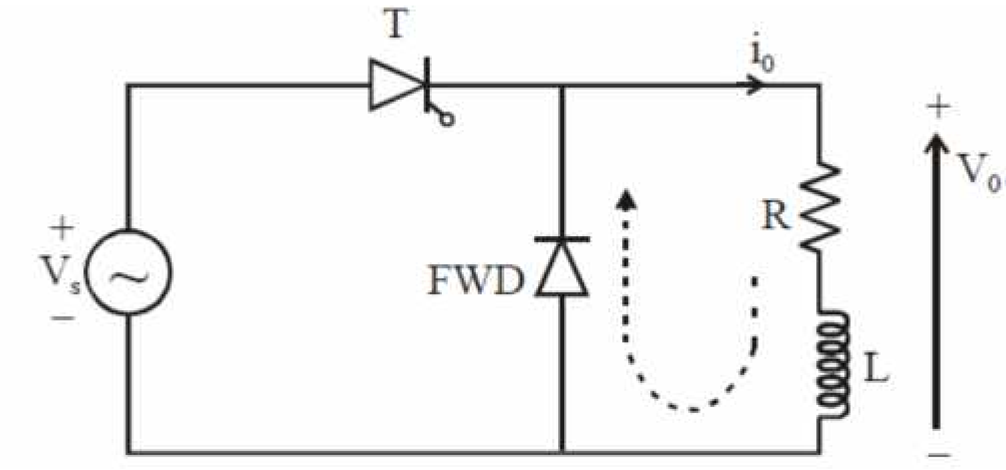
The average output voltage , which is the same as that of a purely resistive load. The output voltage across the load appears similar to the output voltage of a purely resistive load.

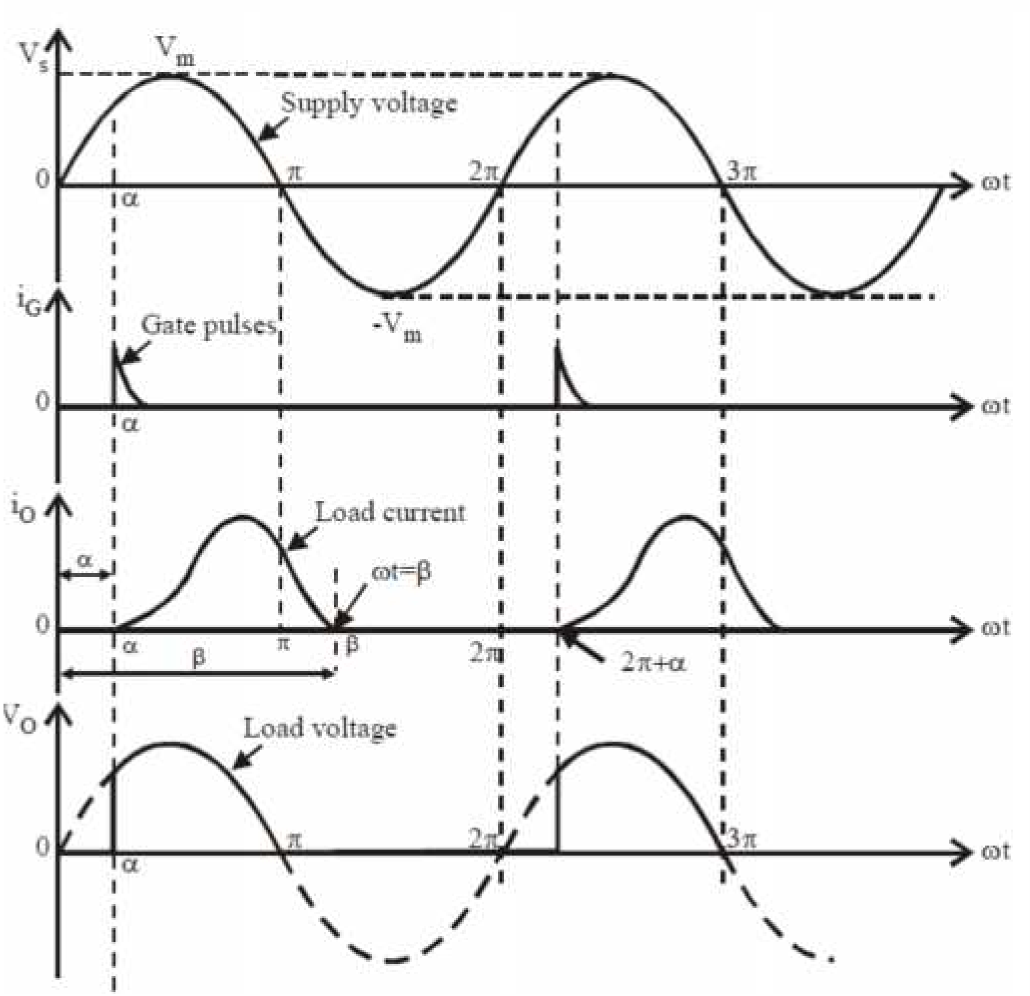
The following points are to be noted.

- If the inductance value is not very large, the energy stored in the inductance is able to maintain the load current only up to $\omega t = \beta$, where $\pi < \beta < 2\pi$, well before the next gate pulse and the load current tends to become discontinuous.

- During the conduction period α to π, the load current is carried by the SCR and during the freewheeling period π to β, the load current is carried by the freewheeling diode.

- The value of β depends on the value of R and L and the forward resistance of the FWD. Generally $\pi < \beta < 2\pi$.





$$i_O = \frac{V_m}{Z}\sin(\omega t - \phi) + A_1 e^{\frac{-t}{\tau}}$$

$Z = \sqrt{R^2 + (\omega L)^2}$ = Load impedance.

$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right)$ = Load impedance angle (power factor angle of load).

$\tau = \frac{L}{R}$ = Load circuit time constant.

Therefore the general expression for the output load current is given by the equation

$$i_O = \frac{V_m}{Z}\sin(\omega t - \phi) + A_1 e^{\frac{-R}{L}t}$$

The value of the constant $_1A$ can be determined from the initial condition. i.e. initial value of load current 0 $i_0 =$, at $\omega t = \alpha$. Hence from the equation for I_0 equating $_o i$ to zero and substituting $\omega t = \alpha$, we get

$$i_O = 0 = \frac{V_m}{Z}\sin(\alpha - \phi) + A_1 e^{\frac{-R}{L}t}$$

$$A_1 e^{\frac{-R}{L}t} = \frac{-V_m}{Z}\sin(\alpha - \phi)$$

$$A_1 = \frac{1}{e^{\frac{-R}{L}t}}\left[\frac{-V_m}{Z}\sin(\alpha - \phi)\right]$$

$$A_1 = e^{\frac{+R}{L}t}\left[\frac{-V_m}{Z}\sin(\alpha - \phi)\right]$$

$$A_1 = e^{\frac{R(\omega t)}{\omega L}}\left[\frac{-V_m}{Z}\sin(\alpha - \phi)\right]$$

By substituting $\omega t = \alpha$, we get the value of constant $_1A$ as

$$A_1 = e^{\frac{R(\alpha)}{\omega L}}\left[\frac{-V_m}{Z}\sin(\alpha - \phi)\right]$$

Substituting the value of constant $_1A$ from the above equation into the expression for
I_0 , we obtain

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

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

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

Therefore we obtain the final expression for the inductive load current of a single phase half wave controlled rectifier with RL load as

$$i_O = \frac{V_m}{Z}\left[\sin(\omega t-\phi)-\sin(\alpha-\phi)e^{\frac{-R}{\omega L}(\omega t-\alpha)}\right] \;; \quad \text{Where } \alpha \le \omega t \le \beta$$

The above expression also represents the thyristor current i_{T1}, during the conduction time interval of thyristor T_1 from $\omega t = \alpha$ to β

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m\, sinwt\; dwt$$

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

$$I_{dc} = \frac{V_{dc}}{Z}$$

$$V_{dcmax} = \frac{V_m}{\pi}$$

$$I_{dcmax} = \frac{V_{dcmax}}{Z}$$

Single phase full- wave controlled rectifier

Single phase full wave controlled rectifier circuit combines two half wave controlled rectifiers in one single circuit so as to provide two pulse output across the load. Both the half cycles of the input supply are utilized and converted into a unidirectional output current through the load so as to produce a two pulse output waveform. Hence a full wave controlled rectifier circuit is also referred to as a two pulse converter

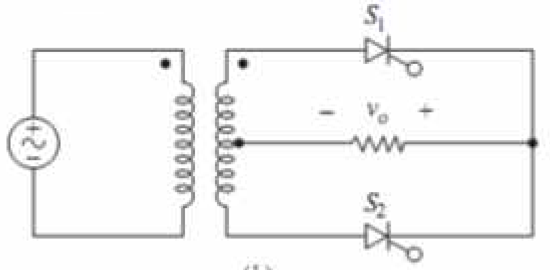
There are two basic configuration of full wave controlled rectifier

- Single phase full wave controlled rectifier using a center tapped transformer (two pulse converter with mid point configuration).
- Single phase full wave bridge controlled rectifier

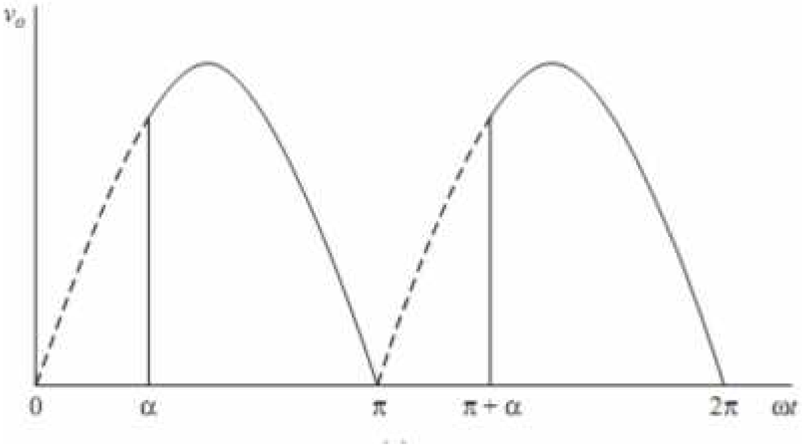
Single phase full wave controlled center tapped rectifier

In figure shows below the basic arrangement of a single phase center tap controlled rectifier with resistive load. Phase control of both the positive and negative halves of the AC supply is now possible, thus increasing the DC voltage and reducing the ripple compared to those of half wave rectifiers**.**

During the positive half-cycle of input voltage, SCR1 is forward biased. If we apply the gate signal at α_1 SCR1 turn on. The output voltage follows the input voltage. At π, when the current through SCR1 becomes zero , it turns off naturally. During the negative half cycle, SCR2 is forward biased. SCR2 is fired at $(\pi+\alpha)$. the current through SCR2 becomes zero at 2π and turn off.



(b)



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

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

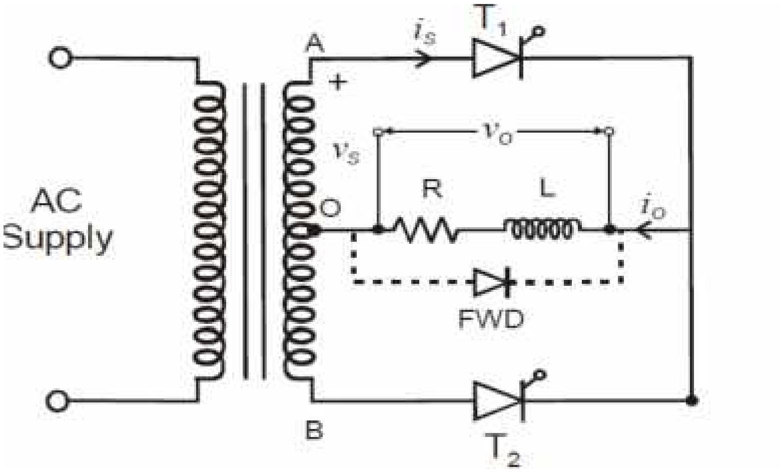
$$I_{\text{rms}} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{V_m}{R}\sin\omega t\right)^2 d(\omega t)}$$

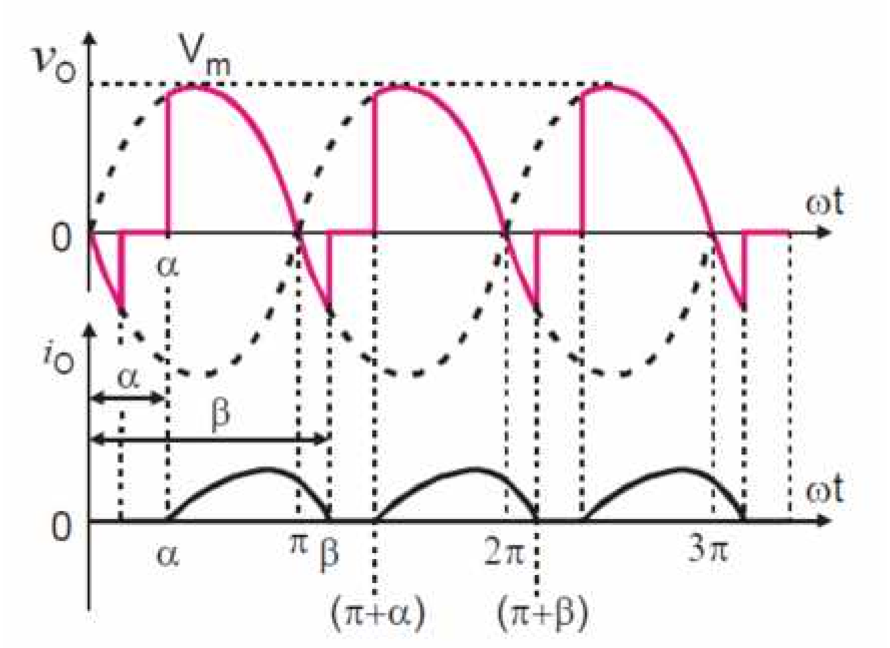
$$= \frac{V_m}{R}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\sin(2\alpha)}{4\pi}}$$

Single phase full wave controlled rectifier using center tapped transformer with inductive-resistive load

This type of full wave controlled rectifier requires a center tapped transformer and two thyristors T_1 and T_2. During the positive half cycle of input supply, when the upper line of the secondary winding is at a positive potential with respect to the center point"O" the thyristor T_1 is forward biased and it is triggered at a firing angle of α. The load current flows through the thyristor T_1 , through the load and through the upper part of the secondary winding, during the period α to β , when the thyristor T_1 conducts. The output voltage across the load follows the input supply voltage that appears across the upper part of the secondary winding from $\omega t = \alpha$ to β . The load current through the thyristor T_1 decreases and drops to zero at $\omega t = \beta$, where $\beta > \pi$ for RL type of load and the thyristor $T1$ naturally turns off at $\omega t = \beta$.

During the negative half cycle of the input supply the voltage at the supply line ‘A’ becomes negative whereas the voltage at line ‘B’ (at the lower side of the secondary winding) becomes positive with respect to the center point ‘O’. The thyristor T_2 is forward biased during the negative half cycle and it is triggered at a delay angle of $(\pi + \alpha)$. The current flows through the thyristor T_2 , through the load, and through the lower part of the secondary winding when T_2 conducts during the negative half cycle the load is connected to the lower half of the secondary winding when T_2 conducts. For low values of load inductance the load current would be discontinuous and the extinction angle $\beta > \pi$ but $\beta < (\pi + \alpha)$. For large values of load inductance the load current would be continuous and does not fall to zero. The thyristor T_1 conducts from α to $(\pi + \alpha)$, until the next thyristor $T2$ is triggered. When $T2$ is triggered at $\omega t = (\pi + \alpha)$, the thyristor T_1 will be reverse biased and hence T_1 turns off





$$V_{O(dc)} = V_{dc} = \frac{2}{2\pi}\int_{\omega t=\alpha}^{\beta} v_O.d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi}\int_{\omega t=\alpha}^{\beta} v_O.d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t.d(\omega t)\right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos\omega t\Big/_{\alpha}^{\beta}\right]$$

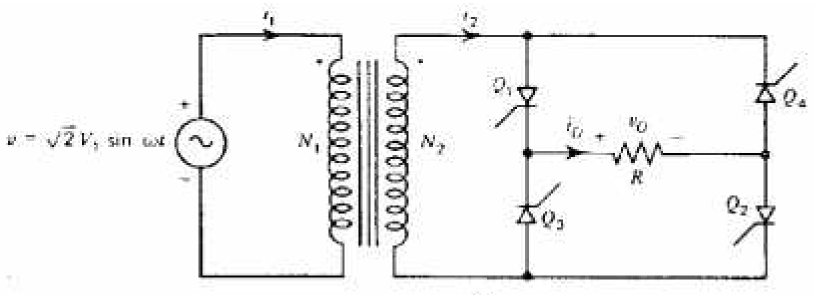
$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}(\cos\alpha - \cos\beta)$$

Single phase full wave controlled by bridge

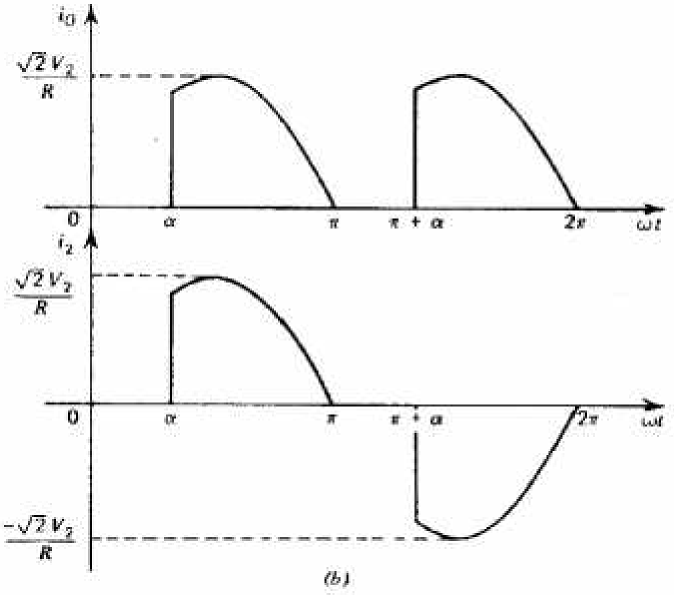
Resistive load

The direct component of source current is eliminated by means single phase full wave controlled rectifier of the bridge circuit shown in Fig.below. In that circuit one pair of thyristors conduct during each half cycle, giving full-wave rectification and a source current with alternating symmetry.

At the positive part of cycle T1 and T2 will be forward biased and T3 and T4 will be reverse biased. When triggering signal applied to the gate of T1 and T2 at time (t=α), the current will pass through T1and the load then T2. During the negative part of cycle the thyristor T3 and T4 will be forward biased and T1 and T2 will be reverse biased. When triggering signal applied to the gate of T3 and T4 the current will pass through T4 and load then T3.



(a)

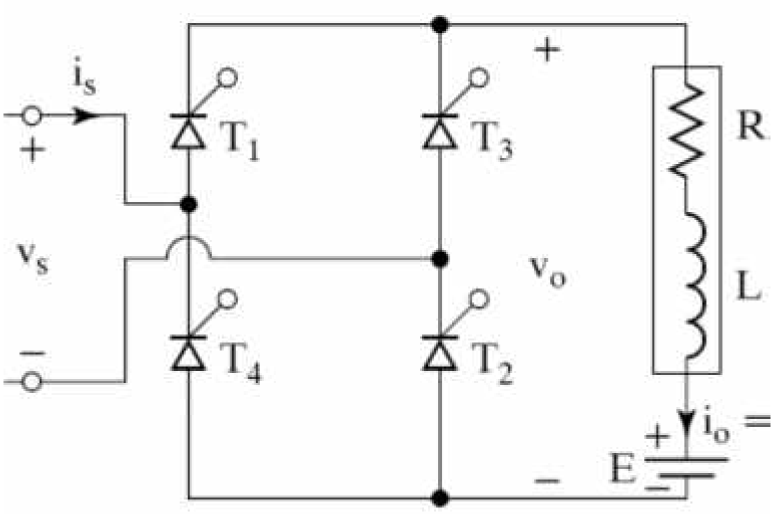


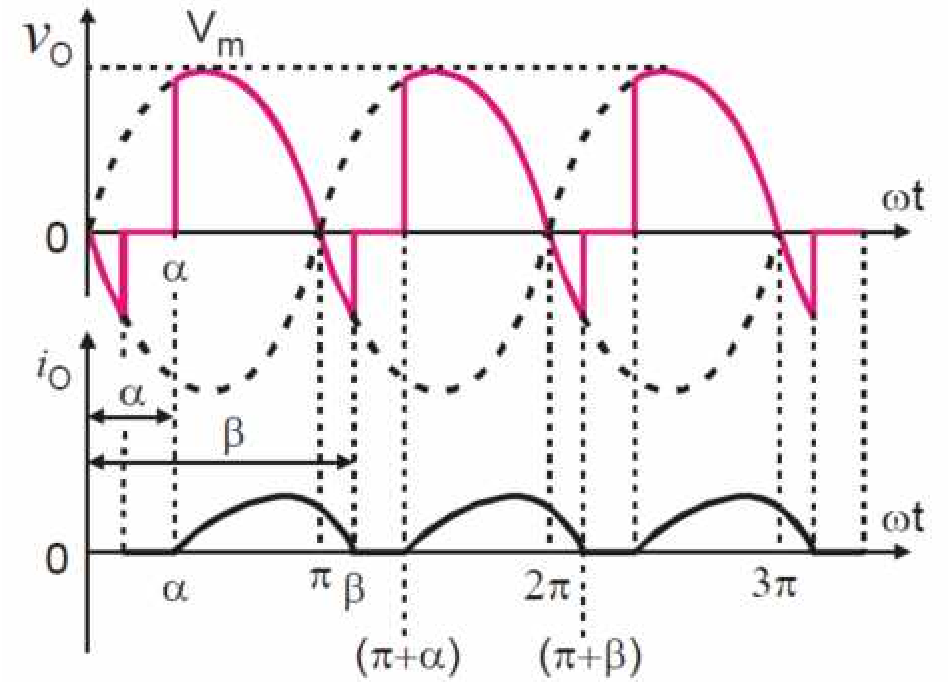
(b)

Single phase full wave controlled by bridge

Resistive –inductive load

The figure below show the bridge rectifier with resistive-inductive load. The load current tends to keep flowing since the inductor induces a voltage that acts to oppose an increase or decrease in current. Therefore, SCR keeps conducting even through the voltage may have fallen to zero. The current maintains conduction in the SCR even after the voltage cross the SCR has reverse.





$$V_{O(dc)} = V_{dc} = \frac{2}{2\pi} \int_{\omega t=\alpha}^{\beta} v_O . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \int_{\omega t=\alpha}^{\beta} v_O . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \left[\int_{\alpha}^{\beta} V_m \sin \omega t . d(\omega t) \right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi} \left[-\cos \omega t \Big/_{\alpha}^{\beta} \right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi} (\cos \alpha - \cos \beta)$$

The average value of this output voltage varies with α,

$$V_{o(avg.)} = \frac{2}{\pi} V_m \cos \alpha$$

A full-wave controlled rectifier with an inductive load is connected to a 120 V source. The resistive portion of the load is equal to 10 Ω. If the delay angle α is 30°, find

a) the average load voltage
b) the average load current
c) the maximum load current
d) the RMS load current
e) the average current in each SCR
f) the power supplied to the load
g) the form Factor
h) the ripple Factor
i) the rectifier efficiency

$$V_m = \sqrt{2}\,(120) = 208 \text{ V}$$

a) average load voltage

$$\begin{aligned} V_{o(avg.)} &= \frac{2}{\pi} V_m \cos\alpha \\ &= \frac{2}{\pi}(208)(\cos 30) \\ &= 115 \text{ V} \end{aligned}$$

b) average load current

$$I_{o(avg.)} = \frac{V_{o(avg.)}}{R} = \frac{115}{10} = 11.5 \text{ A}$$

c) maximum load current = average load current = 11.5 A

d) RMS load current = average load current = 11.5 A

e) Since the SCRs in bridge conduct on alternate half-cycles, the average SCR current is

$$\frac{1}{2} I_{o(avg.)} = 5.75 \text{ A}$$

f) power supplied to the load = $I_{RMS}^2 R = 11.5^2(10) = 1323$ W

g) form factor

$$FF = V_{o(RMS)}/V_{o(avg.)} = 120/115 = 1.04$$

h) ripple factor

$$RF = \sqrt{FF^2 - 1} = \sqrt{1.04^2 - 1} = 0.3$$

i) rectifier efficiency

$$\eta = V_{o(avg.)}/V_{o(RMS)} = 115/120 = 0.96$$

Example 6.6 The full-wave bridge rectifier shown in Figure 6.15 is supplied from a 15
source with a load resistance of 10 Ω. If the firing angle α is 30°, find:

a) the average load voltage
b) the average load current
c) the maximum load current
d) the RMS load current
e) the power supplied to the load
f) the ripple frequency
g) the power factor

Solution

$$V_m = \sqrt{2}\,(150) = 212 \text{ V}$$

a) average load voltage $= \dfrac{V_m(1+\cos\alpha)}{\pi} = \dfrac{(212)(1+\cos 30°)}{\pi} = 126 \text{ V}$

b) average load current $= \dfrac{(V_m)\,(1+\cos 30°)}{R\pi} = 12.6 \text{ A}$

c) maximum load current

$$I_m = \frac{V_m}{R} = \frac{212}{10} = 21.2 \text{ A}$$

d) RMS load current

$$I_{RMS} = \frac{I_m}{\sqrt{2}}\sqrt{\left[1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right]}$$
$$= 14.8 \text{ A}$$

e) power supplied to the load $= I^2_{RMS}R = 14.8^2(10) = 2182 \text{ W}$

f) ripple frequency

$$f_r = 2 * \text{input supply frequency} = 2 * 60 = 120 \text{ Hz}$$

g) $S = V_s * I_{RMS} = 150 * 14.8 = 2220 \text{ VA}$

$$\text{PF} = \frac{P}{S} = \frac{2182}{2220} = 0.98$$

Inverters

The word ***inverter*** in power-electronics denotes alas s of power conversion (or power conditioning) circuits that operates from a dc voltage source or dc current source and converts it into a.c voltage or current , inverter* is sometimes also used for a.c to d.c converter circuts if the power flow direction is from d.c to a.c side .

In other words the circuits that convert dc power to a.c power at desired output voltage and frequency (frequency either be constant or variable) called **inverters circuit** .

This conversion process done by either controlled turn-on and turn-off device such as (BJT , MOSFET ,GTO) which used for low and medium power application or forced commutated thyristors used for high power application .

The output voltage waveform of ideal inverters should be sinusoidal. The waveform of practical inverters are non-sinusoidal and contain harmonics, it may be square, quasi-square. For low and medium application square and quasi-square could be acceptable but for high power application sinusoidal waveform required . The output frequency of inverter determined by :

1- Rate of turn of semiconductor device
2- Rate of turn-off depend on control circuit

Since practical inverters output waveform contain harmonics it could reduced it by using good switching techniques of high speed. Filtering could be used but it is not useful almost for removing harmonics since output frequency varying over wide range and the filter must handling the large power output of inverter (mean the first filter must larg) and this add cost , weight and reduce efficiency due to power losses in filter .

To avoid that the pulse-width modulation (PWM) uses switching scheme within inverter that modify the shape of the output waveform .

The d.c power input to inverter could be d.c power supply , battery ,fuel cell ,photovoltaic cell (solar cell)magneto hydrodynamic (MHD) generators , In most industrial application a.c to d.c converters (inverter) follow by dc to ac converter : this is called d.c link converters .

Inverters used in many applications such as :

1- Variable speed a.c motor .
2- Induction heating .
3- Aircrafts power supply.
4- Uninterruptible power supply.
5- High voltage d.c transmission line .
6- Battery vehicles.
7- Regulated voltage and frequency power supply.

Classification of inverters

Inverters can be classified on the basis of number of factors:

a) *Classification according to the nature of input source* :based on the nature of input power source, inverters are classified as
    I. Voltage source inverters (VSI)
    II. Current source inverters (CSI)

In case of VSI, the input to inverter is provided by a ripple free dc voltage source whereas in CSI, the voltage source is first converted into a current source and then used to supply the power to the inverter.

VSI, is one in which the d.c source has small or negligible impedance. Because the low internal impedance, the terminal voltage of the voltage source inverter remains substantially constant with variations in load. Therefore, it is equally suitable to single motor and multi-motor drivers. Any short circuit across its terminals causes current to rise very fast, due to the low time constant of its internal impedance. CSI, is supplied with controlled current from a d.c source of high impedance. Typically, a phase controlled thyristor rectifier feeds the inverter with regulated current through a large series inductor. Because of a large internal impedance, the terminal voltage of a current source inverter changes substantially with a change in load. Therefore, if used in a multi-motor drive, a change in load on any motor effects other motors. Hence, current source inverters are not suitable for muli-motor drives. Since the inverter current is independent of load impedance, it has inherent protection against short circuit across it terminal

b) *Classification according to the waveshape of output voltage:*
    I. Square-wave inverter

II. Quasi-square wave inverter

III. Pulse width modulated (PWM) inverters

A square wave inverter produces a square wave ac voltage of a constant magnitude. The output voltage of this type of inverter can only be varied by controlled the input dc voltage. Square wave ac output voltage of an inverter is adequate for low and medium power application. The sine wave output voltage is ideal waveform for many high power applications. To make the output closer to sinusoid by filter circuit on the output of inverter. This filter must be capable to handling the large power output of the inverter and this add cost, weight and reduce the efficiency due to power losses in filter. PWM uses a switching scheme within inverter to modify the shape of the output voltage waveshape. So that, PWM considers second method to get the output closer to sinusoid waveform.

c) Classification according to method of commutation

I. Line commutated inverters
II. Forced commutated inverters

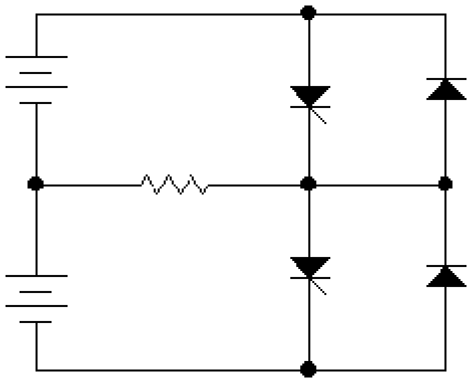
d) Classification according to connections

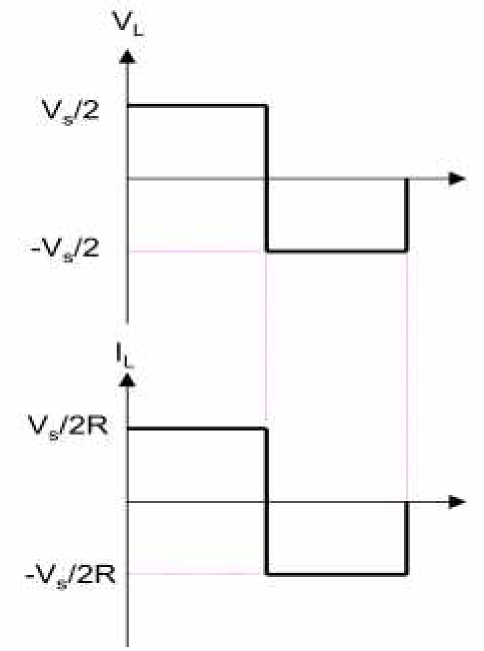
I. Series inverter
II. Parallel inverter
III. Bridge inverters: bridge inverters are further classified as
    i- Half-bridge
    ii- Full bridge

Single phase half bridge inverter

a- Resistive load

This circuit shown below, when thyristor T_1 turn-on for t_1 the output voltage at the load will be ($V_s/2$) and current will be (Vs/2R). When thyristor T_1 turn- off thyristor T_2 will turn- on at the same time and voltage of load will be (-Vs/2) and current will be (-Vs/2R), the waveform of the voltage and current shown below, the result (load) voltage and current are in phase since load resistive only





If the thyristor T_1 and T_2 each closed a time equal to T/2 then the average output voltage:

$$V_{o(avg)} = E\frac{T_{ON}}{T/2} = 2E\frac{T_{ON}}{T} = 2E\,d$$

Where: d is the duty cycle and given by

$$d = \frac{T_{ON}}{T}$$

The r.m.s value given by:

$$V_{o\ (rms)} = \sqrt{2d}\,E$$

The power absorbed by the load(resistor) is:

$$P_L = \frac{V_{o\ (rms)}^2}{R} = 2d\frac{E^2}{R}$$

b) R-L load

This circuit shown below, this circuit has four mode of operation it is :

Mode I ($t_1 < t < t_2$)

S_1 is turned- on at instant t_1, the load voltage is equal to $(V_{dc}/_{2})$ and positive load current increase gradually. At instant t_2, the load current reaches the peak value. Switch S_1 is turned –off at this instant. Due to same polarity of load voltage and load current, the energy is stored by the load

Mode II ($t_2 < t < t_3$)

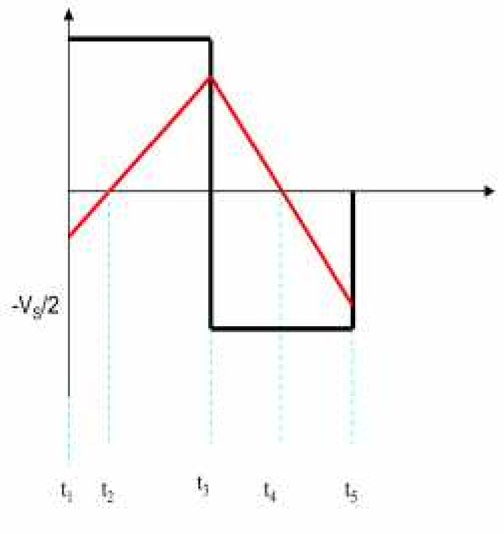
Due to inductive –load the load current direction will be maintained even after S_1 is turned –off. The load current flows through lower half of the supply and D_2. In this mode, the stored energy in load is feedback to the lower half of the source and the voltage is clamped to $(-V_{dc}/2)$.

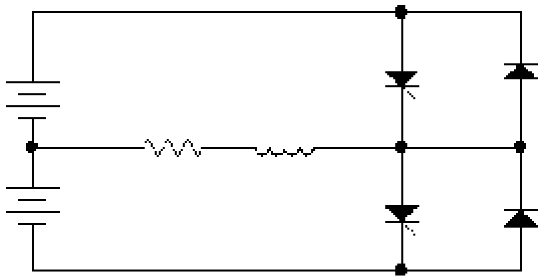
Mode III ($t_3 < t < t_4$)

At instant t_3, the load current goes to zero, the stored energy has been returned back to the lower half of supply. At instant t_3, S_2 is turned- on. This will produce a negative load voltage $(-V_{dc}/2)$ and negative load current, at t_4 current reach peak negative value

Mode IV ($t_4 < t < t_5$)

T_2 is turn off at instant t_4, the load voltage changes its polarity to become positive $(V_{dc}/2)$ load current remains negative and stored energy in the load is returned back to upper half of the source



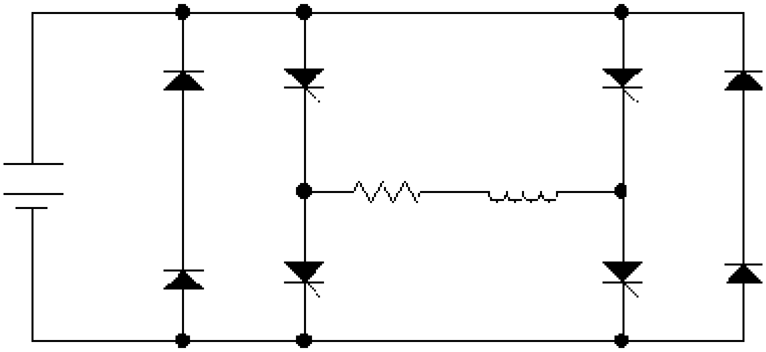


.

Single phase full bridge inverters

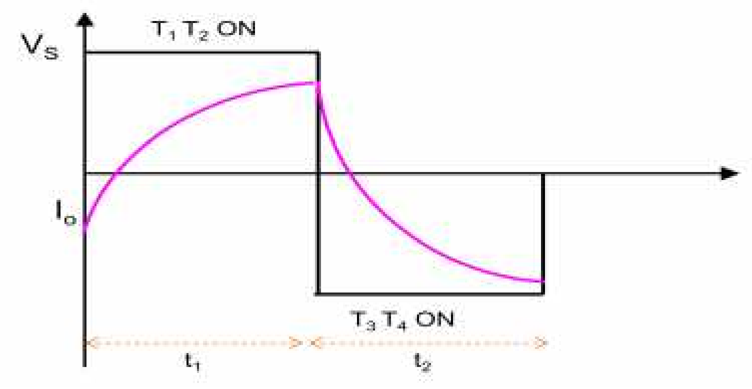
a) Resistive load

This circuit shown below, when thyristors T_1 and T_2 turn on for time t_1 the output voltage at the load will be (V_s) and current will be (V_s/R). when thyistors T_1 and T_2 turn- off thyristor T_3 and T_4 will turn on at the same time and voltage of load will be ($-V_s$) and current will be (V_s/R), the waveform of the voltage shown is the same for half bridge connection.



b) R-L load

When T_1 and T_2 get firing signal at time t_1 they will conduct current pass from source to T_1 to load then T_2 and return to source. Voltage load will be positive V_s and current increase gradually until reach maximum value at end of time t_1, T_1 and T_2 turn off and T_3 and T_4 firing turn –on. Load voltage is ($-V_s$) and current is decayed gradually until reach peak negative value at end time $t_{2.}$



The current pass through the thyristor related to the current pass the load by exponential relation as

$$V_S = L\frac{di}{dt} + I_L\, R \quad this\ \ is\ \ for\ \ time \quad (0 < t < t_1) \qquad ....\ \ ...(1)$$

$$-V_S = L\frac{di}{dt} + I_L\, R \quad this\ \ is\ \ for\ \ time \quad (t_1 < t < t_2) \quad ....\ \ ....(\ 2)$$

$$solving \quad equation \quad (1) \quad [0 < t < t_1]:$$

$$I_L = \frac{V_S}{R} - \left(\frac{V_S}{R} - I_o\right)\, e^{\frac{-t}{\mathrm{T}}}$$

$$where \quad "I_o"\ is\ the \quad initial \quad value \quad of\ current \quad ,if \quad there \quad is \quad no \quad initial \quad equation \quad be:$$

$$I_L = \frac{V_S}{R} \quad (1 - e^{\frac{-t}{\mathrm{T}}})$$

$$where$$

$$\mathrm{T} = \frac{L}{R}$$

$$solving \quad equation \quad (2) \quad [t_1 < t < t_2]:$$

$$I_L = -\ \frac{V_S}{R} \quad (I_o + \frac{V_S}{R})\ e^{\frac{-t}{\mathrm{T}}}$$

$$the \quad initial \quad value \quad I_o = I_L \quad for \quad (0 < t < t_1)$$

The time constant “T” is the sum of two part times as

T= t_1 + t_2

If there is no relation between t_1 and t_2 then assume

Choppers

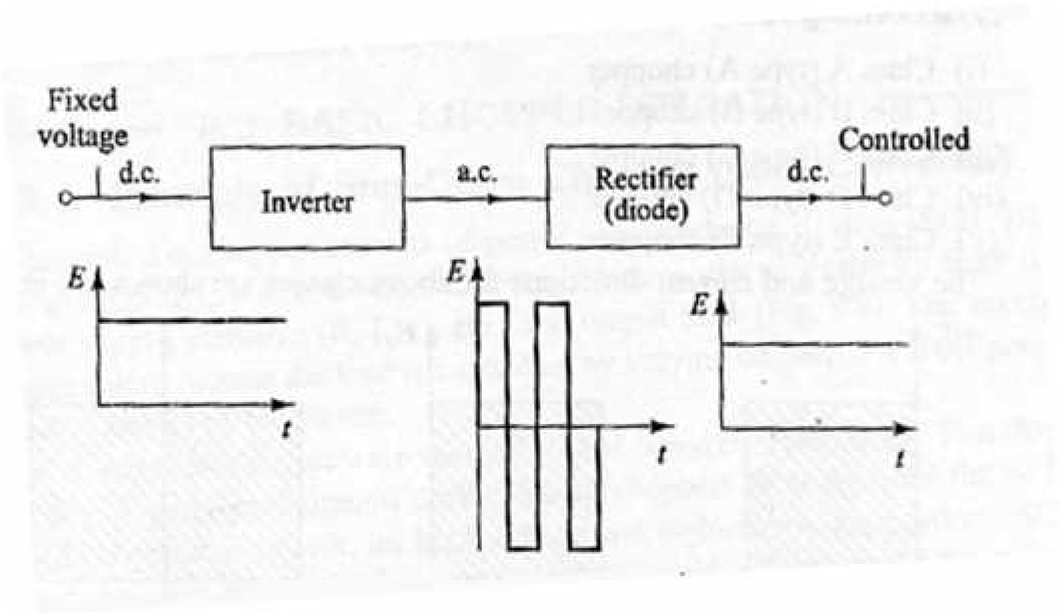
Modern electronic systems require high-quality, small lightweight, reliable, and efficient power supplies. Linear power regulators, whose principle of operation is based on a voltage or current divider, are inefficient. This is because they are limited to output voltages smaller than the input voltage, and also their also their power density is low because they require low frequency (50-60hz) line transformers and filters.

Linear regulators can provide a very high- quality output voltage. Their main area of application is a low power levels. Modern power electronic switches can operate at high frequencies. The dynamic characteristics of convertors improve with increasing operating frequencies. Therefore, high operating frequencies allow for achieving a faster dynamic response to rapid change in the load current and/ or the input voltage.

To produce good quality in many industrial applications this is required use of variable speed drives. These variable speed derivers are DC and AC derivers. All these deriver and process take power from d.c voltage to different level is required. There are many applications required fixed and variable d.c voltage such as subway cars, trolleybuses and battery operated vehicles. For all of these application speed control requires conversions of fixed d.c voltage to variable d.c voltage and this give to armature of d.c motor.

Generally, following techniques are variable for obtaining the variable d.c voltage from a fixed d.c voltage d.c voltage.

1) *Line commutation converters:* conversion of AC supply to variable DC supply using controlled rectifiers.
2) *AC link chopper (inverter-rectifier) :*in this method, the d.c is first converted to a.c, by an inverter (d.c to a.c converter). The obtained ac is then stepped up or down by a transformer and then rectifier back to dc by a rectifier. As the conversion is in two stages, dc to ac and ac to dc, this technique is therefore, costly, bulky and less. However, the transformer provide isolation between load and source. The figure below illustrates the conversion processes.



3) *DC Chopper (d.c. to d.c. power converters)* : A chopper is a static devices (switch) used to abtain variable d.c voltage from a source of constant d.c voltage. Therefore, chopper may be thought of as dc equivalent of an ac transformer since they behave in an identical manner.

The function of d.c to d.c converters are:

1- Convert a dc input voltage V_i into a dc output voltage V_o
2- Regulate the dc output voltage against load and line variations.
3- Reduce the AC voltage ripple on DC output voltage below the required level
4- Provide isolation between the input source and the load (isolation is not required)
5- Protect the supplied system and the input source from electromagnetic interference

Advantage of DC chopper

1- Saving in power the dc chopper
2- Greater efficiency
3- Faster response
4- Lower maintenance
5- Small size
6- Smooth control
7- Lower cost than motor generator sets or gas tubes approaches

Basic Chopper Classification

DC chopper can be classified

A. *According to the input/output voltage levels*
    - Step-down chopper : the output voltage is less than the inputs voltage
    - Step- up chopper : the output voltage is greater than the input voltage

b- *According to the direction of output and current*
    i. Class A
    ii. Class B
    iii. Class C
    iv. Class D
    v. Class E

The voltage and current directions for above classes are shown below

C- According to circuit operation

- i. First- quadrant chopper: the output voltage and current must be positive.
- ii. Two- quadrant chopper: the output voltage is positive and current can be positive or negative (class C) or the output current is positive and the voltage can be positive or negative (class D)
- iii. Four- guardant chopper : the output voltage and current both can be positive or negative (class E)

Basic chopper operation

Principle of step- down chopper (buck converter)

In general dc chopper consist of:

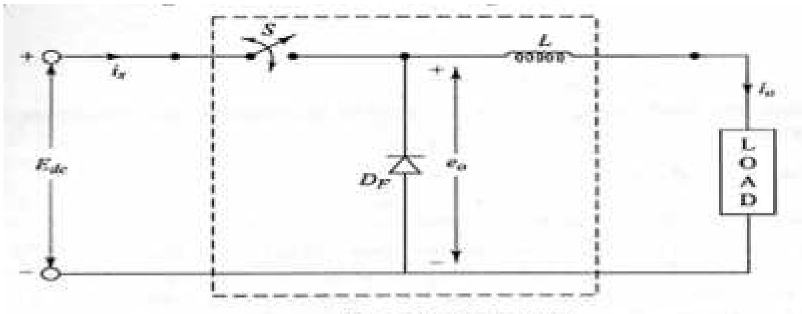
1- Power semiconductor devices such as SCR, BJT, MOSFET, IGBT, GTO and MCT. This work as a switch.

2- Input dc power supply

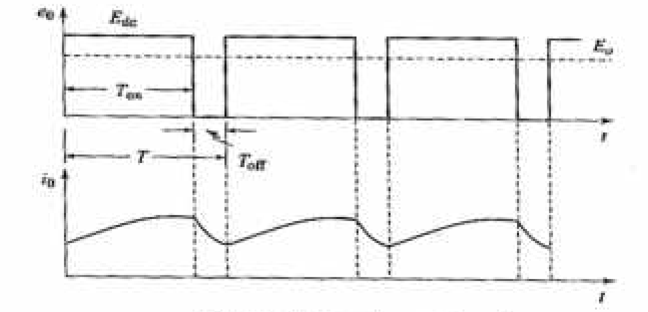
3- Elements (R, L, C)

4- Output load

The average output voltage across the load is controlled by varying ON-OFF period (duty-cycle) of the switch. For high voltage and high current applications SCR based chopper are used. The varation in ON and OFF periods of the switch provides an output voltage with adjustable average value. For circuit shown below the power diodes operate as a freewheeling to provide a path to load current when switch is OFF. The smooth inductor filters out the ripples in the load current. When the switch is ON for period T_{on} and blocked for period T_{off} the chopped output load voltage waveform is shown below. The step- shown chopper is capable of given maximum voltage that slightly smaller than input dc voltage, this mean $V_o < V_{dc}$, so called step down chopper



Basic chopper circuit



Output voltage and current waveforms

The average load voltage is given by :

$$\mathrm{Vo} = \mathrm{V_{d.c}} \frac{T_{on}}{T_{on} + T_{off}}$$

where :

$\mathrm{T_{on}} : ON - time\ of\ the\ chopper$

$\mathrm{T_{off}} : Off - time\ of\ the\ chopper$

$T = T_{off} + T_{on} = chopping\ time\ (chopping\ period)$

$$p = \frac{T_{on}}{T} = duty\ cycle$$

above equation :

$$V_o = V_{d.c} \frac{T_{on}}{T}$$

$$V_o = V_{d.c}\, T_{on}\, f$$

where :

f : choppin frquency

$$V_o = V_{d.c}\, p$$

the RMS value of the output vol atge is :

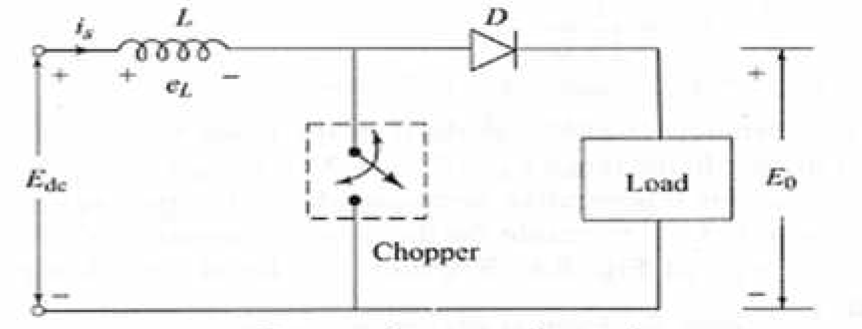
$$V_{rms} = \sqrt{\frac{V_{d.c}^2\, T_{on}}{T}} = V_{d.c} \sqrt{\frac{T_{on}}{T}} = V_{d.c} \sqrt{p}$$

It is obvious that the output voltage varies linearly with the duty-cycle. It is therefore possible to control the output voltage in the range zero to V_{dc}. If the switch S which used in chopper

1- Transistor, base current will control by ON\OFF period
2- GTO thyristor, a positive gate ulse will turn it ON and a negative gate will turn it OFF.
3- SCR thyristor, commutation circuit required to turn it OFF.

Principle of step- up chopper

When the chopper is ON, the inductor L is connected to the supply V_{dc} and inductor stores energy during on- period T_{on}. When and load for a period T_{off}. As the current tends to decrease, polarity of the emf induced in inductor L in reversed to that to shown in figure below



Step-up chopper or boost choppers

and as a result voltage across the load V_o become

$$V_o = V_{d.c} + L\frac{di}{dt}$$

The inductor voltage adds to source voltage to force the inductor current into load the load. In this manner, the energy stored in the inductor is released to the load. Here, higher value of inductance L is preferred for getting lesser ripple in the output.

During the time T_{on}, when the chopper is ON, the energy input to the inductor from the source is given by

$$E_{input} = V_{d.c}\, I_s\, T_{on}$$

During the time T_{off}, when chopper is OFF, energy released by the inductor to the load is given

$$E_{output} = (V_o - V_{d.c})\, I_s\, T_{off}$$

Considering the system to be lossless, and, in the steady- state these two energies will be equal

$$V_{d.c}\, I_s\, T_{on} = (V_o - V_{d.c})\, I_s\, T_{off}$$

$$V_o = V_{d.c}\, \frac{T_{on} + T_{off}}{T_{off}}$$

since $T = T_{off} + T_{on}$

$$V_o = V_{d.c}\, \frac{T}{T - T_{on}}$$

where "T" is the chopping period

$$V_o = V_{d.c}\, \frac{1}{\frac{T}{T} - \frac{T_{on}}{T}}$$

since $\frac{T_{on}}{T} = p$ (duty cycle)

$$V_o = \frac{V_{d.c}}{1 - p}$$

From the equations above, the variation of a duty cycle ρ in the range $0 < \rho < 1$ the output voltage will vary in the range $V_{dc} < V_o < \infty$

This principle of step-up chopper can be employed for regenerative breaking of the dc motors even at lower operating speeds. If we consider V_{dc} represent the dc motor generated voltage and V_o when

$$V_{dc} + L\frac{di}{dt} > V_o$$

Control strategies

The average value of output voltage V_o can be controlled by periodic opening and closing of the switches. The two types of control strategies for operating the switches are employed in dc choppers. They are:

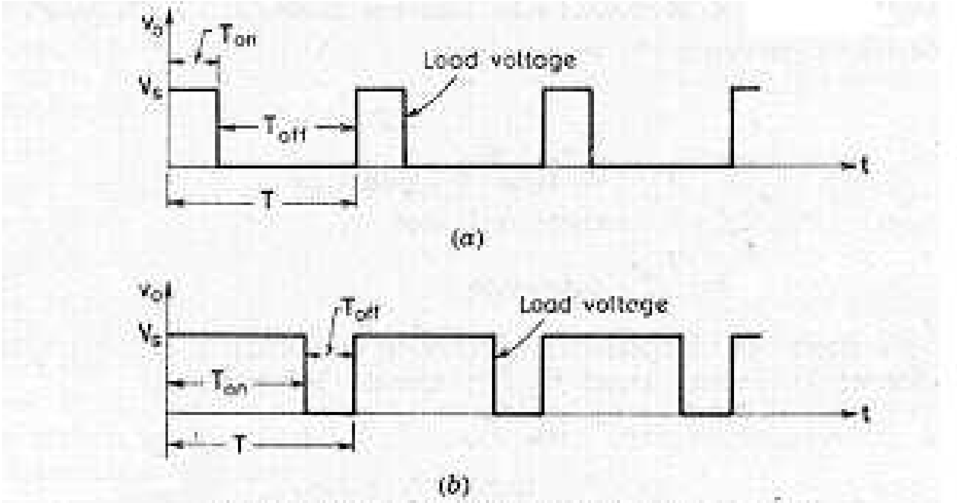
1- Time- ratio control (TRC)

2- Current limit control

Time – ratio control (TRC)

In the TRC, the value of $\frac{T_{on}}{T}$ is varied. This is effected in two ways. They are variable frequency operation and constant frequency operation.

1- Constant Frequency System. In this type of control strategy, the on- time T_{on}, is varied but the chopping frequency f (f=1/ T) and hence the chopping period T is kept constant. This control strategy is also called as *pulse- width modulation control.*



Principle of pulse-width modulation (constant *T*).

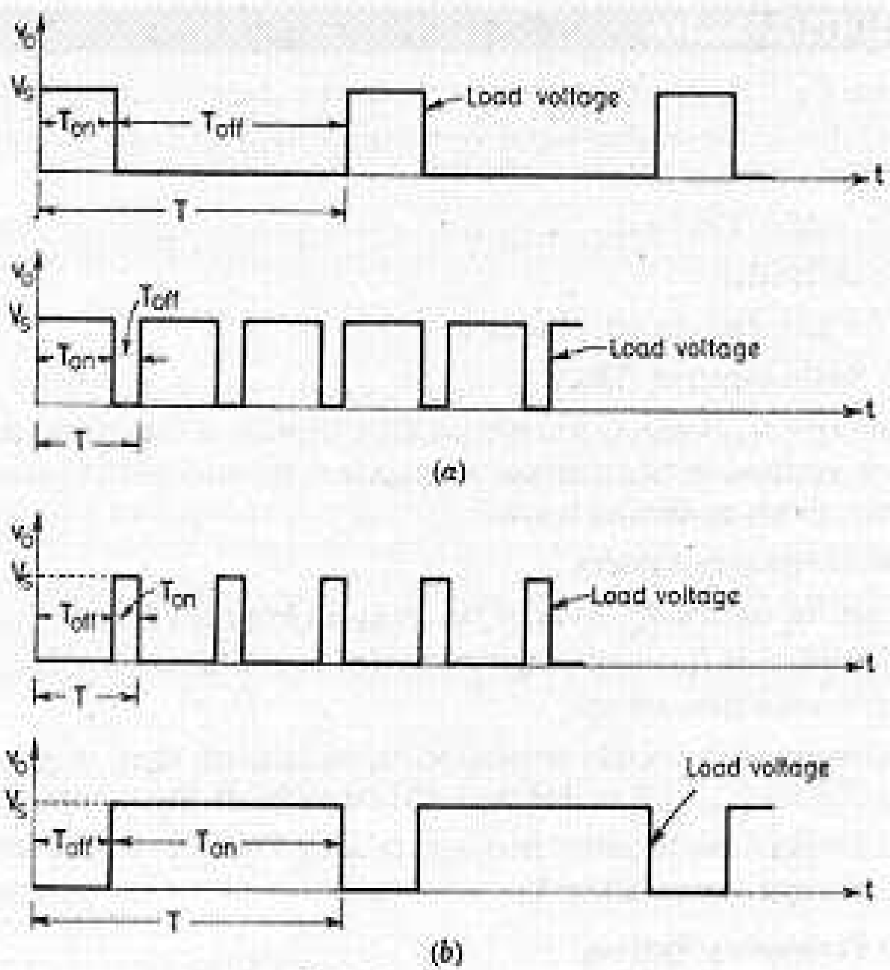
2- Variable Frequency System: In this type of control strategy, the chopping frequency f is varied and either

   a- ON- time is kept constant or

   b- OFF- time is kept constant

This type of control strategy is also called as *frequency modulation control*

The principle of frequency modulation as shown in fig. below, chopping period T is varied but on – time T_{on} is kept constant. The output voltage waveforms are shown for two different duty cycles, chopping period T is varied but T_{off} is kept constant.



Principle of frequency modulation.
(a) on-time T_{on} constant and (b) off-time T_{off} constant.

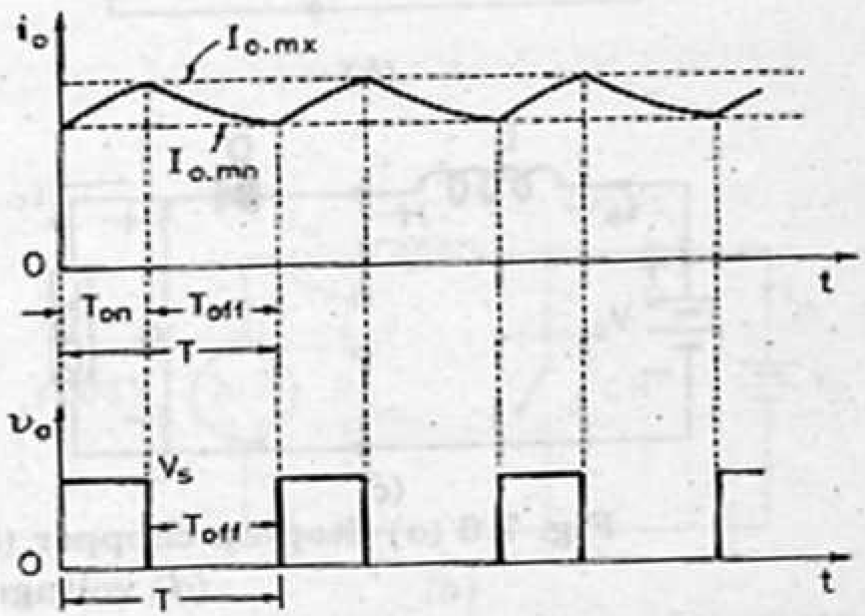
Frequency modulation control strategy has the following major disadvantages compared to pulse- width modulation such as

1- Chopping frequency varied over wide range, so filter design will be difficult.
2- Possibility of interference with signaling and telephone line in frequency modulation scheme
3- Large T_{off} in frequency modulation make load current discontinues which is undesirable.

Current Limit Control

In CLC strategy, the chopper is switched ON and OFF so that the current in load is maintained between two limits. When the current exceeds upper limit, the chopper is switched OFF. During OFF period, the load current freewheels and decrease exponential. When it reaches the lower limit, the chopper is switched ON. CLC is possible either with constant frequency or with constant T_{on}. The CLC is used only when the load has energy storage elements. Switching frequency of chopper can be controlled by setting I_{max} and I_{min}. The ripple current given by

$$I_{ripple} = I_{max} - I_{min}$$



Current-limit control for chopper.

This in turn increases chopper frequency thereby increasing the switching losses.