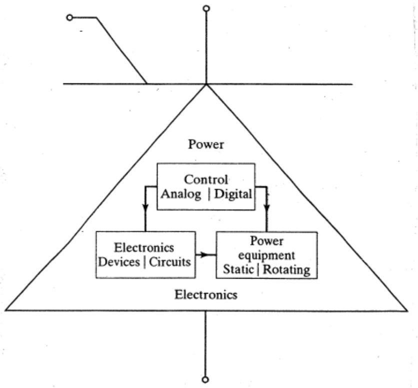
Module 1

Introduction_ Power Diodes_ Diode Rectifiers

Introduction: *Applications of Power Electronics, Ideal Characteristics of switches, Characteristics of practical devices; Specifications of Switches, control characteristics of power devices, Types of Power Electronic Circuits, Peripheral Effects, Intelligent Modules.*
Power Diodes: *Introduction, Diode Characteristics, Reverse Recovery Characteristics, Power Diode Types, Silicon Carbide Diodes, Silicon Carbide Schottky Diodes, Freewheeling diodes, Freewheeling diodes with RL load.*
Diode Rectifiers: *Introduction, Diode Circuits with DC Source connected to R and RL load, Single-Phase FullWave Rectifiers with R load, Single-Phase Full-Wave Rectifier with RL Load.*

Introduction:

Power electronics is the branch of electrical engineering that deals with the processing of high voltages and currents to deliver power that supports a variety of needs. From household electronics to equipment in space applications, these areas all need stable and reliable electric power with the desired specifications. Power supply in one form is processed using power semiconductor switches and control mechanisms to another form, supplying a regulated and controlled power. While switched-mode power supplies are a common application of power electronics where power density, reliability, and efficiency are of prime importance, motor control is gearing up with more electrification in transportation systems. Precise control and efficiency are key characteristics for power control applications.

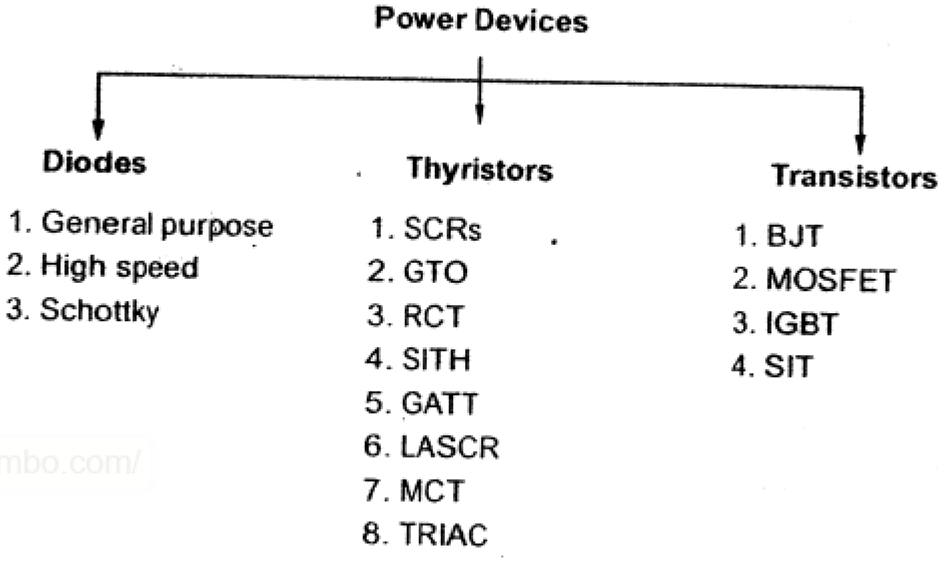


Applications of Power Electronics:

Commercial Applications: Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipment, Uninterruptible Power Supplies (UPS), Elevators, and Emergency Lamps.
Domestic Applications: Cooking Equipment, Lighting, Heating, Air Conditioners, Refrigerators & Freezers, Personal Computers, Entertainment equipment, UPS.
Industrial Applications: Pumps, compressors, blowers, and fans; machine tools; arc furnaces; induction furnaces; lighting control circuits; industrial lasers; induction heating; welding equipment.
Aerospace Applications: Space shuttle power supply systems, satellite power systems, aircraft power systems.
Telecommunications: Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers.
Transportation: Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls.

Power semiconductor devices:

The power semiconductor devices are used as ON/OFF switches in power control circuit. These devices are classified as follows:

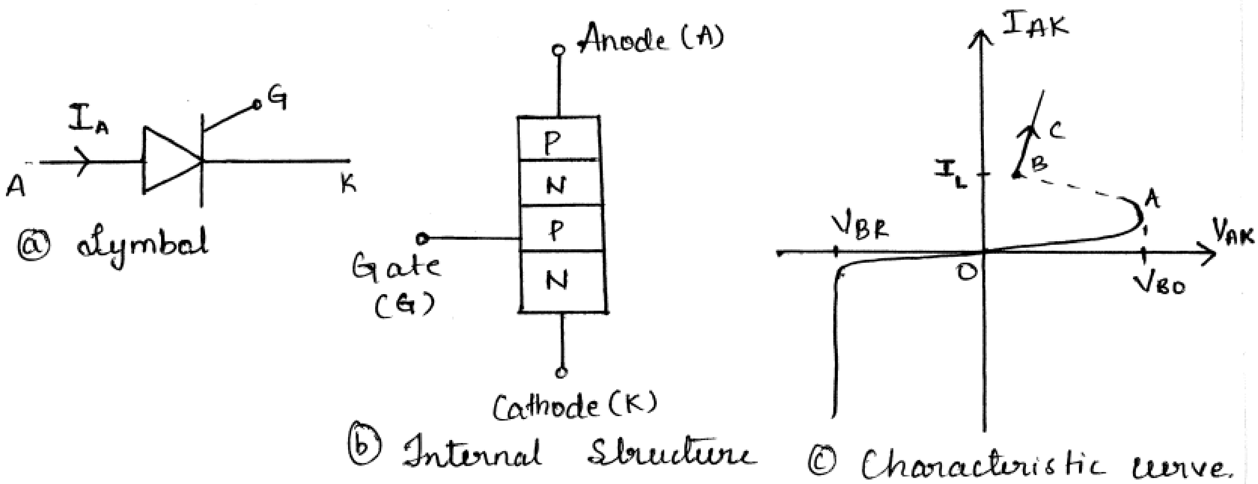


Characteristics and Specifications of Switches:
Thyristors family
Input/Output Characteristics of power semiconductor devices:

There are 8 types of power devices in the thyristor family, they are:

I. Silicon Controlled Rectifiers (SCR)
2. Gate turn-off thyristor (GTO)
3. Reverse conducting thyristor (RCT)
4. Static Induction thyristor (SITH)
5. Gate-assisted Turn-Off thyristor (GATT)
6. Light-activated silicon-controlled rectifier (LASCR)
7. MOS- Controlled thyristor (MCT)
8. TRIAC

1. Silicon Controlled Rectifiers (SCR):



(a) symbol (b) Internal Structure (c) Characteristic curve.

- The SCR has three terminals namely

Anode(A)
Cathode (K)
Gate (G)

- Internally it is having 4 layers PNPN shown in figure (b).
- When anode is made positive with respect to cathode then SCR is forward biased
- A small positive voltage is applied between gate and cathode to turn on the SCR. Now current flows from anode to cathode in the SCR.
- When the thyristor is in a conduction mode, the forward voltage drop is very small typically 0.5 to 2 volts. Once the SCR is turned **ON** the gate has no control over the conduction of SCR. Even if the gate is remote SCR does not **turn off.**
- A conduction thyristor can be turned off by making the potential of the anode equal to or less than the cathode potential.

Advantages:

- Very small amount of gate drive is required.
- SCR's with high voltage and current ratings are available.
- ON state losses in SCR's are reduced.

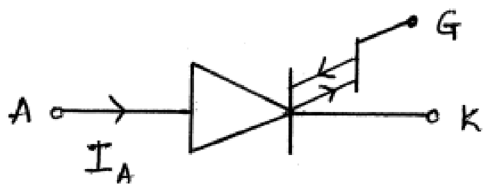
Disadvantages:

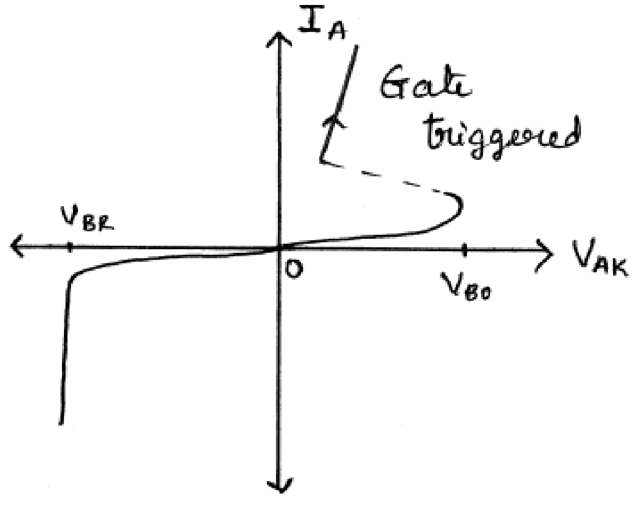
- Gate has no control once the SCR is turned ON.
- External circuits are required to turn off the SCR.
- Operating frequencies are very low.
- Snubber (RC circuits) are required for dv/dt protection.

Applications:

- SCRs are best suited for controlled rectifiers.
- AC regulators, lighting and heating applications.
- DC motor drives, large power supplies and electronic circuit brakes.

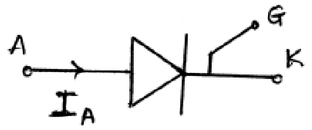
2. Gate Turn OFF Thyristor:

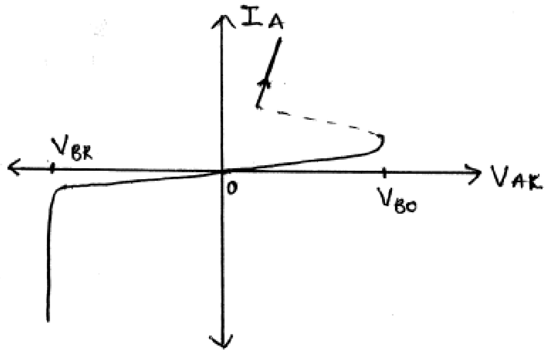




- GTO can be turned off by applying negative gate pulse. The gate has full control over the conduction of GTO. GTO do not require any commutation circuit.
- GTO is turned ON by giving positive gate pulse.
- When input is not given and gate pulses made positive then GTO is in the turn-OFF state. When input is given and gate pulse is made positive then GTO is turned ON.
- GTO are used for low power applications. The gate drive (pulse) required for turn-off is very large. Hence driver circuit of GTO required more power.

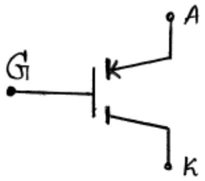
3. Static Induction Thyristor:

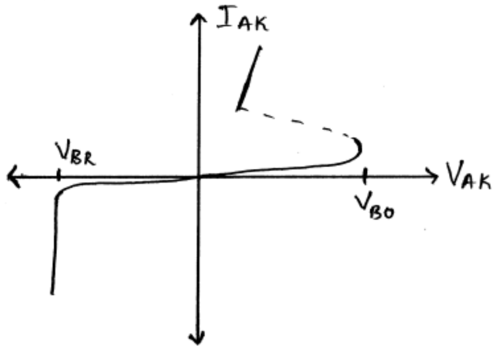




- SITH can be turned OFF by applying a negative gate pulse. Thus gate has full control over the conduction of SITH.
- SITH do not require any commutation circuit.
- SITH is turned ON by giving a positive gate pulse.
- When input is not given and gate pulse is made positive then SITH is in turn OFF state.
- When input is given and gate pulse is made positive then SITH is in turn ON state.
- SITH are used in medium power converter circuits.

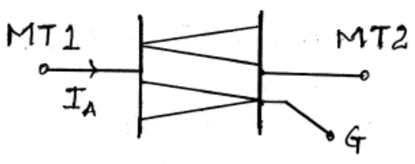
4. MOS Controlled Thyristor-MCT:

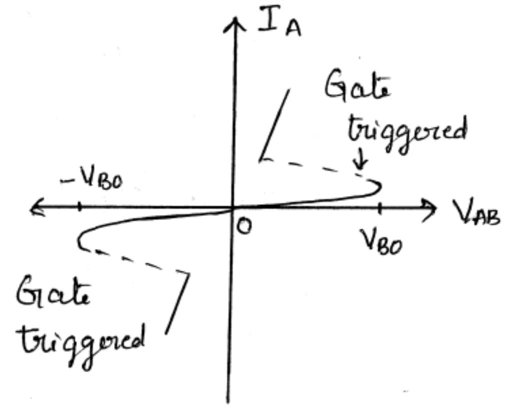




The MCT can be turned on by negative voltage to the gate and it can be turned off by positive voltage. MCT's have lower power ratings than GTO and SITH.

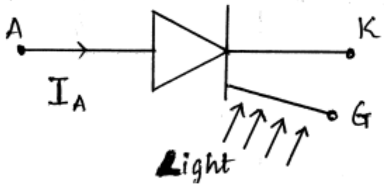
5. TRIAC:

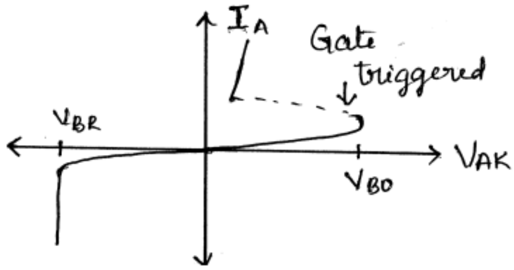




- TRIAC can be considered as antiparallel SCR. TRIAC conducts in both directions and it has single gate. The current flows through a TRIAC can be controlled in either direction
- TRIAC are widely used in all types of simple heat controls, light controls, motor controls and AC switches.

6. Light-activated silicon-controlled rectifier (LASCR):





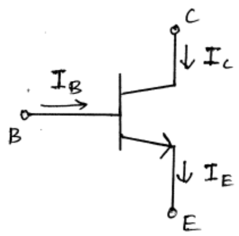
- The LASCR can be turned ON by light signal. The gate is photosensitive and SCR turns ON when light falls on it.
- LASCRs provides isolation between the gate and the drive circuit.
- LASCRs are used in HVDC transmission.

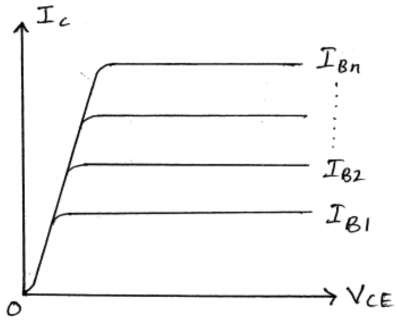
7. Reverse Conducting Thyristor (RCT): An RCT has an SCR with an antiparallel diode. It has high current capability in forward direction, but less capability in reverse direction. RCT's are particularly suitable for inductive load.

8. Gate Assisted Turn-off Thyristor (GATT): GATT are particularly suitable for high speed switching, medium power applications. They require forced turn-off circuits.

Transistor Family: In the transistor family of devices there are Bipolar Junction Transistors (BJT), Metal Oxide Field Effect Transistors(MOSFET), Insulated Gate Bipolar Transistors(IGBT) and SIP.

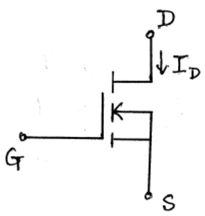
1. BJT:

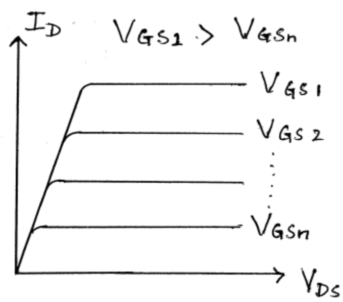




- A bipolar transistor has three terminals base, emitter and collector. It is normally operated as a switch in the common emitter configuration.
- When base voltage is at a higher potential then the emitter and base current is sufficiently large to drive the transistor is the saturation region, the transistors remains ON.
- The forward drop of a conducting transistor is in the range of 0.5 to 1.5V.
- When base voltage is removed transistor remains in OFF mode.

2. N- Channel MOSFET:



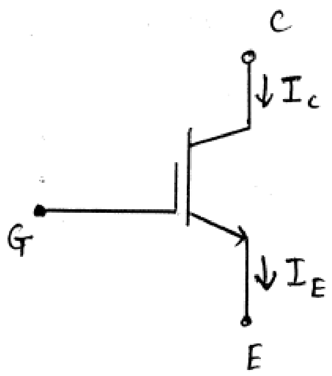


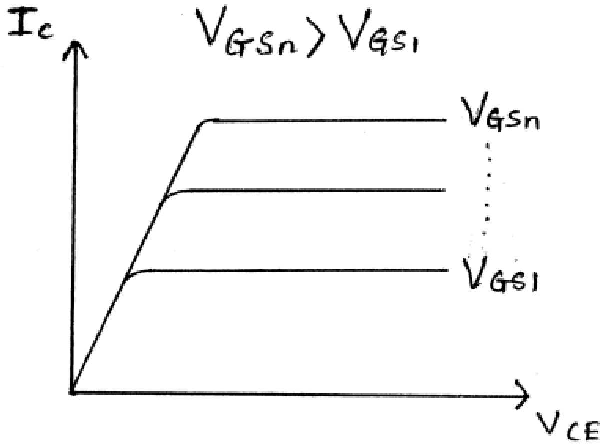
- There are two types of MOSFET's namely

N-channel MOSFET
P-Channel MOSFET

- MOSFET's are used for low power and high speed applications at a frequency of several tens of kilohertz

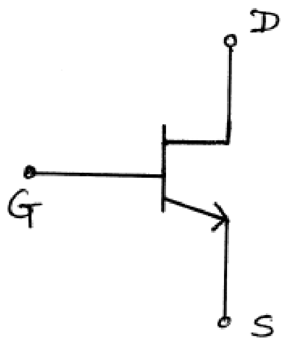
3. IGBT:

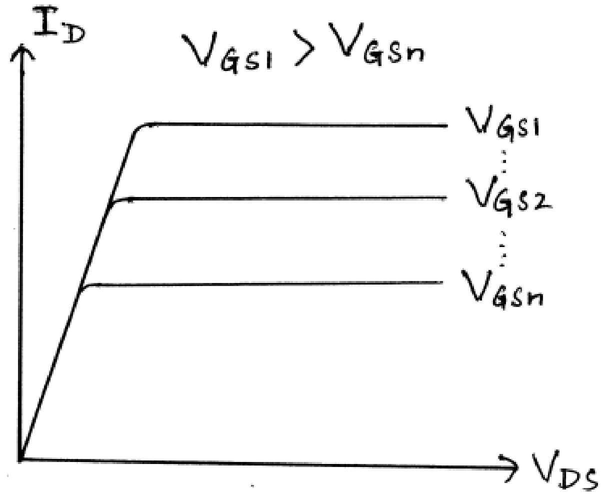




- IGBT are voltage controlled power transistors. They are inherently faster than BJT's but less faster than MOSFET's.
- The drive and output characteristics of IGBTs are for superior than BJTs.
- IGBTs are suitable for high current and frequencies up to 20 KHz.
- IGBT's are available up to 1200V,400A.

4. SIT- Static Induction Transistors:



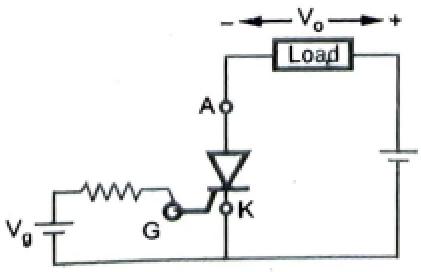


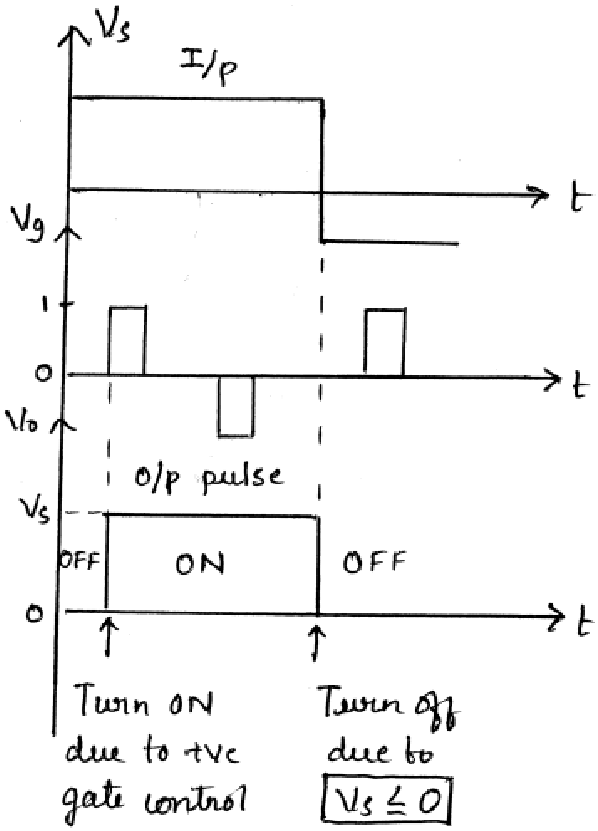
- A SIT is a high-power, high frequency device. It is similar to a JFET. It has a low noise, low distortion, high audio frequency power capability.
- The turn ON and turn OFF times are very short typically 0.25 microseconds.
- The current rating of SITs can be up to 1200 V, 300 A and the switching speed can be as high as 100 KHtz.

Applications:
SITs are most suitable for high-power, high-frequency applications.
Ex: Audio,VHF/UHF and microwave amplifiers.

Control Characteristics of Power Semiconductor Devices:

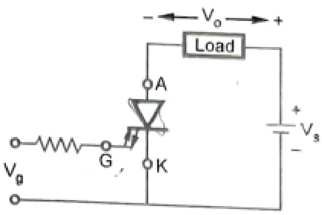
Control Characteristics of SCR:



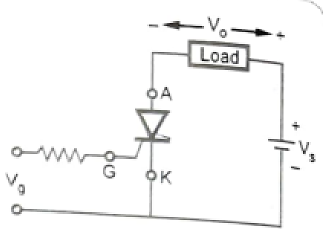


A positive voltage (Vs) is applied through load across the anode-cathode of the SCR. A positive voltage (Vg) ia applied across the gate-cathode. applied across gate-cathode. A positive gate voltage turns on the SCR. Hence complete Vs appears across the load. Gate has no control over the conduction of the SCR, once it is turned on. Hence applying negative gate pulse does not turn-off the SCR.

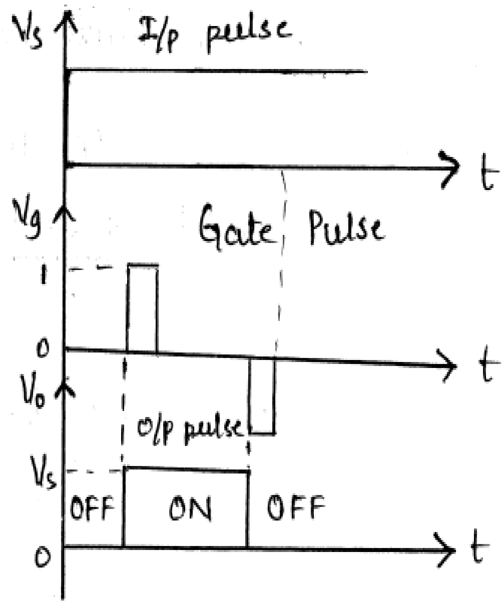
Control Characteristics of GTO and SITH:



(a) Circuit of GTO



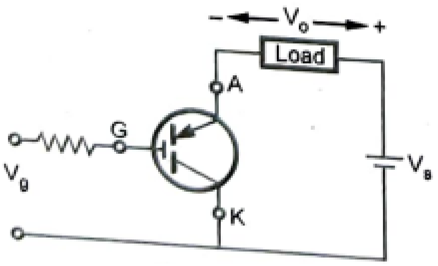
(b) Circuit of SITH

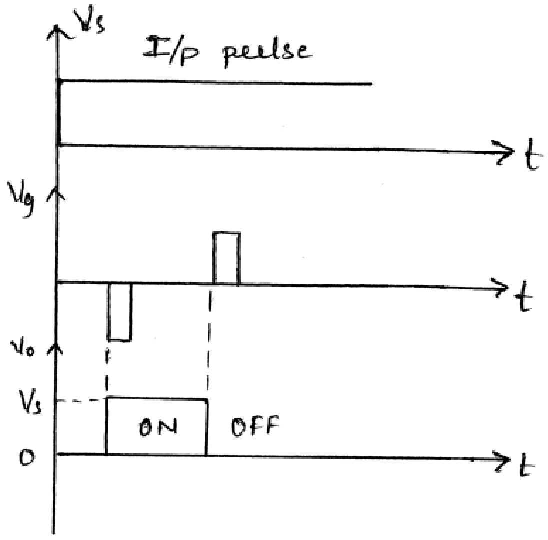


GTO and SITH have similar control characteristics. As shown in Fig. a positive voltage (v s) is applied through load across anode-cathode.Whenever the devices turns-on, this voltage appears across the load. When the device is turns off, the output voltage is zero. A positive gate voltage tums on GTO and SITH. They can be turned-off with the help of negative gate-cathode voltage.

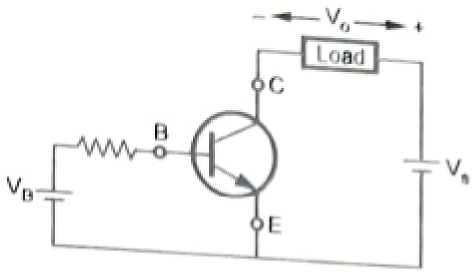
Control Characteristics of MCT:

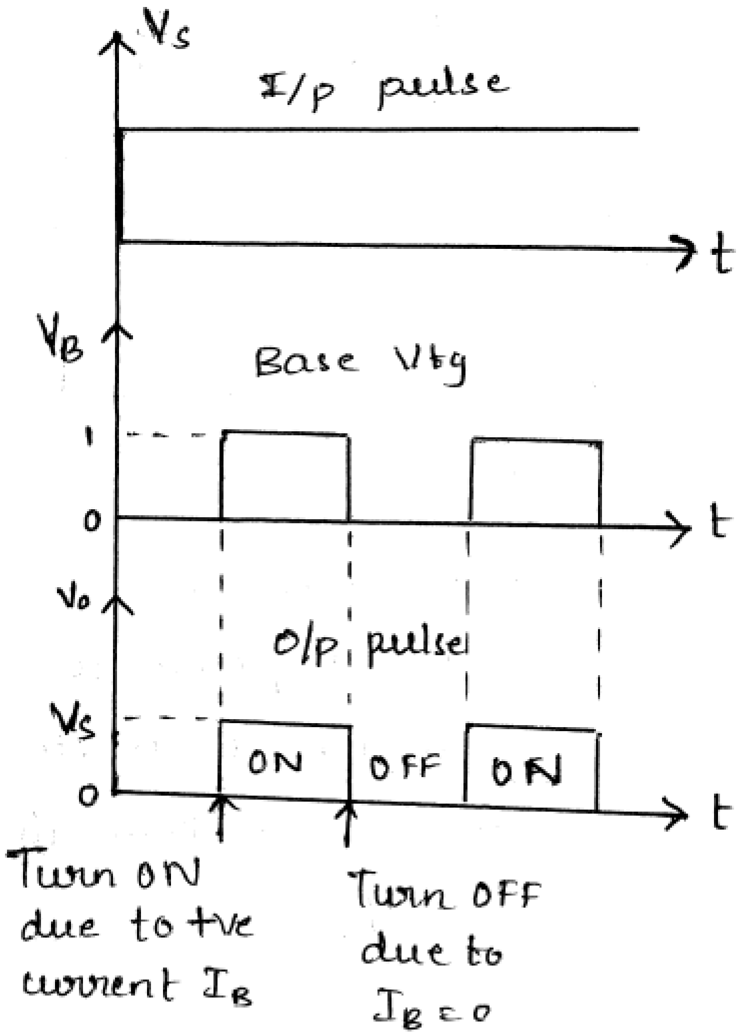
A positive voltage (Vs) is applied through load between anode-cathode of MCT. A negative voltage between gate-cathode turns-on the device and supply voltage (Vs) appears across load. A positive gate voltage turns-off the device and load voltage becomes zero.





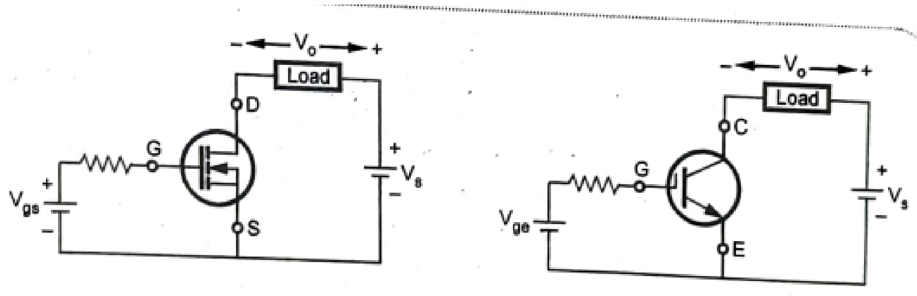
Control Characteristics of BJT:





A positive voltage (Vs) is applied through load between collector and emitter of the transistor. The control voltage is applied base-emitter. When base-emitter voltage is positive, BJT turns on and supply voltage Vs appears across load. The BJT turns-off when base-emitter voltage is zero. Hence output voltage is also zero.

Control Characteristics of MOSFET and IGBT:

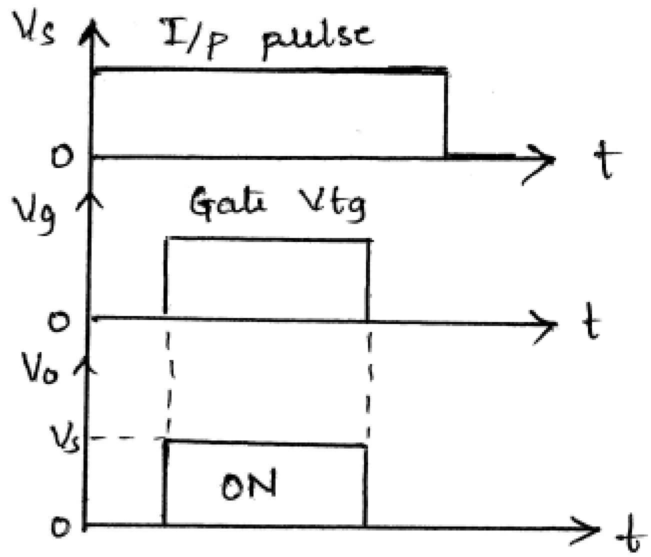


(a) Circuit of MOSFET

(b) Circuit of IGBT

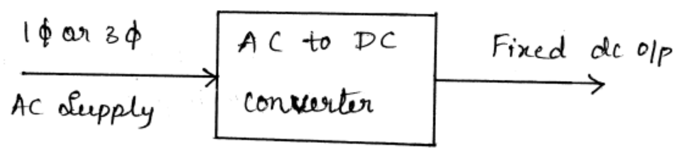
As shown in Fig.(a), the positive voltage (Vs) is applied between drain-source through load. A positive gate-source voltage tums-on the MOSFET. The load voltage is equal to supply voltage. When gate-source is zero, the MOSFET turns-off and load voltage is zero.

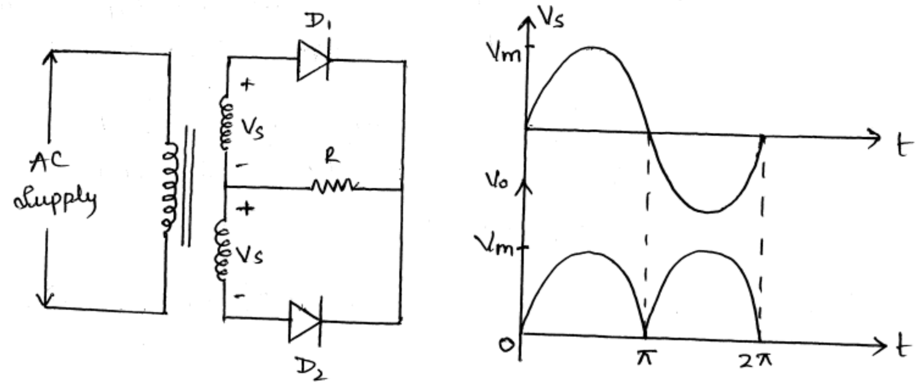
• Similarly in Fig. .1.5.5 (b) observe that positive supply voltage Vsis applied through load between collector-emitter of IGBT. A positive gate-emitter voltage tums-on IGBT and supply voltage (Vs) appears across the load. Zero gate-emitter voltage turns off the device and load voltage is zero.



Types of Power Electronic Circuits:

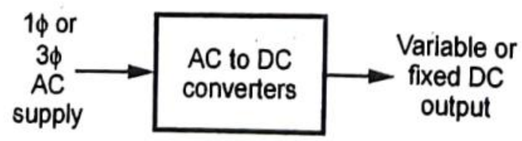
Diode Rectifier:

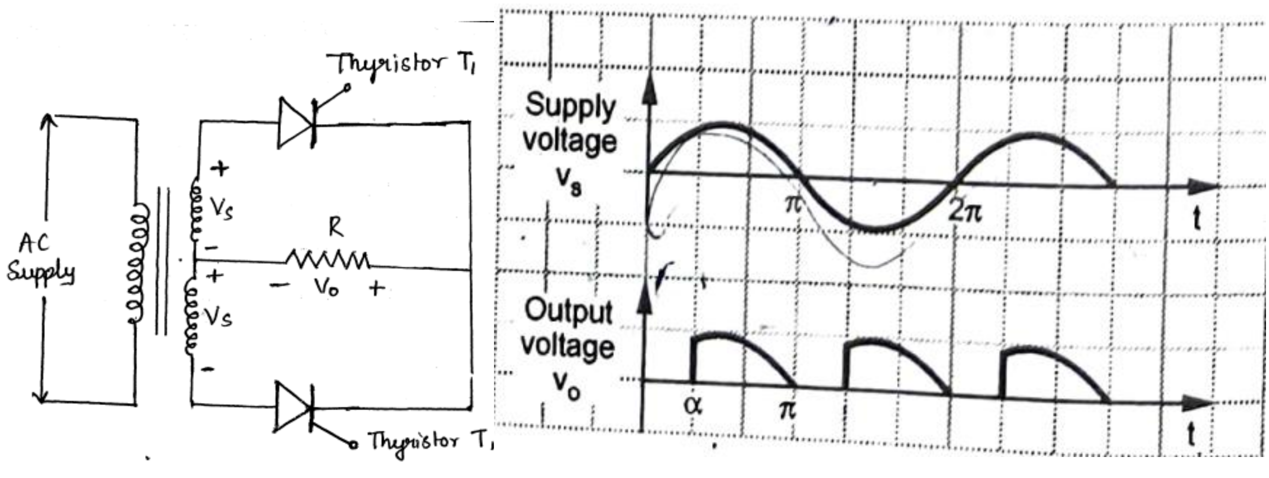




A diode rectifier circuit converts AC voltage into fixed DC voltage as shown in figure. The input voltage to the rectifier voltage could be single phase or three phase.

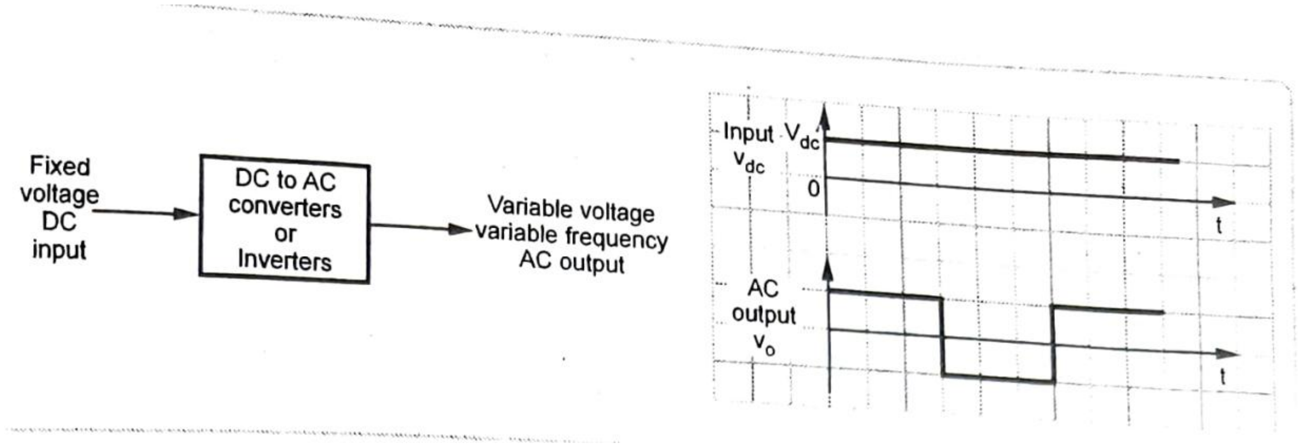
AC to DC Converters (Controlled rectifier):





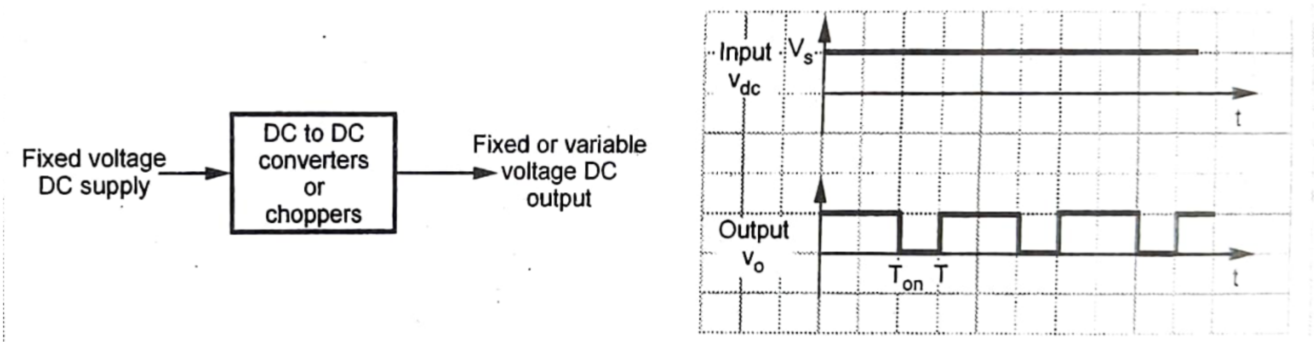
- The input is single-phase or three-phase AC supply normally available from the mains. The output is the DC-controlled voltage and current.
- The AC to DC converters include diode rectifiers as well as controlled rectifiers. The controlled rectifiers -mainly use the SCR. Since the input is AC supply, the SCRs are turned off by natural commutation. Hence external commutation circuits are not required
- The average value of the output voltage can be controlled by varying the firing angle α.
- . These converters are used for DC drives, UPS and HVDC system.

DC to AC Converters (Inverters):



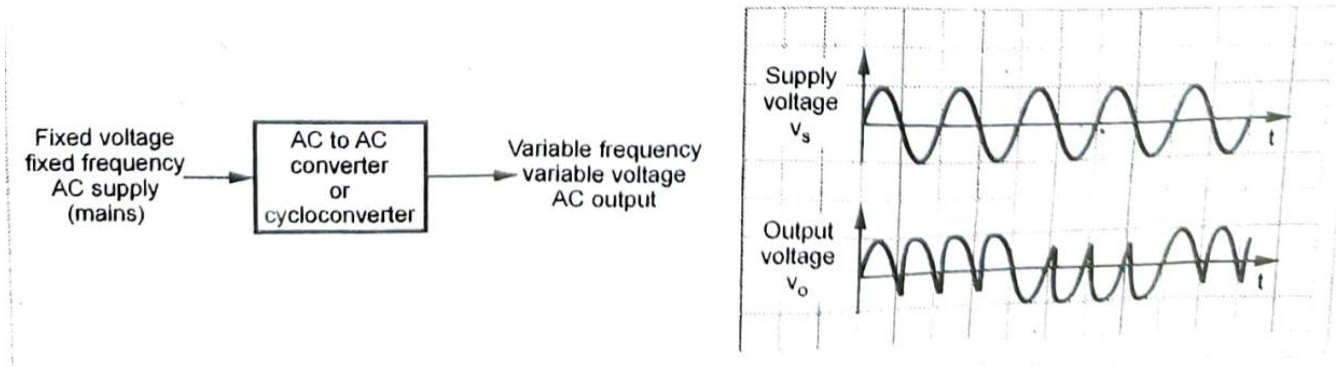
- These Converters are commonly called as inverters.
- The input to the inverter is fixed DC voltage. Normally this DC voltage is obtained from the batteries. The output of the inverter is the fixed or variable frequency AC voltage. The AC voltage magnitude is also variable.
- Inverters are mainly used whenever mains is not available.
- UPS use inverters inside to generate AC output from batteries. Inverters are also used for speed of Induction motors.

DC to DC Converters (Choppers):



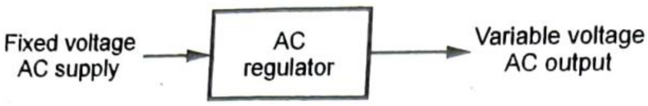
- The choppers take input from fixed voltage DC supply such as a battery or output of an uncontrolled rectifier.
- The output of the chopper is fixed or variable DC voltage. The Choppers are normally used in DC drives. The speed of the motor can be controlled in forward and reverse directions. The choppers are also used in Switched Mode Power Supplies (SMPS).

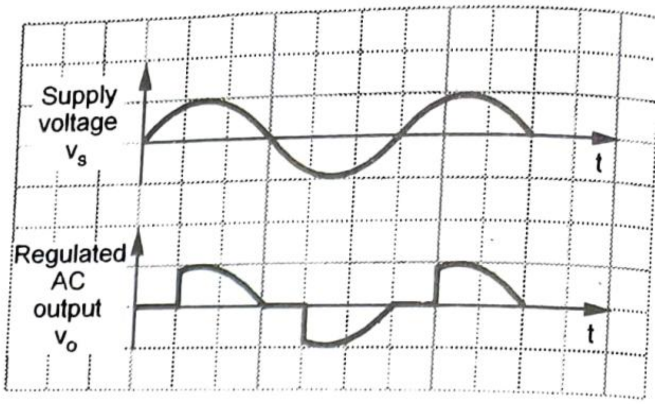
AC to AC converters or Cycloconverters:



The input to the cycloconverters is normally 1 or 3 AC mains supply. It is fixed voltage and fixed frequency. The cycloconverters provide the output which has variable voltage and variable frequency.
The output frequency is lower than the input frequency. The cycloconverters are used mainly for AC traction drives.

AC Regulators:



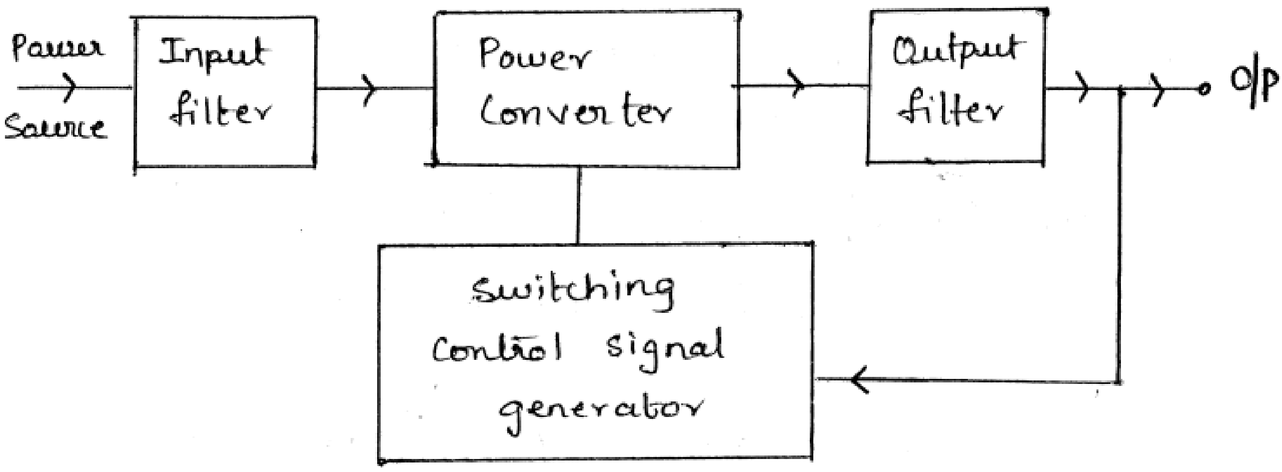


- The input to the AC regulator is fixed voltage AC mains. The output is variable AC voltage which is suitable for load.
- Output frequency is same as input frequency. Thus AC regulators does not change the frequency.

Peripheral Effects:

Fig shows the block diagram of a power electronic converter. It takes input power from the power source and delivers it to the load. The power converter normally uses switches to convert input power in the required form. Because of the switching actions following things take place.

1. Switching voltage/current pulses are induced in the power supply.
2. Harmonics are induced in the power supply due to improper waveforms.
3. Load contains voltage/current spikes and harmonics.
4. Interference is radiated (RFI and EMI) due to switching of devices.



These effects certainly affect other loads which are connected to the same power supply. Similarly, output of the power converter is also distorted. Hence it affects the performance of the load connected to it.
These problems can be reduced considerably by putting filters before and after the power converters. There filters attenuate the harmonics and noise spikes.
In order to reduce this problem, it is required to know the quality of power and content of harmonics.

This can be analysed by calculating the total

Total harmonic distortion (THD)
Displacement factor or harmonic factor (HF)
Input power factor are measures of the quality of the waveforms
To evaluate the performance of a converter, the input and output voltages/currents of a converter are expressed in Fourier series. The quality of a power converter is judged by the quality of its voltage and current waveforms.

Advantages and Disadvantages of Power Electronic Controller:

Advantages:

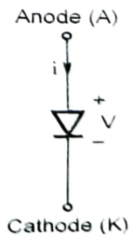
1. Fast dynamic response due to static devices.
2. High efficiency of conversion due to low losses in electronic devices.
3. Compact size and light weight of the controllers due to electronic devices.
4. Increased operating life and reduced maintenance since there are no moving parts.
5. Power electronic controllers use digital or microprocessor based control. Hence their operation is
6. highly flexible.
7. Since solid-state devices are used, the electromagnetic interference and acoustic noise is reduced.

Disadvantages:

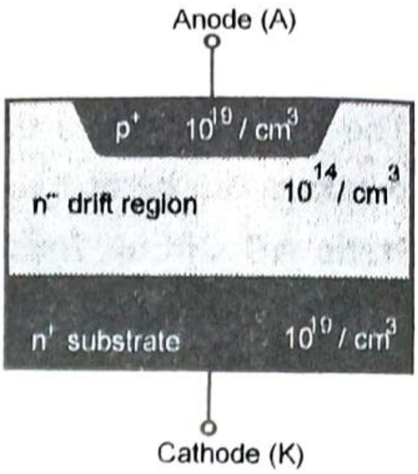
1. The power electronic controllers generate harmonics. These harmonics affect the performance of other loads.
2. The power factor _of some power electronic controllers is very low. Hence power factor correction is necessary to reduce reactive power.
3. For very simple conversion requirements, power electronic converters may be costly.

Power Diodes:

Power diodes are required in most of the power converters. The power diode is an uncontrolled device. When anode (A) is positive with respect to cathode (K), diode starts conducting. Normally a forward bias of 1 volt is sufficient to push the diode in conduction. Current flows from anode to cathode. The diode does not conduct when anode to cathode voltage is negative. The diode is said to be reverse-biased.



Structure of Power Diode:



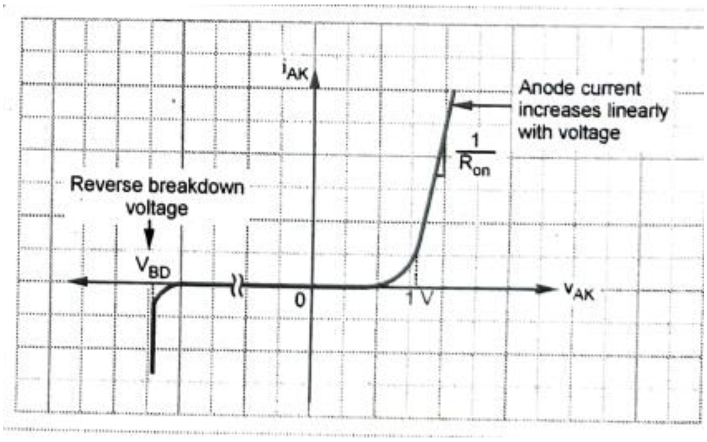
The structure of the power diode is little different than the small signal diodes. Fig. shows the structure of power diode. In this figure observe that there is heavily doped n^+ substrate with doping level of $10^{19}/cm^3$. This substrate forms a cathode of the diode. On n^+ substrate, lightly doped n^- epitaxial layer is grown.

Conductivity modulation of the drift layer
• Now let us see what will happen when the power diode is forward biased. Under this condition, the holes will be injected from the region into the drift region. Some of the holes combine with the electrons in the drift region. Since injected holes are large, they attract electrons from the n^+ layer. Thus holes and electrons are injected in the drift region simultaneously. Hence resistance of the drift region reduces significantly. Thus diode current goes on increasing, but drift region resistance remains almost constant. Hence on-state losses in the diode are reduced. This phenomenon is called conductivity modulation of drift region. This phenomena is present in almost all the power devices.

VI Characteristics of Power Diode:

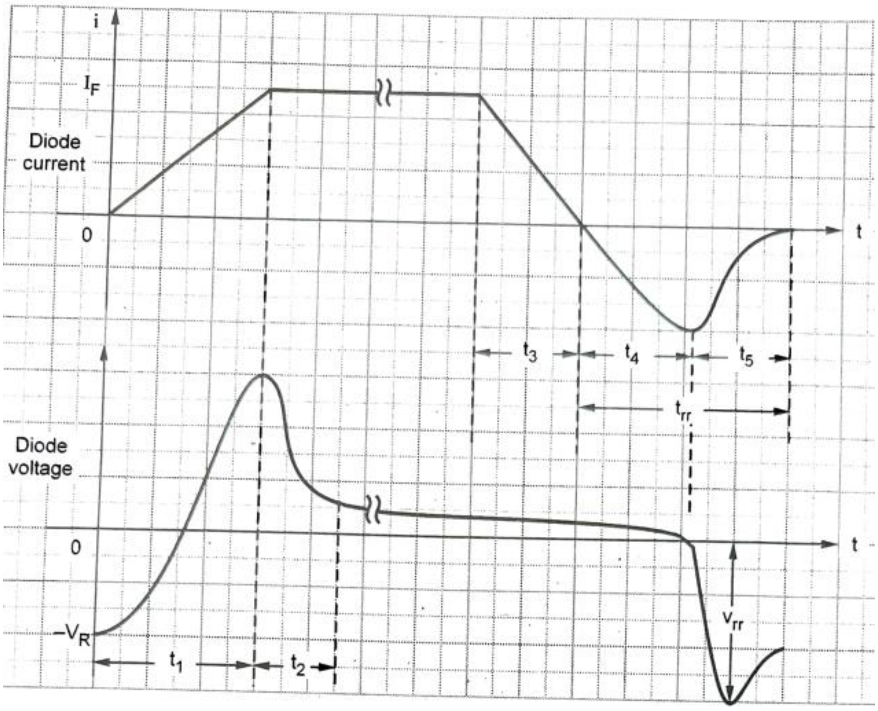
In the forward biased condition, anode current increases linearly with voltage. In lower-power diodes, current increases exponentially. The linear rise takes place because of ohmic resistance in n $^-$ layer. The n $^-$ drift region is lightly doped. Hence, it appears as low value internal resistance of the diode. Therefore current is linearly proportional to voltage. A forward bias of 1 V is sufficient to trigger diode into conduction.

When the diode is reverse biased, a very small anode current flows. This current is called leakage current. When the reverse bias is greater than reverse breakdown voltage, anode current starts rising rapidly. Hence, large power dissipation takes place in the diode and it is damaged.



Switching Characteristics of Diodes or , Reverse Recovery Characteristics:

Power diodes are mainly used in commutation and freewheeling circuits. The di/dt through the diode is controlled by these circuits. The voltage across the diode changes according to current through it.



As shown in the figure, the diode is reverse biased (—VR) initially. Hence space charge is stored in the depletion region. When diode current starts increasing during period t_1, the voltage also increases. At the end of t_1, voltage across diode at peak. This voltage overshoot occurs, because there is no conductivity modulation during t_1. Hence, ohmic resistance of the drift region and inductance offered by the silicon wafer is high. Therefore there is large voltage drop in the diode. There is large amount of carrier injection in the drift region. Hence, space charge in the drift region is discharged to its thermal equilibrium. By this time diode current reaches to its steady state value. Then during time t_2', conductivity modulation begins and resistance of drift region starts reducing. Hence, voltage across diode reduces and comes down to minimum value. At the end of time t_2, diode voltage drop becomes minimum and remains steady.

Now let us consider the case when di/dt is negative. That is when diode current reduces. As shown in Fig. the voltage also reduces by small value. During t_3 and t_4, diode current is reducing. But voltage drops by a small value. During this period there are excess carriers in the drift region. Hence, even if diode current is negative in t_4, the voltage drops by a small value. At the end of t_4, all the excess carriers in drift region are removed. Hence, the junctions p^+n^- and n^+n^- are reverse biased. The negative current continues to flow in t_5. Hence, depletion regions are created in drift layer. Therefore diode voltage becomes

negative. The negative diode current goes to zero at the end of t5 since there are no carriers. Hence, the diode voltage falls-to negative bias voltage $-V_R$ as shown in Fig.
During t_4 and t_5, excess carriers are removed from the diode and reverse voltage is buildup. This period is called reverse recovery period of the diode. And the portion of characteristics from t_3 to t5 is called reverse recovery characteristics.

Types of Power Diodes:

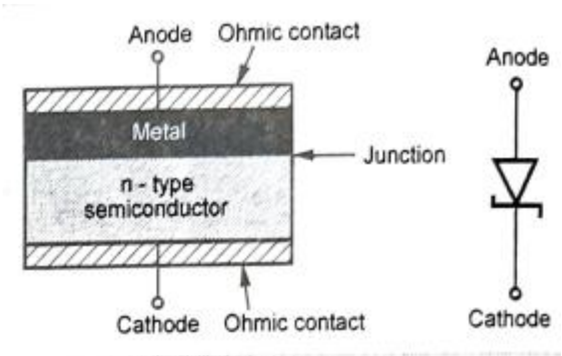
There are 3 types of power diodes
1) General purpose diodes
2) High speed (Fast recovery) diodes
3) Schottky diodes

1. General purpose diodes: These diodes have high reverse recovery time of about 25usec. Hence these are used in low speed applications such as rectifiers and converters. They can operate 1Khz. The rating are from IA/50V to IOOOA/500V.

2. Fast recovery diodes: These diodes have the reverse recovery time less than 5usec. Hence these diodes are used in high speed applications such as choppers and inverters. These diodes have ratings from IA/ 50V to 100A/3KV.

3. Schottky Diode:

- In Schottky diodes, the pn junction is eliminated. A thin film of metal is placed directly on the semiconductor as shown in figure. Aluminum is deposited on n-type semiconductor. The metal is anode and the semiconductor is cathode.
- Since there is no pn junction, the storage time is absent. Hence turn-off time is very small. So Schottky diodes have high switching frequencies. Schottky diodes are used in low voltage converters as feedback and freewheeling diodes.

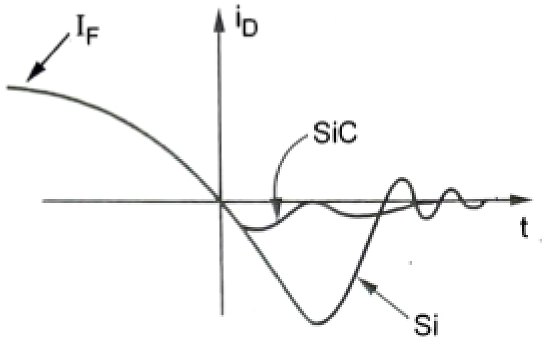


Applications of Power Diodes:

1. Power diodes are used in uncontrolled rectifiers
2. Feedback and freewheeling operations in choppers, inverters and controlled converters use power diodes.
3. Almost all the commutating circuits for SCR's use power diodes.
4. Half-controlled converters and half-bridge inverters use power diodes.

Silicon Carbide(SiC) Diodes:

- Silicon Carbide (SiC) have better physical properties compared to Si and GaAs. SiC diodes are manufactured by Infineon technologies.
- SiC diodes have very low reverse recovery time as shown in Fig. The reverse recovery current is reduced for SiC diodes.



Reverse recovery times of Si and SIC diodes

Features of SiC Diodes:

1. They have no reverse recovery time

2. Their switching is extremely fast.
3. Switching behaviour is unaffected by temperature.
4. Very small power loss.
5. High reliability,

Advantages:

1. High efficiency
2. Solution size is reduced
3. High switching frequencies
4. Reduced / small electromagnetic interference (EMI)

Applications:

1. Energy Saving power supplies
2. Efficient %lar energy conversion
3. Welding equipment
4. Air conditioning
5. Transportation

Silicon Carbide (SiC) Schottky Diodes:

- Instead of Silicon or GaAs, SiC diodes use Silicon Carbide (SiC) as the semiconductor material.
- A thin film of metals such as gold, platinum or silver is placed on the n - type Silicon Carbide semiconductor. Thus instead of pn -junction, there is metal - semiconductor junction.
- Fig. shows the structure and symbol of Schottky diodes. All Schottky diodes operate with only majority carriers. There are no minority carriers. Hence there is no reverse leakage current in Schottky diodes.
- The metal region large number of conduction band electrons. The n-type silicon carbide region is lightly doped.
- When the diode is forward biased, the higher energy electrons in the n-type region are injected into metal region. Thus, the current flow is established due to electrons only.

Advantages and Features of SiC Schottky Diodes:

1. Switching Speeds are very high.
2. Highly reliable and rugged.
3. Reduced costs due to no additional cooling.
4. High power density.
5. Switching are very low.
6. Stable at high Surge currents.
7. Operates at high frequencies

Diode Switched RL Load:

Diode Circuit with RL Load:

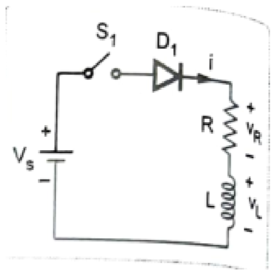


Fig. shows the diode circuit with RL load. Here the supply voltage Vs is supposed to be fixed DC. It is connected to the RL circuit through switch S_1.
When the switch S is closed, the current ' i ' starts flowing through the circuit.
Applying KVL to the RL circuit we get,

$$V_s = v_R + v_L$$

$$V_s = iR + L\frac{di}{dt}$$

At t = 0, i= 0 since initially there is no current in the circuit. Solving above differential equation,

$$i(t) = \frac{V_s}{R}(1-e^{-t\,R/L})$$

or

$$i(t) = \frac{V_s}{R}(1-e^{-t/\tau}),\ \tau=\frac{L}{R} \qquad \text{……(1)}$$

Here

$$\tau = \frac{L}{R} \text{ is called time constant of RL circuit.}$$

The rate of change of current will be,

$$\frac{di(t)}{dt} = \frac{V_s}{R}e^{-t\,R/L}\times\frac{R}{L} = \frac{V_s}{L}e^{-t\,R/L}$$

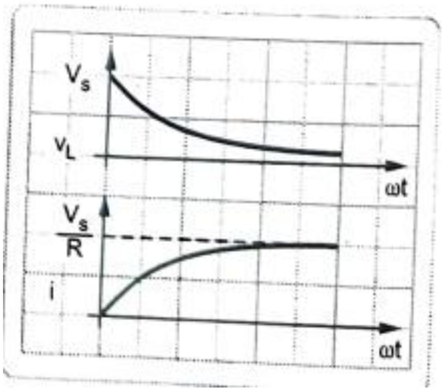
Initial rate of rise of current will be,

$$\left.\frac{di(t)}{dt}\right|_{t=0} = \frac{V_s}{L}$$

The voltage across inductor is expressed as,

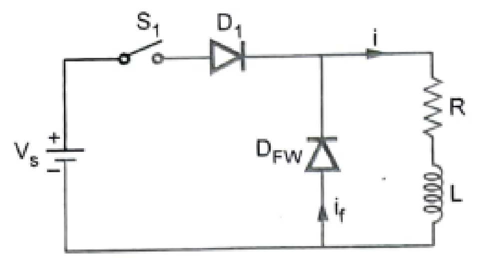
$$v_L = L\frac{di}{dt} = L\cdot\frac{d}{dt}\frac{V_s}{R}(1-e^{-tR/L})$$

$$v_L = V_s e^{-tR/L} = V_s e^{-t/\tau} \qquad \text{……(2)}$$



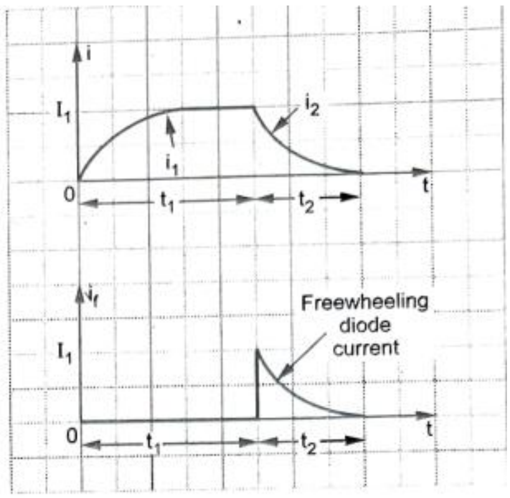
- Fig. 1.102 shows the sketches of inductor voltage and current according to equations (1) and (). Note that the current reaches to maximum value Of Vs/R as inductance fully saturates.
- Initial Inductor current is zero and voltage is Vs. The energy stored in the inductor is 0.5 Li^2. It is transformed with high reverse voltage across the switch S_l and diode D_l. This energy may damage diode D1. Hence a free wheeling is connected across RL load.

freewheeling Diodes with Switched RL Load:



(a) RL load with freewheeling diode

- Fig (a) shows the diode switched RL load with freewheeling diode D_{FW}. Fig (b) shows the waveforms of the load current (i) and freewheeling diode current (i_f).

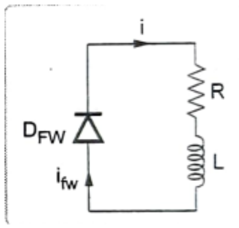


(b) Load and freewheeling diode currents

- The switch S_l is closed at t = 0 assuming that no initial current in the load. Hence load current (i) increases from zero with the initial slope of Vs/ L.

The current i_1 (t) is expressed as,

$$i_1(t) = \frac{V_s}{R}(1-e^{-t\,R/L}) \quad \text{for} \quad 0 \le t \le t_1 \qquad \text{………(1)}$$



If the switch is closed for long time, then the load current settles to its value of $I_l = V_s/R$ as shown in the waveform.

At the end of time t_l the switch S_l is opened, Hence the load current 'i' starts flowing through Freewheeling diode D_{FW} and load as shown in Fig.

This current is shown as i_2 in the waveforms of Fig. (b) and it flows for the time t_2. We can write,

$$0 = L\frac{di_2}{dt} + Ri_2$$

With initial value of $i_2 = I_l$ at the beginning of time t_2, the solution of above equation becomes,

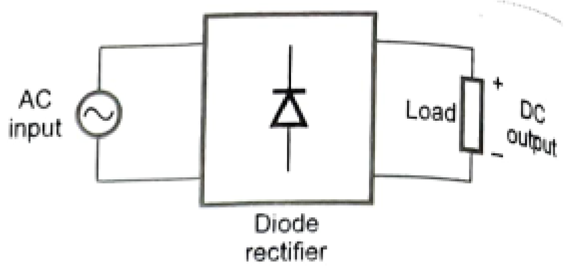
$$i_2(t) = I_1 e^{-tR/L} \qquad \text{……..(2)}$$

For t_2 very large, i_2 =0 at the end of t_2.

Diode Rectifiers:

Introduction:

The rectifier has AC input and DC output. As long as the input AC voltage is fixed, the output DC voltage is also fixed.



Classification and types of rectifiers:

i) 1Ø diode rectifiers

- 1Ø half wave rectifiers
- 1Ø Full wave rectifiers
- 1Ø bridge rectifiers

ii) 3Ø diode rectifiers

- 3Ø half wave rectifiers
- 3Ø Full wave rectifiers
- 3Ø bridge rectifiers

Advantages:

1. Simple circuits available at all power capacities
2. No control circuits are required.
3. Single rectifiers are available in 10 and 34.
4. High frequency as well as low frequency rectifiers are available.

5. Low cost.

Disadvantages:

1. Output voltage is uncontrolled.
2. Power flow is unidirectional.
3. High ripple content for 1Ø rectifiers.

Applications:

1. UPS
2. Simple electronic circuits.
3. Low power battery chargers.
4. Simple and low power supplies.

Performance Parameters:

1. Rectification efficiency or ratio of rectification (η): It is the ratio of DC load power to AC or rms load power.

Rectification efficiency, $\eta = \dfrac{DCor\ average\ load\ power}{AC\ or\ rms\ load\ power}$

$$\frac{P_{0(av)}}{P_{0(rms)}} = \frac{V_{0(av)}\, I_{0(av)}}{V_{0(rms)} I_{0(rms)}}$$

$V_{0(av)}$ & $I_{0(av)}$ $are\ output\ average\ voltages\ and\ current$

$V_{0(rms)}$ & $I_{0(rms)}$ $are\ output\ rms\ voltages\ and\ current$

2. Form Factor (FF): It is the measure of shape of output voltage. i.e.,

$$FF = \frac{V_{0(rms)}}{V_{0(av)}}$$

3. Ripple Factor (RF): It is the measure of ripple content. i.e

$$RF = \sqrt{\left[\frac{V_{o(rms)}}{V_{o(av)}}\right]^2 - 1} = \sqrt{FF^2 - 1}$$

4. Transformer utilization factor: It is the measure of size of the transformer. It is defined as the ratio of load average power to total power at transformer secondary.

$$TUF = \frac{P_{o(av)}}{V_{s(rms)} \cdot I_{s(rms)}}$$

Here Vs(rms) and Is(rms) are transformer secondary rms voltage and currents respectively.

5. Displacement Factor (DF) or Displacement Power Factor (DPF) : It is the cosine of angle between fundamental components of input or supply current and voltage. ie.,

$$DF = \cos\phi$$

6. Harmonic Factor (HF) or Total Harmonic Distortion (THD): It is the measure of ripple content or distortion in input or supply current.

$$HF = \sqrt{\left[\frac{I_{s(rms)}}{I_{s1\,(rms)}}\right]^2 - 1}$$

Is(rms) is rms value of supply current.

I_{s1} (rms) is rms value of the fundamental component of the supply current.

7. Crest Factor (CH): It is the ratio of peak value of supply current to rms value of supply current.

$$CF = \frac{I_{s(peak)}}{I_{s(rms)}}$$

8. Power Factor (PF): It is the measure of reactive power content in the supply due to load.

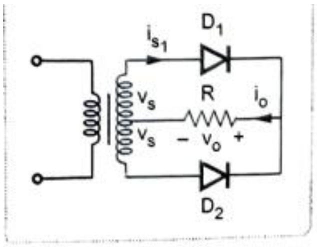
$$PF = \frac{V_{s(rms)}\, I_{s1\,(rms)} \cos\phi}{V_{s(rms)} \cdot I_{s(rms)}}$$

$$= \frac{I_{s1\,(rms)}}{I_{s(rms)}} \cos\phi$$

Single Phase Full Wave Rectifier (Center Tapped Transformer):

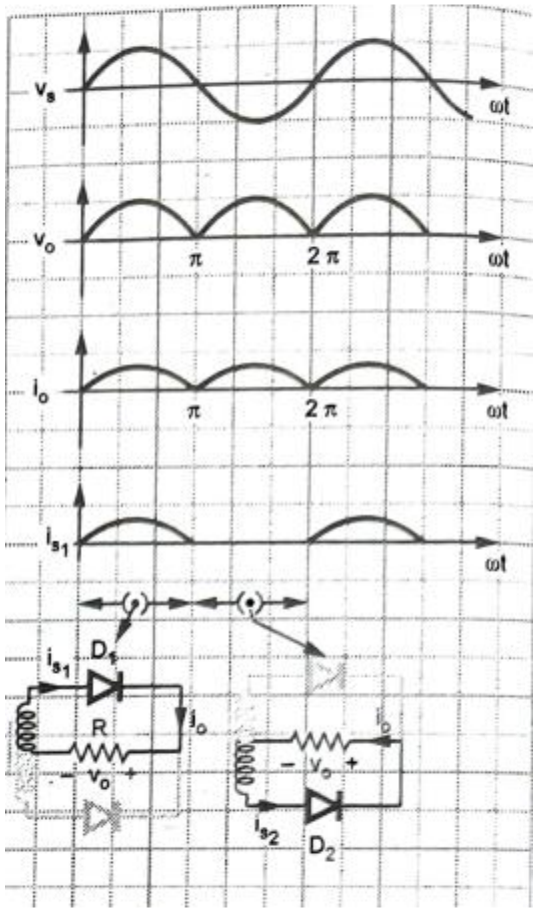
Single Phase Full Wave Rectifier with R Load:

- Fig shows full wave rectifier with R load and center tap connection. Note that the load is connected between the junction of two diodes D_1 and D_2 to center tap of secondary of transformer.
- Diode D_1 conducts in positive half cycle of the supply voltage and diode D_2 conducts in negative half cycle of the supply voltage.
- Note that both the half cycles of the supply voltage are rectified.



1ϕ full wave rectifier with R load

Mathematical analysis



1. Output average voltage $V_{o(av)}$

$$V_{o\,(av)} = \frac{1}{T}\int_0^T V_o(\omega t)\,d\omega t$$

From the waveform of Fig. 1.14.2 observe that T = π and

$$v_o(\omega t) = v_s = V_m \sin \omega t \text{ for } 0 \le \omega t \le \pi.$$

$$\therefore \quad V_{o(av)} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t\,d\omega t$$

$$= \frac{V_m}{\pi}[-\cos\omega t]_0^{\pi} = \frac{2V_m}{\pi}$$

$$\therefore \quad V_{o\,(av)} = \frac{2V_m}{\pi} = 0.637\,V_m$$

2. Output rms voltage :

$$V_{o\,(rms)} = \left[\frac{1}{T}\int_0^T v_o^2(\omega t)\,d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t\,d\omega t\right]^{\frac{1}{2}}$$

$$= \left[\frac{V_m^2}{\pi}\int_0^{\pi} \frac{1-\cos 2\omega t}{2}\,d\omega t\right]^{\frac{1}{2}}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\int_0^{\pi} d\omega t - \int_0^{\pi} \cos 2\omega t\,d\omega t\right]\right\}^{\frac{1}{2}} = \left\{\frac{V_m^2}{2\pi}\left[\omega t\Big|_0^{\pi} - \frac{\sin 2\omega t}{2}\Big|_0^{\pi}\right]\right\}^{\frac{1}{2}} = \frac{V_m}{\sqrt{2}}$$

$$V_{o\,(rms)} = \frac{V_m}{\sqrt{2}} = V_{s(rms)} = 0.707\,V_m$$

3. Form Factor (FF)

$$FF = \frac{V_{o\,(rms)}}{V_{o\,(av)}} = \frac{0.707\,V_m}{0.637\,V_m} = 1.11 \quad \text{or} \quad 111\ \%$$

4. Ripple Factor (RF)

$$RF = \sqrt{FF^2 - 1} = \sqrt{1.11^2 - 1} = 0.4817 \quad \text{or} \quad 48.17\ \%$$

5. Rectification efficiency

$$\eta = \frac{P_{o\,(av)}}{P_{o\,(rms)}} = \frac{V_{o(av)}^2/R}{V_{o(rms)}^2/R} = \frac{(0.637\,V_m)^2}{(0.707\,V_m)^2} = 0.812 \quad \text{or} \quad 81.2\ \%$$

6. Transformer Utilization Factor

$$TUF = \frac{P_{o(av)}}{V_{s(rms)} \cdot I_{s(rms)}}$$

Here

$$P_{o\,(av)} = \frac{(0.637\,V_m)^2}{R}$$

$$V_{s(rms)} = \frac{V_m}{\sqrt{2}} - 0.707\,V_m$$

$$I_{s(rms)} = \frac{I_{o\,(rms)}}{\sqrt{2}} = \frac{V_{o\,(rms)}/R}{\sqrt{2}} = \frac{V_m/\sqrt{2}}{\sqrt{2}\,R} = \frac{V_m}{2R}$$

Since the transformer is center tapped the total secondary VA will be $2V_{s(rms)} \cdot I_{s(rms)}$. Hence equation can be written as,

$$TUF = \frac{(0.637\,V_m)^2/R}{2V_{s(rms)} \cdot I_{s(rms)}} = \frac{(0.637\,V_m)^2/R}{2 \times 0.707\,V_m \cdot V_m/2R} = 0.574 \quad \text{or} \quad 57.4\ \%$$

7. PIV of diode

Because of center tapped transformer double of peak supply voltage appears across the diode when other diode conducts. Thus,

$$PIV = 2V_m.$$

8. Crest Factor

$$I_{s(peak)} = \frac{V_m}{R}$$

$$I_{s(rms)} = \frac{V_m/\sqrt{2}}{R} = \frac{V_m}{\sqrt{2}\,R}$$

$\therefore$

$$CF = \frac{I_{s(peak)}}{I_{s(rms)}} = \frac{V_m/R}{V_m/\sqrt{2}R} = \sqrt{2}$$

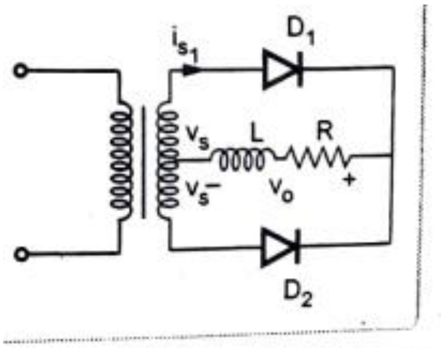
9. Power Factor

$$PF = \frac{\text{Active load power}}{\text{Total transformerVA}}$$

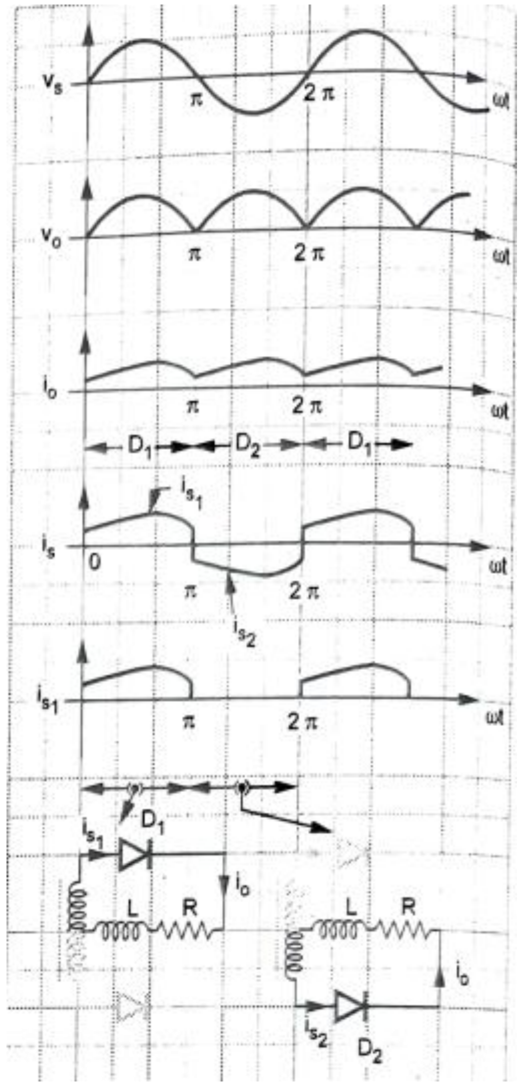
$$= \frac{P_{o\,(rms)}}{2 \cdot V_{s(rms)} \cdot I_{s(rms)}} \quad \text{for center tapped transformer secondary VA is doubled}$$

$$= \frac{V_{o\,(rms)}^2/R}{2 \times 0.707\,V_m \cdot V_m/2R} = \frac{(0.707\,V_m)^2/R}{2 \times 0.707\,V_m \cdot V_m/2R} = 0.707$$

Single Phase Full Wave Rectifier with RL Load: Since load is inductive, current waveform is sinusoidal. Supply current waveform of both the phases i_{s1} and i_{s2} is just closed to square wave.



1ϕ full wave rectifier with RL load



Mathematical analysis

Since load voltage is similar for R and RL loads,

$$\therefore \quad V_{o\,(av)} = \frac{2V_m}{\pi} = 0.637\,V_m$$

and
$$V_{o\,(rms)} = \frac{V_m}{\sqrt{2}} = 0.707\,V_m = V_{s(rms)}$$

$$FF = 1.11 \text{ or } 111\%$$

$$RF = 0.4817 \text{ or } 48.17\ \%$$

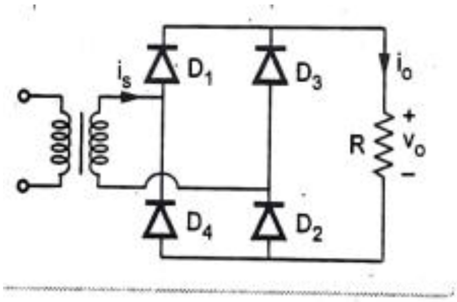
$$\eta = 0.812 \text{ or } 81.2\ \%$$

$$PIV = 2V_m$$

Single Phase Full Bridge Rectifier:

Single Phase Bridge Rectifier with R Load:

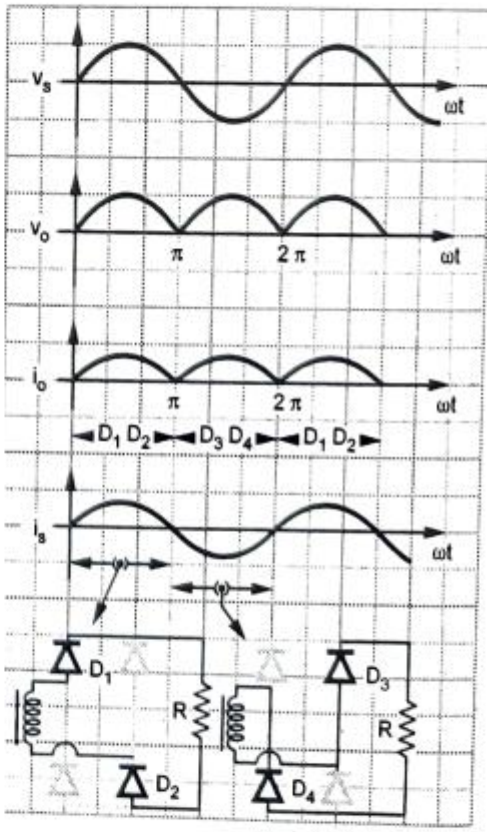
- Fig. shows the circuit diagram of the bridge rectifier with R load. There are four diodes. Hence it is called bridge rectifier.
- There is no need of center tapped transformer.
- Diodes D_1 and D_2 conduct in positive half cycle and D_3 and D_4 conduct in negative half cycle.
- Observe that the waveforms of bridge rectifier are exactly similar to those of center tap transformer-based full wave rectifier.
- The supply current waveform is different in case of bridge rectifier. Note that supply current waveform is sinusoidal for bridge rectifier.



1ϕ bridge rectifier

Mathematical analysis:

Since the output voltage waveforms of center tap based singlewave rectifier and bridge rectifier are same, all the performance parameters will also be same except TUF and PIV.



$$V_{o\,(av)} = \frac{2V_m}{\pi} = 0.637\,V_m$$

$$V_{o\,(rms)} = \frac{V_m}{\sqrt{2}} = 0.707\,V_m = V_{s\,(rms)}$$

$$\text{FF} = 1.11 \quad \text{or} \quad 111\ \%$$

$$\text{RF} = 0.4817 \quad \text{or} \quad 48.17\ \%$$

$$\eta = 0.812 \quad \text{or} \quad 81.2\ \%$$

$$\text{CF} = \sqrt{2}$$

$$\text{TUF} = \frac{P_{o\,(av)}}{\text{Transformer secondary VA}} = \frac{V^2_{o\,(av)}/R}{V_{s\,(rms)} \cdot I_{s\,(rms)}}$$

$$= \frac{(0.637\,V_m)^2\ /\ R}{(V_m/\sqrt{2}) \cdot I_{o\,(rms)}} \qquad \text{Here} \quad I_{o\,(rms)} = I_{s\,(rms)}$$

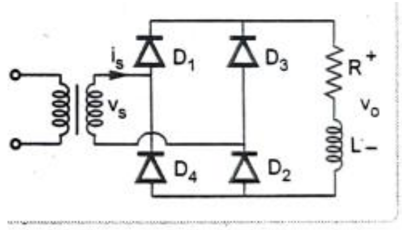
$$= \frac{(0.637\,V_m)^2\ /\ R}{(V_m/\sqrt{2}) \cdot \left(\frac{V_m/\sqrt{2}}{R}\right)} \qquad \text{Here} \quad I_{o\,(rms)} = \frac{V_{o\,(rms)}}{R} = 0.81 \quad \text{or} \quad 81\ \%$$

PIV of diode

Since the transformer secondary peak voltage is V_m,

$$PIV = V_m$$

Single Phase Bridge Rectifier with RL Load: • Fig. shows the circuit diagram of bridge rectifier with RL load. Diodes D_1 and D_2 conduct in positive half cycle and diodes D_3 and D_4 conduct in negative half cycle.



1φ bridge rectifier with RL load

Mathematical analysis: Note that the waveforms of the bridge rectifier for RL load are same as that for the center tap transformer-based full wave rectifier.

$$V_{o\,(av)} = \frac{2V_m}{\pi} = 0.637V_m \quad \text{... (1.15.3)}$$

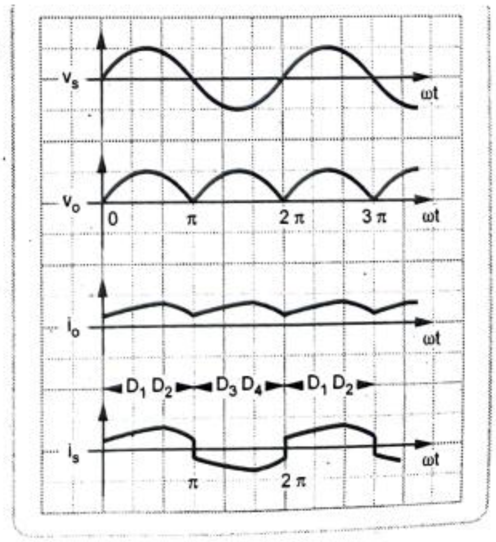
$$V_{o\,(rms)} = \frac{V_m}{\sqrt{2}} = 0.707V_m = V_{s(rms)} \quad \text{... (1.15.4)}$$

FF = 1.11

RF = 0.4817 or 48.17

η = 0.812 or 81.2 %

PIV = V_m



Waveforms of 1φ bridge rectifier with RL load