(AFFILIATED TO THE UNIVERSITY OF MUMBAI) & applications

Candidate Roll No. ____________ (In figures)

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Electronic devices like diodes, bipolar junction transistor (BJT), zener diodes, field effect transistors (FET) etc. are fabricated using semiconductors.

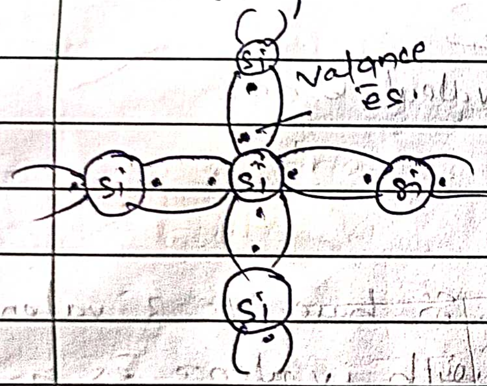
Semiconductors.

Intrinsic (Pure)

EF = lev.

- Silicon
- Germanium

Poore conductors at room temp.



4 valance ēs.
4 ēs are shared with adjoining atom & form 8 valance ēs. outermost shells of atom are completely filled.

Extrinsic (Impure)

P type N type.

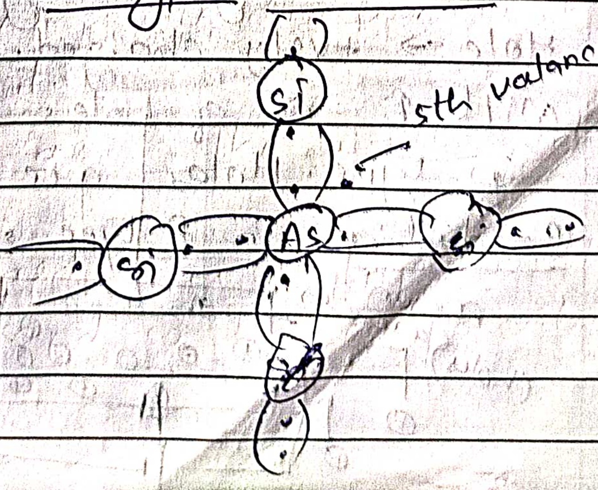
Prepared by adding impurity in intrinsic semiconductors to ↑ conductivity.

2 types of dopant materials
(1) Donor (2) Acceptor.

Donor – Pentavalent impurity. 5 valence ēs
e.g. Arsenic, Phosphorous, Antimony

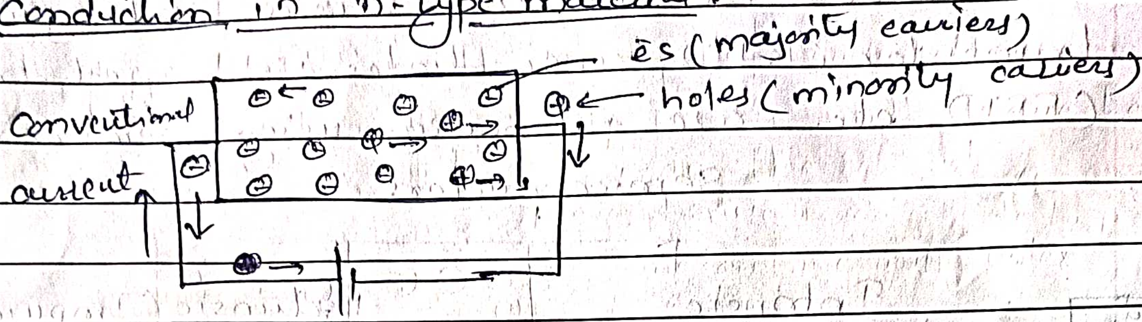
Acceptor – Trivalent. (3 valance ēs)
e.g. Boron, Gallium, Al, Indium.

N type Semicondr.

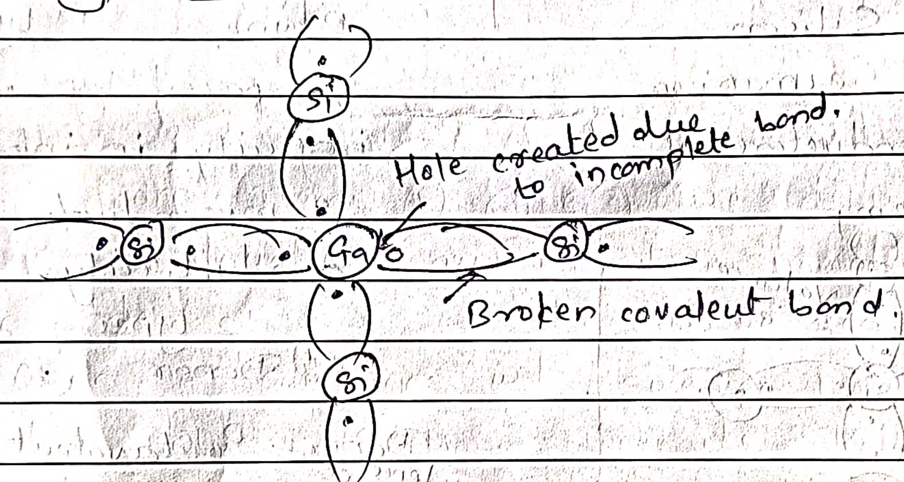


N type semicon^r :- Pentavalent impurity + Si
large no. of free ēs are present along with small no. of thermally generated holes in n-type semicond^r.
Conduction is mainly due to free ēs. So ēs are called as "majority carriers" and holes are known as "minority carriers".

Conduction in n-type material :-

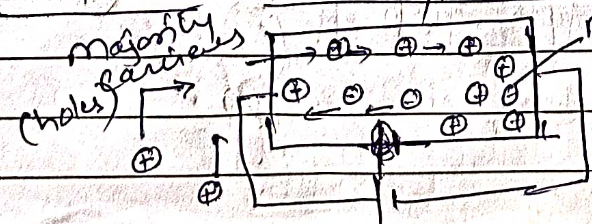


P-type semicond^r (Trivalent impurity + Si)



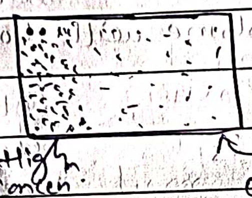
When Ga is added to Si base, its 3 valence ēs form covalent bonds with valence ēs of three neighbouring Si atoms.
Fourth covalent bond remains incomplete.
This resulting vacancy is called as "hole".
Hole → +vely charged. Absence of -ve charge.
With ↑ no. of holes semiconductor becomes P-type. Holes are majority carriers.

Conduction in P-type semi^r



Two types of currents flow in semiconductor.
1) Drift current 2) Diffusion current.

- Drift current flows inside the semiconductor under the influence of externally applied electric field.
- Transport of charges in semiconductor due to diffusion causes diffusion current.
- Concentration of ēs in n-type semi^r or holes in p-type semicond^r is always non-uniform.
- ēs or holes tend to travel from higher concentration area to lower concentration area. This movement cause diffusion current.

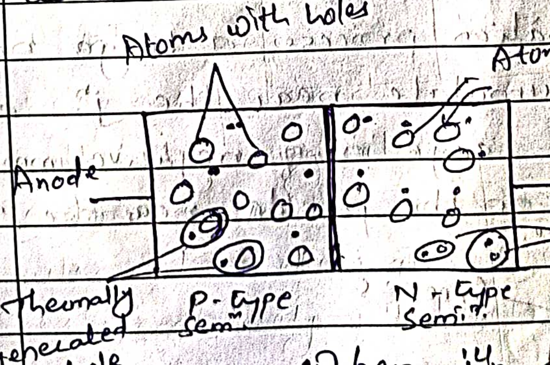


Diffusion current flows due to non-uniform concentration or concentration gradient.

P-N Junction.

P-N junction is a basic building block for all different types of semiconductor devices.
e.g. diode, transistor etc.

Diode :- Device with two elements or electrodes i.e. anode & Cathode.
p-n junction is having two electrodes, so it is used as diode.

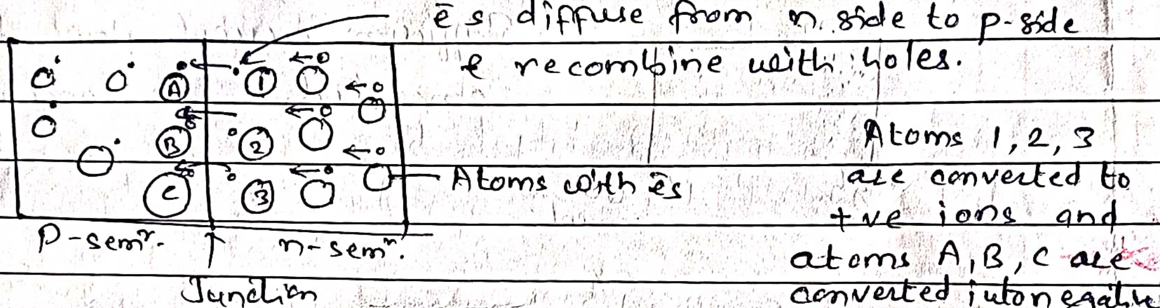


Formation of p-n junction

When j^n of p-n semiconductors is formed, at j^n one side has a high concentration of holes & the other side has high concentration of ēs. Due to this, concentration gradient is created across the junction.

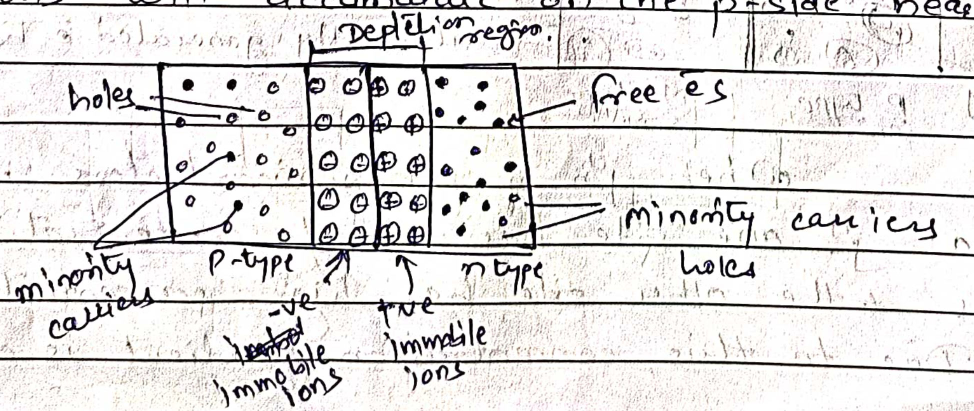
Depletion Region formation in p-n jⁿ diode

- After the formation of p-n j^n, immediately it behaves like (without external voltage) bet^n the terminals of p-n j^n ju^n is said to be unbiased.
- Free ēs from n side will diffuse into p-side and recombine with the holes around them.
- each ē diffusing into p side will leave behind a positive immobile ion on the n-side.



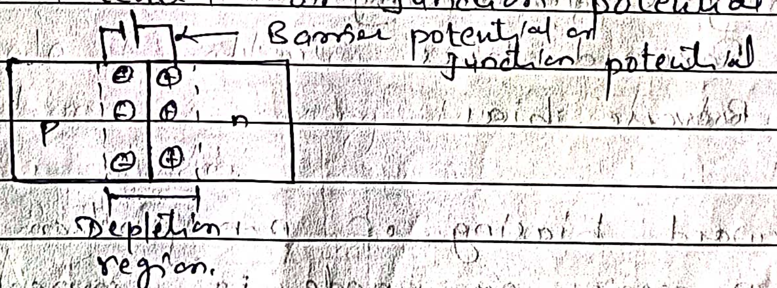
e.g.

- ēs from atoms ①, ② & ③ are diffused into p type material & leave positive immobile ion on n-side. 1, 2 & 3 in the above dia.
- when ē combines with hole on p side, an atom which accepts ē, loses its electrically neutral state & becomes a negative immobile ion as shown in the above dia.
- Due to the recombination process, a large no. of positive ions accumulate near the j^n on the n side and a large no. of negative immobile ions will accumulate on the p-side near the j^n.



- -vely charged ions on p-side will start repelling ēs which attempt to diffuse into the p-side and after some time the diffusion will stop completely.
- Junction attains an equilibrium state.
- Near the junction the region on both the sides of j^n contains only immobile ions & no free charge carriers as ēs or holes. The region is depleted of the charge carriers. So this region is called as "depletion region". Also known as free charge region.
- In the equilibrium state, the depletion region gets widened to such an extent that ēs cannot cross the j^n any more.
- Due to the depletion region, the ēs or holes cannot diffuse to the other side. So, the depletion region acts as a barrier.
- Practically width of depletion region is of the order of 0.5 to 1 micron
- w.r.t. width of p & n j^n width of depletion region is very less or thin

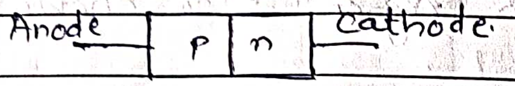
Barrier Potential or Junction potential



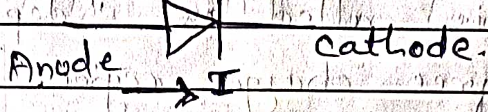
- Due to the depletion region at the p-n j^n, on both the sides of j^n electric field is created across the j^n which is known as barrier potential / j^n potential / cut-in volg.
- Polarities are decided by the type of immobile ions present on the two sides of the j^n.
- It acts as a barrier to oppose the flow of ēs & holes across the j^n.

- For the flow of ēs & holes barrier potential has to be overcome.
  For Si it is 0.6V, For Ge it is 0.2V
- Depletion region always penetrates more on the side which is lightly doped as compared to the other.

p-n Junction Diode



Symbol

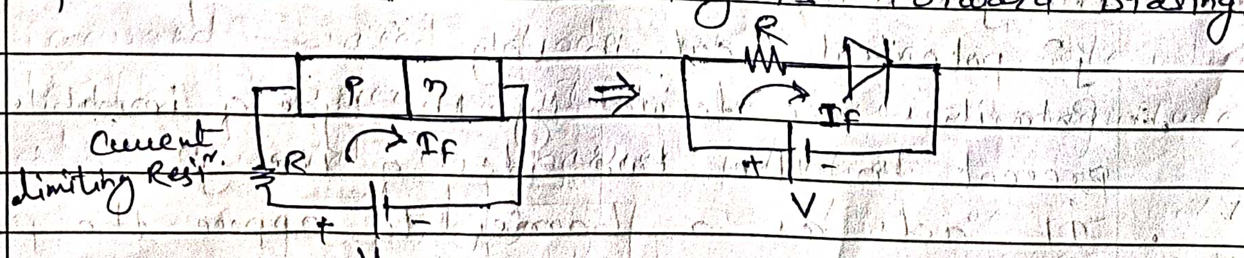


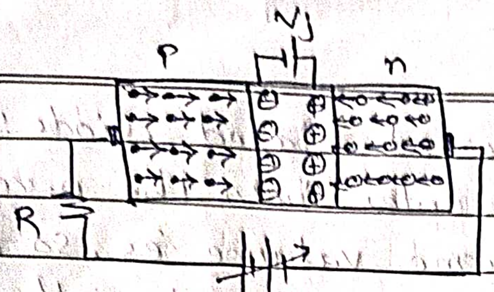
Biasing of a p-n junction diode (p-n jn with external bias)

- When p-n jn is formed, depletion region is created and movement of ēs and holes stops. Current thr' unbiased diode is zero.
  For current to flow through diode, it needs to be biased.
- Biasing is the process of applying external DC voltage to the diode.
  2 types of biasing
  1. Forward bias
  2. Reverse bias

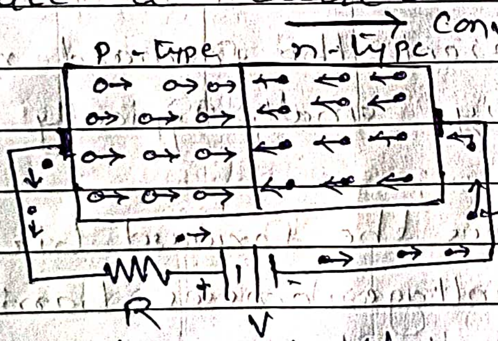
Forward biasing of p-n junction diode:

- p-region or anode is connected to the positive terminal of the external DC source and n-region or cathode to the negative terminal of the DC source biasing is Forward Biasing.





- As n is connected to the negative terminal of the DC supply, free ēs from n-side are pushed towards the p-side. Similarly the positive end of the supply will push holes from p-side towards n-side.
- With increase in the external supply volg. V more and more no. of holes and ēs start travelling towards the jn as shown in the above dia.
- Holes will start converting the negative ions into neutral atoms and the ēs will convert the positive ions into neutral atoms. As a result of this, the width of the depletion region will reduce.
- Barrier potential will also reduce. At a particular value of V, depletion region will collapse. There is no opposition to the flow of ēs and holes.
- So a large no. of ēs and holes can cross the jn under the influence of external DC bias.
- Large no. of majority carriers crossing the jn constitute a current called as forward current.



Current flow in forward bias

ē current is in the opposite direction to that of a conventional current.

Effect of forward bias on the width of depletion region:-

With ↑ in forward bias voltage, width of depletion region ↓ and so barrier potential also

Current flow in forward biased diode :-

- As soon as free ēs enter into the p-region from n-side, they become valance ēs, so these ēs will jump from one atom to the other to fill up the holes present there.
- Thus movement of ēs on p-side will be due to the movement of holes.
- These ēs move towards the positive end of the source and the holes will move towards the jn.
- Thus current thru' the p-region flows due to the movement of majority carriers.
- Similarly current on n-side is due to the movement of free ēs which are the majority carriers.

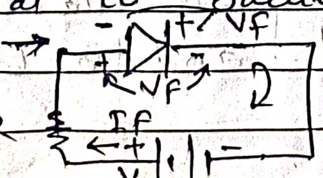
* Forward current thru' p-n jn diode flows due to the majority carriers and its direction of flow is always from anode to cathode.

Forward resistance of diode :

- The forward current of a diode I_F is the current flowing thr' the forward biased diode, due to majority carriers. It is few mA.
- Due to large current, the forward resistance of the diode is very small. Typically 10 to 100Ω.

Voltage drop across the forward biased diode

- When exteral voltage crosses barrier potential, the currents start flowing.
- There is a potential drop across the conducting forward biased diode, which has opposite polarities to the barrier potential but has a magnitude almost equal to barrier potential.



V_F - for Si → 0.7 V
for Ge → 0.3 V

EEEE Module 2 (02)

Electronic Devices & Applications

2/2019/26,000

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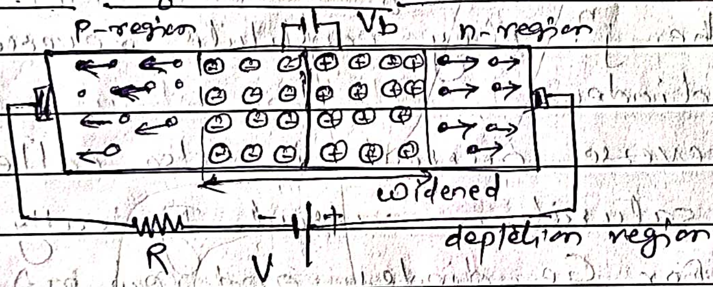
Reverse biasing a diode:-

To limit reverse current

- p-region connected to -ve terminal of external volg. supply & n-region connected to +ve terminal of supply.
- I_R - Reverse current flows from cathode to anode.
- R - to limit reverse current.

Operation of a reverse biased diode:-

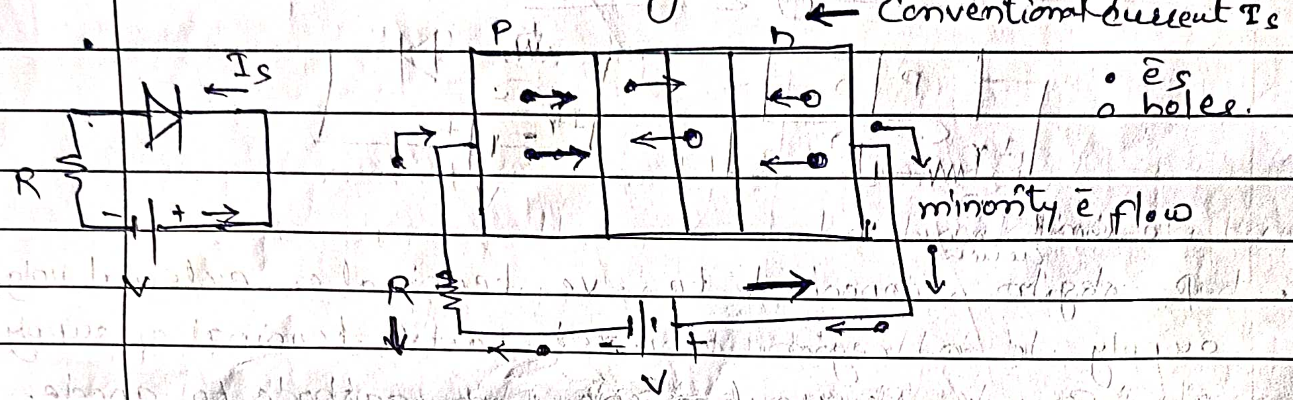


- When a diode is reverse biased, holes in the p-region are attracted towards -ve terminal of the supply and ē on the n-side are attracted towards the positive terminal of the supply.
- Due to the movement of ēs and holes away from the jn. width of the depletion region ↑. This happens due to the creation of more no. of +ve and -ve immobile ions.
- Due to more no. of ions present on opposite sides of jn. barrier potential or jn. potential will ↑.
- The process of widening of depletion region does not continue for a long time, because there is

no steady flow of holes from right to left from n-side to p-side.

Current flow in the reverse biased diode:-
(Reverse Saturation Current)

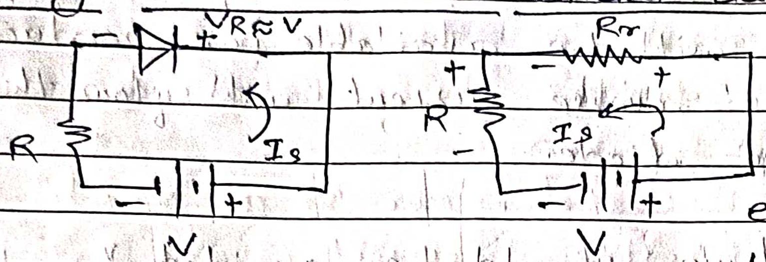
- There are ēs as minority carriers in p-region and holes as minority carriers in n-region in small no. These are generated thermally.



- Minority ēs in p-region are attracted by the positive end of the dc supply. As these ēs cross the jn they constitute reverse current I_s of the diode.
- The reverse current is also called as the Reverse saturation current. Typically value is in few μA for Ge diodes and few nA for Si diode.
- The reverse saturation current depends on the temp. It doubles its value for every 10°C rise in temp. At a const. temp. the reverse saturation current remains const. independent of the reverse volg.
- Reverse current flows due to minority carriers which are generated due to thermal effect. So reverse current is dependent on temp.
- Reverse current flows from cathode to anode
- Flows due to minority carriers.
- Very small than forward current.
- It is independent of reverse volg. but dependent on temp.

• Resistance of reverse biased diode: (R_r)
Due to very small reverse current, resi. of reverse biased diode is very large. Generally its value is few hundred kΩ.

Volg. across reverse biased diode:-



equi. ckt of reverse biased diode.

Reverse volg. V_R across the diode is given by

$$V_R = \frac{R_r}{R+R_r} \times V$$

But $R_r >> R$

$$\therefore V_R \approx \frac{R_r V}{R_r} \approx V$$

• Reverse volg. ≈ applied volg. & its polarity is as shown in the dia.

Breakdown in the reverse biased diode
Breakdown in reverse biased diode happens due to:
1) Avalanche effect 2) Zener diode

Avalanche effect:-
• Due to large reverse volg. the velocity of the minority carriers will ↑ to a great extent. So, kinetic energy associated with them will also ↑.
• While travelling, these minority carriers will collide with the stationary atoms and impart some of the kinetic energy to the valance $\bar{e}$s present in the covalent bonds.
• Due to this additionally aquired energy, these valance $\bar{e}$s will break the covalent bonds and

jump into the conduction band to become free for conduction.

- These free ēs will be accelerated and they knock out some more valence ēs by means of collisions. This chain reaction is called as Avalanche effect.
- In a very short time, a Large no. of free minority ēs will be available for conduction and a Large reverse current will flow thr' the reverse biased diode.

Why breakdown should be avoided ?

- At the time of the avalanche breakdown, a Large reverse volg. appears across the diode and a Large reverse current flows thr' it.
- Therefore a Large power gets dissipated in the diode. Junction temp. of the diode may exceed its safe limits and the diode will be damaged permanently.
- So, the reverse breakdown should be always avoided.

Breakdown due to zener effect :-

- Reverse breakdown can happen due to zener effect.
- In zener breakdown following events occur.
  - Due to heavy doping of p and n-sides of the diode, the depletion region is narrow in the reverse biased condition. All the reverse volg. V appears across the depletion region.
  - Across the depletion region, the electric field which is Volg/distance is very intense.
  - This intense electric field can pull some of the valance ēs by breaking the covalent bonds. These ēs are available as free ēs.

A large no. of such Es can constitute a large reverse current thr' the diode.
This is called as the breakdown due to Zener effect.

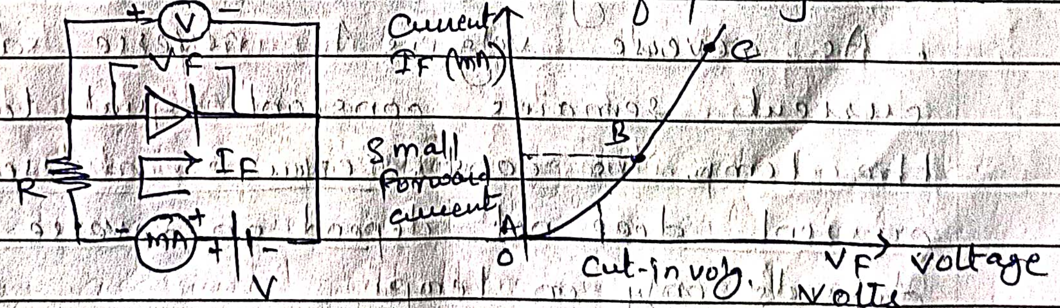
If breakdown in p-n jn diode is allowed for longer time without any external control, diode gets permanently damaged.

To avoid the damage of diode in reverse bias mode, external current limiting resistor to keep the reverse current low & make power dissipation in the diode below the dangerous level.

V-I characteristics of a diode.

- V-I characteristic of diode is useful to indicate behavior of p-n jn diode.
- It is a graph of volg. across the diode Vs current flowing thr' it.
- V-I characteristic can be divided in 2 parts
  1. Forward characteristics
  2. Reverse characteristics.

1. Forward characteristics of p-n jn diode.



Graph of forward volg. VF Vs IF

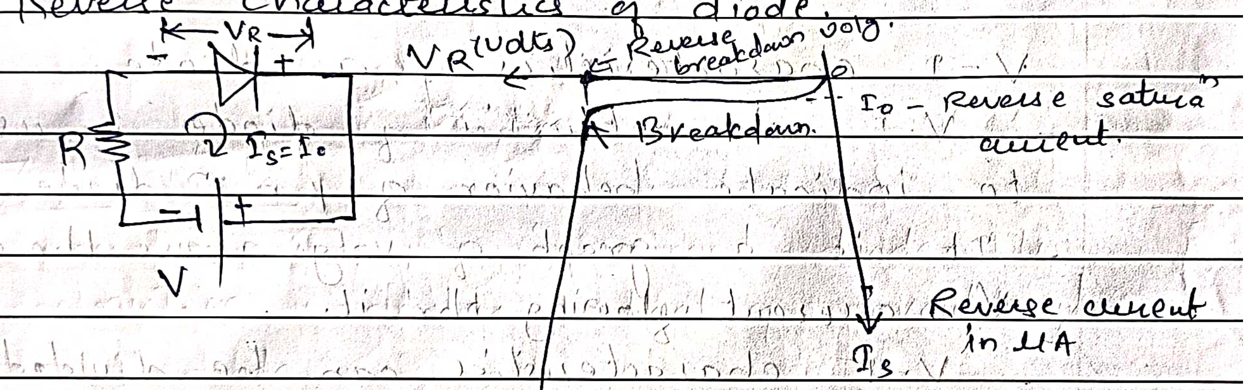
Region A to B

- Forward volg is small and less than cut in volg. So, forward current flowing thr' the diode is small. With further ↑ in forward volg. it reaches the level of the cut-in volg. & the width of depletion region goes on decreasing.

Region B to C

- When forward volg. equals the cut-in volg, current thr' the diode ↑ suddenly. It increases exponentially. Large forward current flowing thr' diode can be limited by connecting R in series with the diode. Forward current is of few mA.
- Forward current flows from anode to cathode so it is positive current.

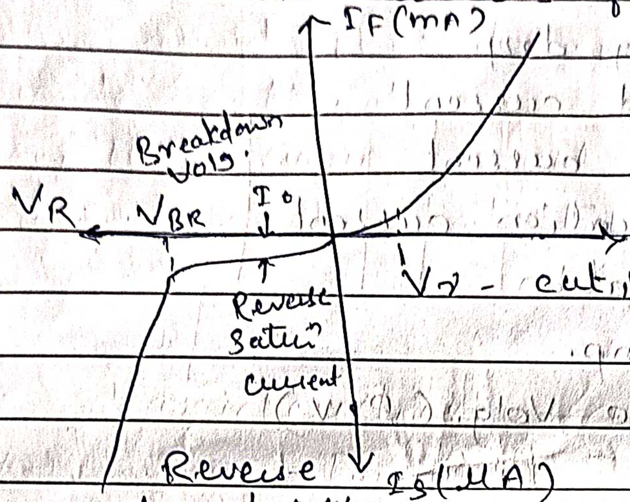
Reverse characteristics of diode.

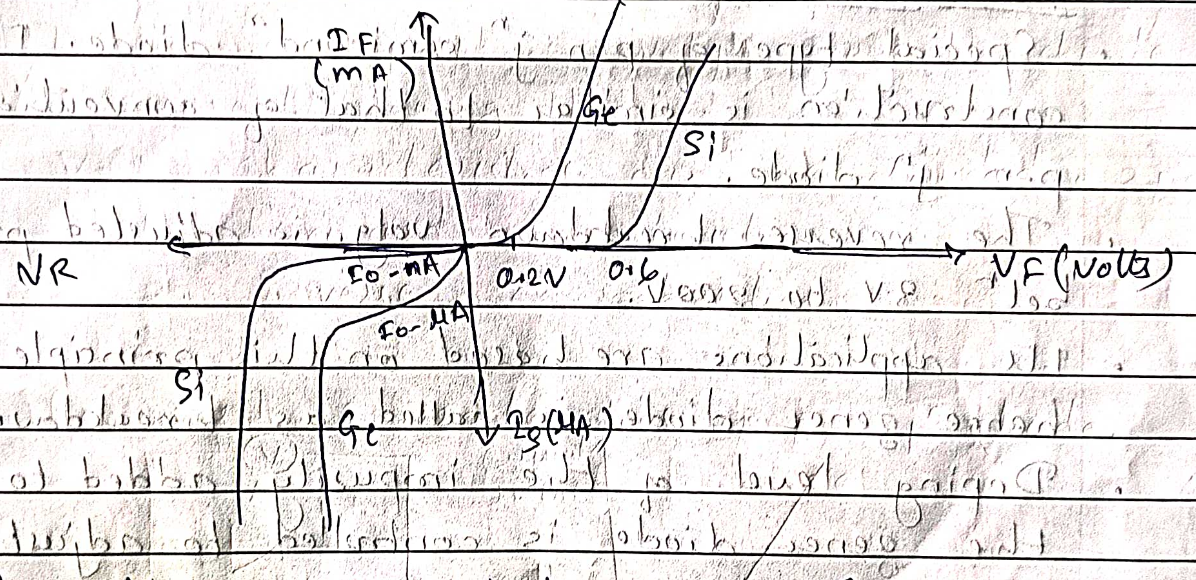


- Current flowing thr' diode in reverse biased state is the reverse saturation current which flows due to the minority carriers.
- It is negative current.
- As reverse volg is ↑, reverse saturation current remains constant equal to I_o if the temp. is const. Because reverse saturation current does not depend on reverse volg. but depends only on temp.
- But when reverse volg. reaches the breakdown volg. value, a large current flows thr' the diode due to avalanche & zener breakdown.
- Operation in the breakdown region should be avoided because the diode may be damaged due to excessive power dissipation.

• Reverse breakdown volg. for p-n j^n diode is in the range of 50V to 100V typically.
• Resi. of the diode in the reverse biased condition is called as the reverse resi. & its value is very high (of the order of few hundred kΩ)

Overall V-I characteristics of p-n j^n diode.





Parameter	Si diode	Ge diode
1. Material	Silicon	Germanium
2. Cut in volg.	0.6V	0.2V
3. Reverse satu^n current	In nAmp.	In μA
4. Effect of temp.	Less	More
5. Breakdown volg.	Higher	Lower
6. Appl^ns	Rectifiers, clippers, clampers, freewheeling	low volg. low temp. appl^ns.

Applications of p-n j^n diode
1. Rectifier 2. Clipper 3. Clamper 4. Volg. multiplier 5. A.M. Detector 6. Feedback diode 7. Freewheeling diode 8. Log and antilog amp^n using op-amp 9. Precision rectifier using op-amp.

Diode specifications:
1. Forward volg. drop
2. Max. forward current
3. Avg. forward current
4. Reverse saturation current
5. Power dissipation
6. Junction temp.
7. Peak Inverse Volg. (PIV)

Zener Diode :-
- Special type of p-n j^n semicond^n diode. Its construction is similar to that of conventional p-n j^n diode.
- The reverse breakdown volg. is adjusted precisely bet^n 3V to 200V.
- Its applications are based on this principle hence zener diode is called as breakdown diode.
- Doping level of the impurity added to manufacture the zener diode is controlled to adjust the precise value of reverse breakdown volg.

Operation:
- In forward biased mode operation is same as that of p-n j^n diode.
- In reverse biased mode operation is different than p-n j^n reverse biased diode.

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03

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Module 2

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Elect. devices & appl'ns

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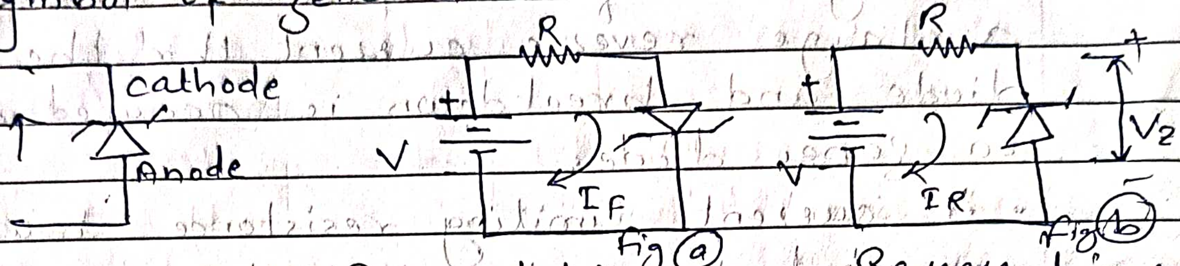
Symbol of zener diode :

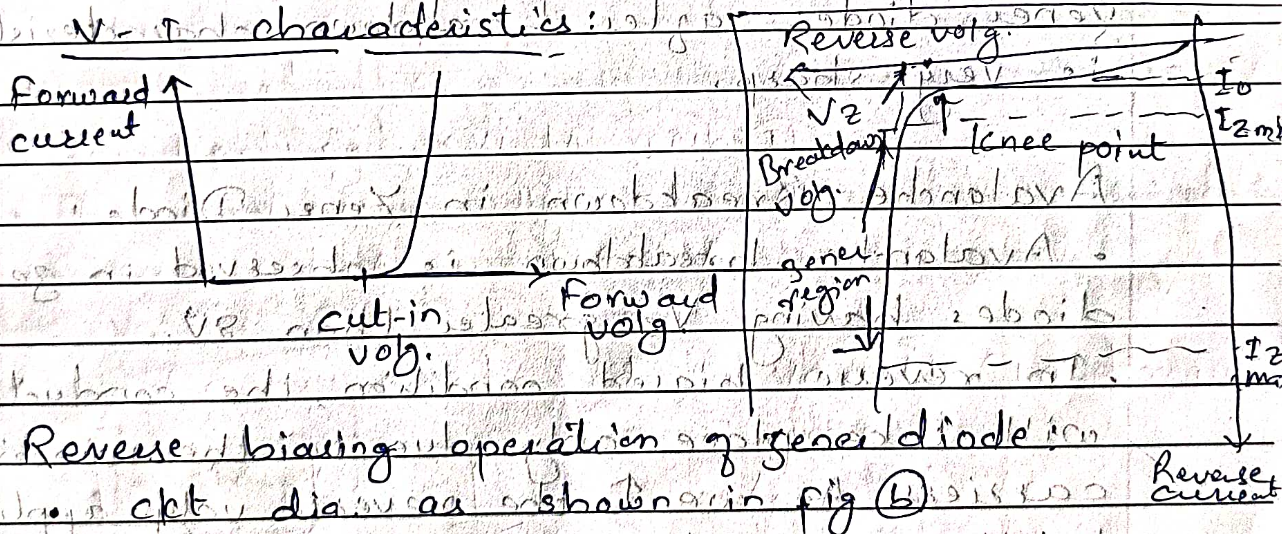


Forward bias   Reverse bias

Forward bias operation

- ckt as shown in fig (a)
- Working is same as forward biased p-n jn diode
- Generally zener diode is not used in the forward biased condition.

V-I characteristics :



Reverse biasing operation of zener diode :

- ckt dia as shown in fig (b)

In zener diode two diff breakdown mechanisms :

1. Zener breakdown 2. Avalanche breakdown

Zener Breakdown :

- When a reverse volg (5V or less) is applied to a zener diode, it causes a very intense electric field to appear across a narrow depletion region. Field intensity is of the order of 3×10^5 V/cm

- This intense electric field is strong enough to pull some of the valence ēs into the conduction band by breaking their covalent bonds. These ēs become free ēs and are available for conduction.
- Large no. of such free ēs will form a large reverse current thr' the zener diode and breakdown is occured due to zener diode.
- A current limiting resistance should be connected in series with the zener diode to protect it from damage due to excessive heating.
- In zener breakdown, the breakdown volg. depends on the temp. of p-n j^n. The breakdown voltage decreases with increase in the j^n temp^n.
- In V-I characteristics for reverse biased zener diode, after breakdown characteristics is very sharp.

Avalanche Breakdown in Zener Diode:

- Avalanche breakdown is observed in zener diodes having V_Z greater than 8V.
- In reverse biased condition, the conduction will take place only due to the minority carriers. As we ↑ the reverse volg. applied to the zener diode, these minority carriers tend to accelerate. Therefore kinetic energy associated with them ↑.
- While travelling, these accelerated minority carriers will collide with the stationary atoms and impart some of the kinetic energy

to the valance ēs present in the covalent bonds.

• Due to this additionally acquired energy, these valance ēs will break their covalent bonds and jump into the conduction band to become free for conduction.

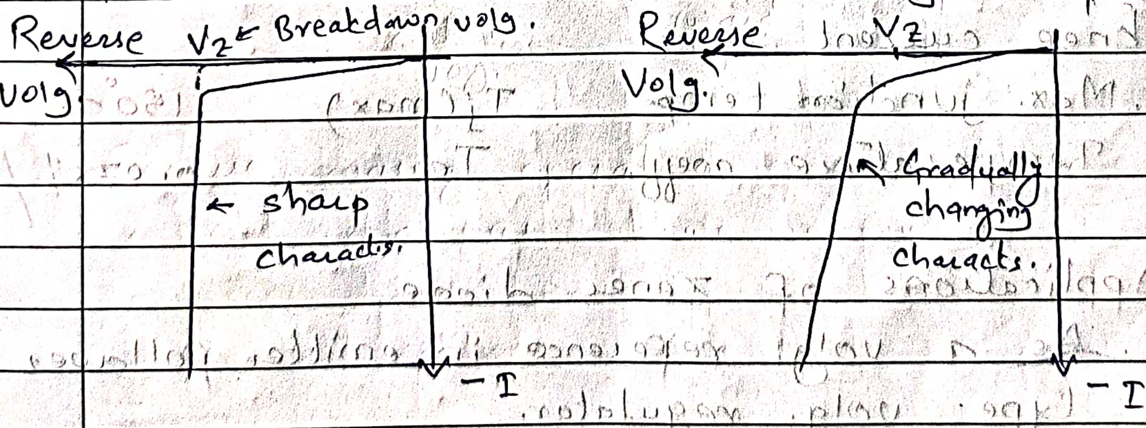
• These newly generated free ēs will get accelerated. They will knock out some more valance ēs by means of collision. This phenomenon is called as "carrier multiplication".

• In a very short time, a large no. of free minority ēs and holes will be available for conduction and the carrier multiplication process becomes self sustained.

• This self sustained multiplication is called "Avalanche Effect". A large reverse current starts flowing thr' the zener diode and the avalanche breakdown is occured.

• A current limiting resistor should be connected in series with the zener diode to protect it against the damage due to excessive heating.

• The breakdown volg. in the avalanche breakdown increases with increase in the jn. temp.



Zener Breakdown Avalanche Breakdown

Zener Breakdown	Avalanche Breakdown
1. This is observed in zener diodes having V_Z betⁿ 5 to 8 Volts.	1. This is observed in zener diodes having V_Z greater than 8V.
2. Valance ēs are pulled into conduction band due to very intense electric field appearing across the narrow depletion region.	2. Valance ēs are pushed into conduction band due to the energy imparted by colliding accelerated minority carriers.
3. V-I characteristic with zener breakdown is very sharp.	3. V-I characteristics with the avalanche breakdown increases gradually.
4. Breakdown volg. decreases with increase in temp.	4. Breakdown volg. increases with ↑ in temp.

Zener diode Specifications (For 1N2816)

Specification	Unit	Value
1. Zener volg.	V_Z	18 V
2. Max. power dissipation	$P_{d(max)}$ at $25°C$	50W
3. Dynamic impedance	r_Z	2Ω
4. Breakover current or knee current	I_{Zk}	5mA
5. Max. junction temp.	$T_{j(max)}$	150°C
6. Temperature coeff.	T_C	0.075%/°C

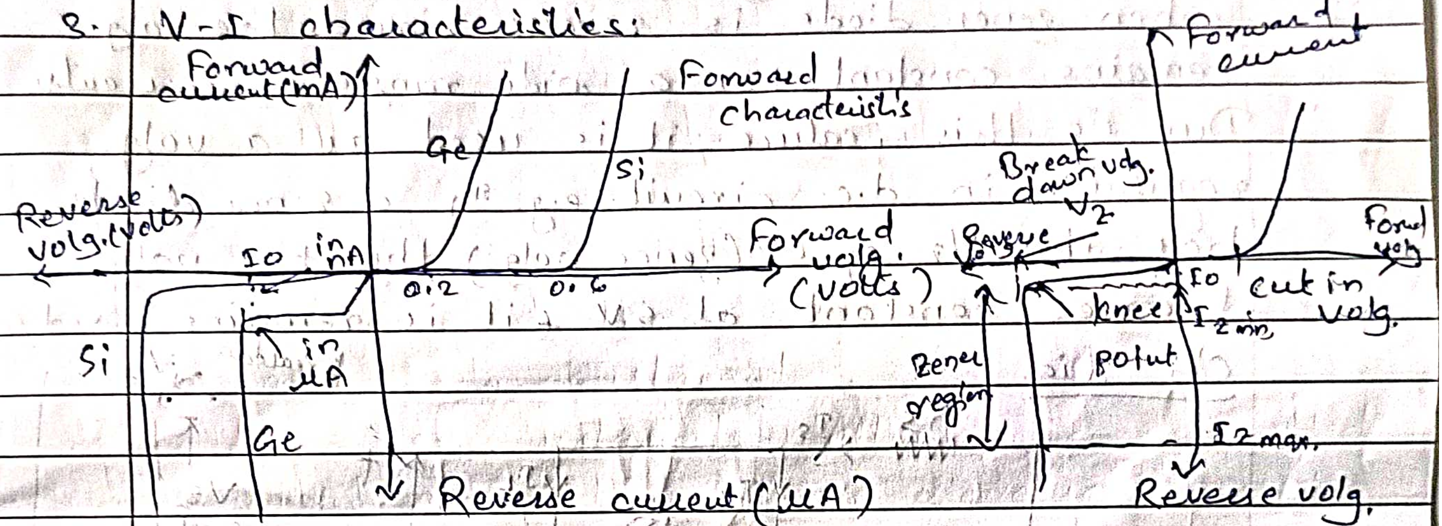
Applications of Zener diode

1. As a volg. reference in emitter follower type volg. regulator.
2. As a regulated power supply.
3. In protection ckts for MOSFET.
4. In clipping ckts.
5. In pulse ampʳ.

Comparison of Zener Diode and p-n junction Diode:

	p-n junction diode	Zener diode
1.	Symbol 	
2.	Operated in forward biased condition	Zener is operated in the reverse biased condition

3. V-I characteristics:

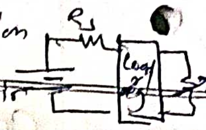


4. Applications:- In rectifiers, clippers, clampers, volg. multipliers

4. Volg. regulators, volg. limiters etc.

Volg. Regulator

Line Regulation | Load regulation



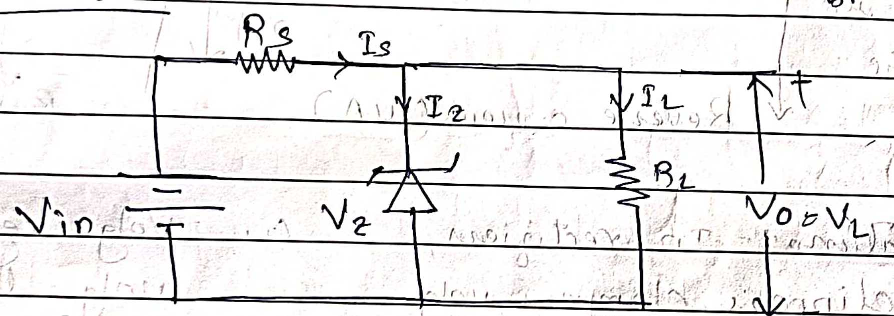
Zener diode as voltage regulator:-

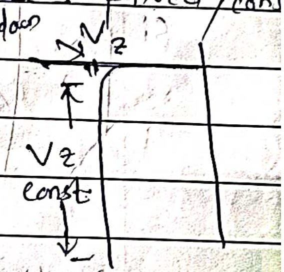
What is voltage regulator?

A voltage regulator is a circuit with a combination of elements designed to ensure that the output volg. of supply remains constant.

W.r.t. the working of zener diode we know that when zener diode is reverse biased, the volg. remains constant for a wide range of currents. Due to this feature, it is used as a volg. regulator in d.c. circuit. e.g. If a zener diode has its V_Z of 5V (zener volg.), then the volg. becomes constant at 5V & it is remains fixed/const.

ckt dia.





Rs - Current limiting resistor.

1. If $V_{in} < V_Z$, zener diode off
2. if $V_{in} > V_Z$ zener reverse breakdown.

This 2nd condition is required to use zener as volg. regulator. In this case volg. across zener diode remains const = V_Z.

Load current $= I_L = \dfrac{V_L}{R_L}$

$$V_L = V_Z$$

$$\therefore I_L = \frac{V_Z}{R_L}$$

$$I_S = \frac{V_{in} - V_Z}{R_S}$$

$$I_S = I_Z + I_L \quad \text{or} \quad I_Z = I_S - I_L$$

Power dissipation across zener diode

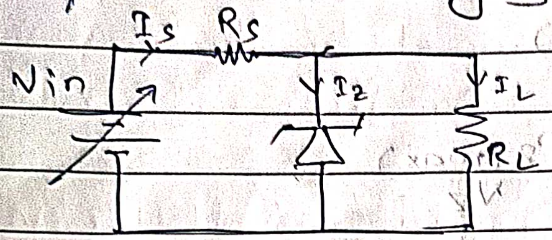
$$P_Z = V_Z \times I_Z$$

Volg. across zener diode

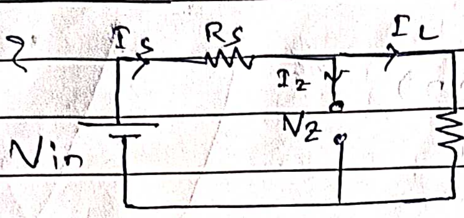
$$V_Z = \frac{R_L}{R_L + R_S} \times V_{in} \quad , \quad I_{zm} = \frac{P_{max}}{V_Z}$$

I_{zk} : knee current of zener diode.

case 1 If V_{in} is varying (Line Regulation)



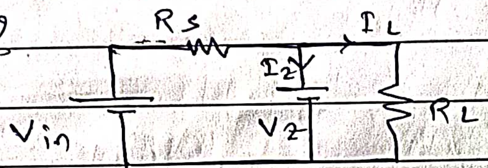
$V_{in(min)} = ?$



$$V_Z = \frac{R_L}{R_S + R_L} \times V_{in}$$

$$\therefore V_{in(min)} = \frac{(R_S + R_L) \times V_Z}{R_L}$$

$V_{in(max)} = ?$



Max. current thr' zener diode will limit

$$I = I_Z + I_L$$

$$\therefore I = I_{Zmax} + I_L$$

$$\therefore I_{Zmax} = \frac{P_{Zmax}}{V_Z}$$

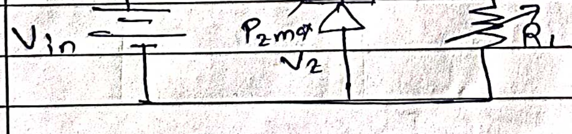
$$I_L = \frac{V_Z}{R_L}$$

Applying KVL to mesh (I)

$$V_{in(max)} - I_S R_S - V_Z = 0$$

$$\therefore V_{in(max)} = I_S R_S + V_Z$$

Case 2 If V_{in} is fixed and R_L variable (Load regu^n)



$R_L\ min = ?$

$$\therefore V_Z = \frac{R_L}{R_S + R_L} \times V_{in}$$

$$V_Z R + V_Z R_L = R_L V_{in}$$

$$V_Z R = R_L (V_{in} - V_Z)$$

$$R_{L(min)} = \frac{V_Z \times R}{(V_{in} - V_Z)}$$

$R_L(max) = ?$

$P_{Z\,max} = V_Z \cdot I_Z(max)$

$\therefore I_Z(max) = \frac{P_Z(max)}{V_Z}$

$I = I_Z(max) + I_L(min)$

$I_L(min) = I - I_Z(max)$

$= \frac{V_{in} - V_Z}{R} - \frac{P_Z(max)}{V_Z}$

$R_L(max) = \frac{V_Z}{I_L(min)}$

Module 6

Rectifiers

11

Syllabus :

Analysis of half wave and full wave rectifiers with resistive load and its parameters, Ripple factor, Rectification efficiency and regulation. Rectifier circuits with capacitive filter only.

11.1 Introduction :

- All the electronic circuits need a dc voltage for their operation. The dc supply voltage is derived from the single phase ac mains circuit.
- For this purpose we have to use a regulated dc power supply. The block diagram of a rectifier is as shown in Fig. 11.1.1.

Rectification :

- Rectification is the process of converting the alternating voltage or current into the corresponding direct (dc) quantity (direct voltage or current).
- The input to a rectifier is ac whereas its output is unidirectional or dc.
- The electronic circuit which carries out rectification is called as rectifier.

Rectifiers :

- Rectifier is an electronic device which is used for converting an alternating (ac) voltage or current into a unidirectional (dc) voltage or current.
- Block diagram of a rectifier is shown in Fig. 11.1.1.
- A step down transformer is used to reduce the ac mains voltage to an adequately small value. The turns ratio of the transformer is adjusted to obtain a stepped down ac voltage.
- This voltage is converted into a **pulsating dc voltage** by the rectifier. The type of rectifiers used are half wave rectifier, full wave rectifier or bridge rectifier.

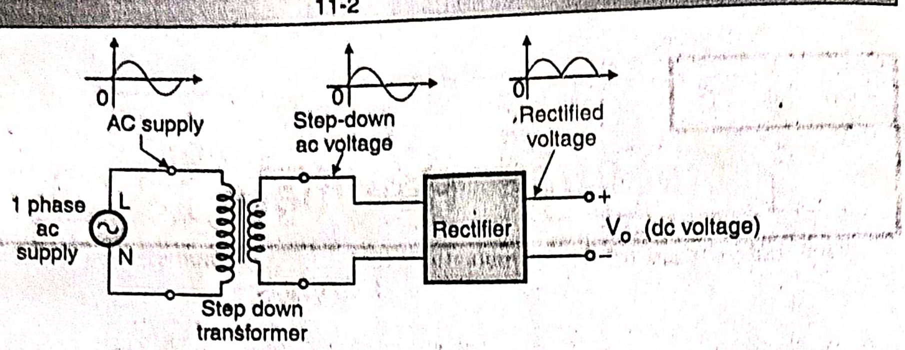


Fig. 11.1.1 : Block diagram of a rectifier

Need of rectification :

- Every electronic circuit such as amplifiers, needs a dc power source for its operation.
- This dc voltage has to be obtained from the ac supply.
- For this the ac supply voltage has to be reduced (stepped down) first using a step down transformer as shown in Fig. 11.1.1 and then converted to dc by using a rectifier.

11.1.1 Polarities of Transformer Voltages :

To understand the operation of a rectifier circuit we must know the polarities of voltages associated with the transformer.

Single phase AC supply voltage :

- The primary of a transformer is connected to the single phase ac supply available from MSEB. This supply voltage has two terminals namely Live and Neutral. And the voltage at the live terminal with respect to neutral is sinusoidal as shown in Fig. 11.1.2.

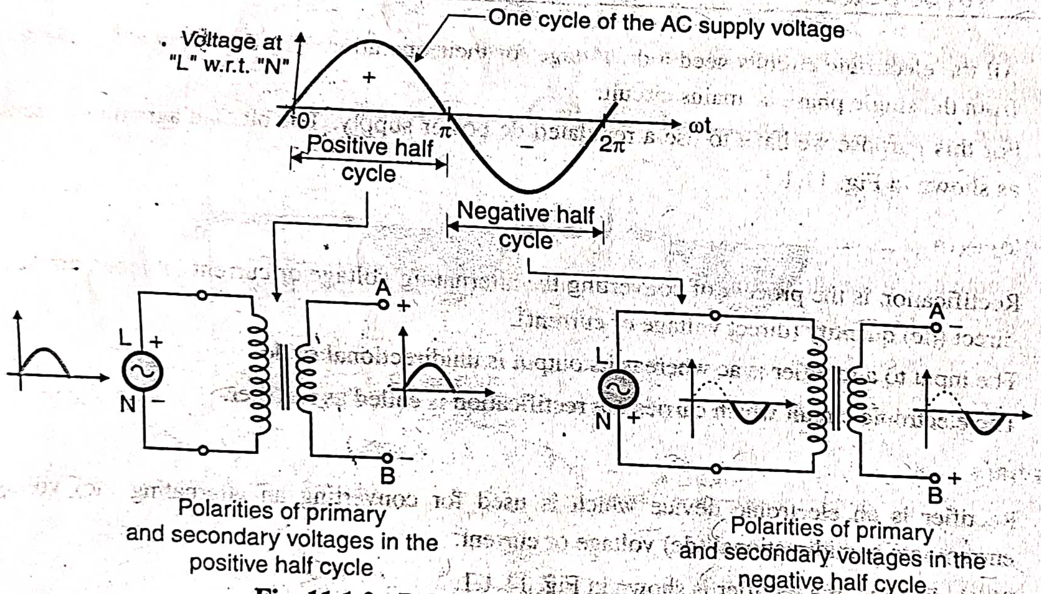


Fig. 11.1.2 : Polarities of transformer voltages

- The positive half cycle extends from $\omega t = 0$ to π radians. In this half cycle "live (L)" is positive with respect to "neutral (N)" and the secondary voltage V_{AB} is positive.

- The negative half cycle extends from $\omega t = \pi$ to 2π radians. "L" is negative with respect to "N" and the secondary voltage V_{AB} is negative, as shown in Fig. 11.1.2.

11.2 Classification of Rectifier Circuits :

Rectifier is a circuit which converts an alternating (ac) voltage into a direct (dc) voltage. The classification of rectifier configurations is as shown in Fig. 11.2.1.

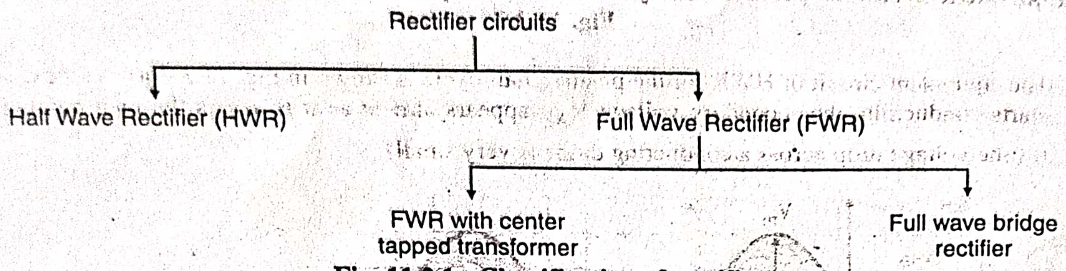


Fig. 11.2.1 : Classification of rectifiers

11.3 Half Wave Rectifier (HWR) :

Concept :

- In half wave rectifier, the rectifier is on only during one half cycle of the ac supply.
- So output is produced only in that half cycle. The output is suppressed in the other half cycle.
- The conduction takes place only in one half cycle of supply, hence the name of this circuit is half wave rectifier.

Circuit diagram :

- The circuit configuration of a half wave rectifier is as shown in Fig. 11.3.1 is the input step down transformer.
- R_L is the load resistance. The resistance of the diode in the on state be R_F and let the resistance of the secondary winding be R_S.

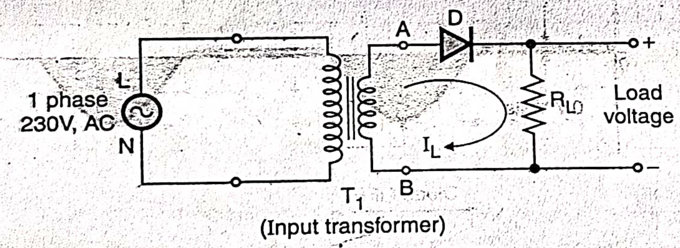


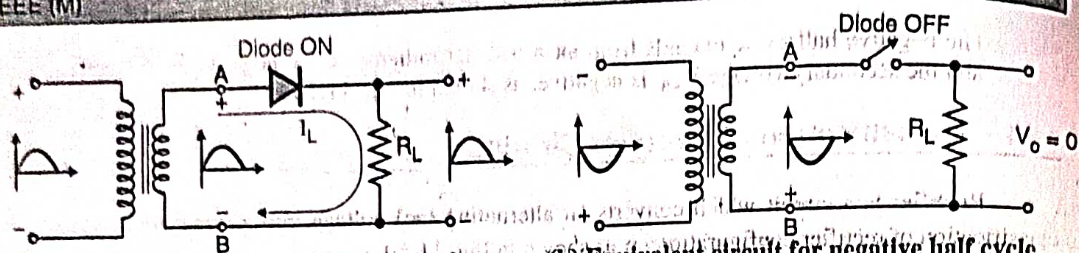
Fig. 11.3.1 : Half wave rectifier

11.3.1 Operation of the HWR :

The operation of HWR circuit is as follows :

Operation in the positive half cycle of ac supply (0-π) :

- In the positive half cycle (0-π) of the ac supply, the secondary voltage V_{AB} is positive, i.e. A is positive with respect to B. Hence the diode is forward biased and starts conducting.



(a) Equivalent circuit for positive half cycle (b) Equivalent circuit for negative half cycle

Fig. 11.3.2

- The equivalent circuit of HWR for the positive half cycle is shown in Fig. 11.3.2(a). As the diode starts conducting, the secondary voltage V_{AB} appears almost as it is across the load resistance (as the voltage drop across a conducting diode is very small).

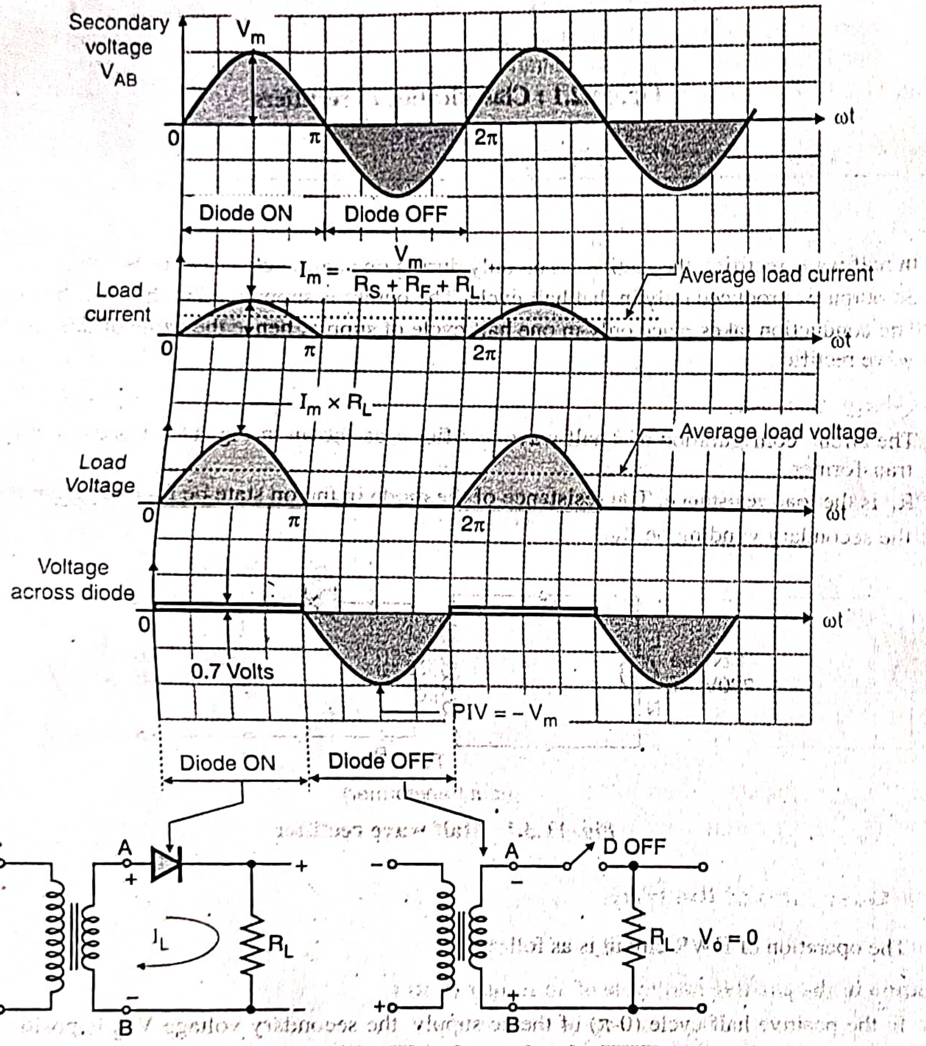


Fig. 11.3.3(a) : Waveforms for the HWR

- The load voltage is thus positive and almost equal to the instantaneous secondary voltage V_{AB}.
- The load current has the same shape as that of the load voltage since the load is purely resistive. The waveforms for HWR are shown in Fig. 11.3.3(a).
- The instantaneous load current i_L is equal to the ratio of instantaneous secondary voltage (V_{AB}) and total resistance ($R_S + R_F + R_L$).

$$I_L = \frac{V_{AB}}{(R_S + R_F + R_L)} \quad ...(11.3.1)$$

Operation in the negative half cycle of ac supply (π to 2π) :

- Refer to the equivalent circuit shown in Fig. 11.3.2(b). In the negative half cycle of the ac supply (π to 2π), secondary voltage V_{AB} is negative, i.e. A is negative with respect to B.
- Hence the diode is reverse biased and offers a very high resistance. Hence we can replace it by an open circuited switch.
- The load is disconnected from the secondary. Hence the load voltage and load current both are zero and the voltage across the diode is equal to the instantaneous secondary voltage V_{AB}. The waveforms are shown in Fig. 11.3.3(a).

Why the name Half Wave Rectifier ?

This circuit is called as half wave rectifier because it delivers power to the load during only one half cycle of the ac supply voltage.

11.3.2 Negative Half Wave Rectifier :

- In the circuit discussed now, the diode is conducting in the positive half cycle. But it is also possible to have a half wave rectifier which responds only to the negative half of the ac supply.
- Such a half wave rectifier is shown in Fig. 11.3.3(b). It produces a negative dc voltage across the load.

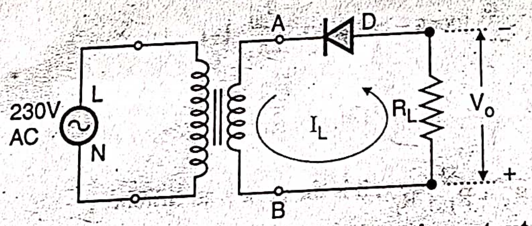


Fig. 11.3.3(b) : Half wave rectifier to produce negative output voltage

11.3.3 Analysis of Half Wave Rectifier :

The important performance parameters of a rectifier are as follows :

- Average load current ($I_{L\,dc}$)
- Average load voltage ($V_{L\,dc}$)

- RMS load current ($I_{L\,rms}$)
- RMS load voltage ($V_{L\,rms}$)
- Ripple factor
- Voltage regulation
- Rectification efficiency and TUF.

11.3.4 DC or Average Load Current (I_{Ldc}) :

- By definition the average value of a periodic function is given by the area under one cycle of the function divided by the base (period).
- Refer to the load current waveform of Fig. 11.3.3(c). We have to consider one complete cycle of this waveform from $\omega t = 0$ to $\omega t = 2\pi$.

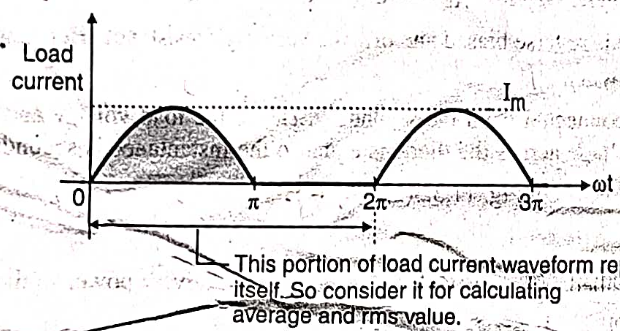


Fig. 11.3.3(c) : Load current waveform

$$\therefore \quad I_{av} = I_{L\,dc} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin \omega t \, d\omega t = \frac{-I_m}{2\pi}[\cos \omega t]_0^{\pi}$$

where I_m = Peak amplitude of the load current

$$= \frac{-I_m}{2\pi}[\cos\pi - \cos 0] = \frac{-I_m}{2\pi}[-1-1]$$

$$\therefore \quad I_{Ldc} = \frac{I_m}{\pi} \qquad \ldots(11.3.2)$$

where $I_m = \frac{V_m}{R_S + R_F + R_L}$, it is the peak load current

R_F = Diode forward resistance, R_S = Transformer secondary resistance

V_m = Maximum or peak secondary voltage

11.3.5 DC or Average Load Voltage (V_{Ldc}) :

As the load is purely resistive the average load voltage is given as :

$$V_{Ldc} = I_{Ldc} \times R_L \qquad \ldots(11.3.3)$$

Substituting the value of I_{Ldc} we get,

$$V_{Ldc} = \frac{I_m}{\pi} \times R_L$$

$$= \frac{V_m}{\pi(R_S + R_F + R_L)} \times R_L \quad \text{...Exact} \qquad \text{...(11.3.4)}$$

Usually R_S and R_F are small as compared to R_L

$\therefore \; (R_S + R_F + R_L) \approx R_L$

Hence Equation (11.3.4) can be approximated as,

$$V_{Ldc} \approx \frac{V_m}{\pi} \quad \text{...Approximate} \qquad \text{...(11.3.5)}$$

where V_m = Peak secondary voltage

11.3.6 AC or RMS Load Current $(I_{L\,rms})$:

- Refer to the load current waveform of Fig. 11.3.3(c). Consider one complete cycle of the load current waveform $(0 - 2\pi)$ to write.

$$I_{L\,rms} = \left[\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2} = \left[\frac{I_m^2}{2\pi}\int_0^{\pi}\left(\frac{1-\cos 2\,\omega t}{2}\right) d\omega t\right]^{1/2}$$

$$= \frac{I_m}{2}\left[\frac{1}{\pi}\left(\pi - \frac{1}{2}\sin 2\,\pi\right)\right]^{1/2}, \quad \text{But } \sin 2\pi = 0$$

$$\therefore \; I_{L\,rms} = \frac{I_m}{2} \qquad \text{...(11.3.6)}$$

- This is the rms or effective value of the load current.

11.3.7 AC or RMS Value of Load Voltage $(V_{L\,rms})$:

Since the load is purely resistive, the rms value of load voltage is given by,

$$V_{L\,rms} = I_{L\,rms} \times R_L = \frac{I_m}{2} \times R_L$$

$$= \frac{V_m}{2(R_S + R_F + R_L)} \times R_L \quad \text{... (Exact)}$$

But $(R_S + R_F) <<< R_L$

$$\therefore \; V_{L\,rms} \approx \frac{V_m}{2} \quad \text{...(Approximate)} \qquad \text{...(11.3.7)}$$

11.3.8 Ripple Factor (RF) :

>>> [Asked In Exam : Dec. 05 !!!]

- The rectifier output consists of AC as well as DC components. The ripple factor measures percentage of AC component in the rectifier output.
- The ripple factor indicates how close the rectified output is to the pure ideal dc voltage waveform. So it is a figure of merit for the rectifiers.
- Small values of ripple factor indicate that the rectifier output waveform is close to being pure dc.
- The ideal value of RF should be zero and practically it should be as small as possible.
- Ripple factor is denoted by "r".

$$\text{Ripple factor} = \frac{\text{RMS value of the AC component of output}}{\text{DC or average value of the output}}$$

$$\therefore \quad r = \frac{\left[V_{L\,rms}^2 - V_{L\,dc}^2\right]^{1/2}}{V_{L\,dc}}$$

Substituting the approximate values we get,

$$r = \frac{\left[(V_m/2)^2 - \left[(V_m/\pi)^2\right]^{1/2}\right]}{V_m/\pi}$$

$$r \approx 1.21 \text{ or } 121\ \% \qquad \text{...(11.3.8)}$$

Equation (11.3.8) indicates that the ripple content in the output voltage is 1.21 times the dc component. This is a very high value of ripple factor which indicates that the output of HWR is no way close to the pure dc voltage. A filter is required to reduce the ripple factor.

11.3.9 DC Output Power (P_{Ldc}) :

The dc or average output power delivered to the load is given by,

$$P_{Ldc} = I_{Ldc}^2 \times R_L$$

$$= \left[\frac{I_m}{\pi}\right]^2 R_L = \frac{I_m^2}{\pi^2} R_L \qquad \text{...(11.3.9)}$$

Substituting the expression for I_m we get,

$$\therefore \quad P_{Ldc} = \frac{V_m^2}{\pi^2 (R_S + R_F + R_L)^2} \times R_L$$

If $R_L >> (R_S + R_F)$ then,

$$P_{Ldc} \approx \frac{V_m^2}{\pi^2 R_L}$$

But $V_m/\pi = V_{Ldc}$, $P_{Ldc} = \dfrac{V_{Ldc}^2}{R_L}$ ...(11.3.10)

11.3.10 AC Input Power :

- The ac input power to a rectifier is the power supplied by the secondary winding of the transformer. It is given by,

$$P_{ac} = I_{s\,rms}^2 \times (R_S + R_F + R_L) \quad \text{...(11.3.11)}$$

where $I_{s\,rms}$ = RMS value of the secondary current

- For a HWR, the secondary current is same as the load current. Hence RMS value of the secondary current is same as the RMS value of load current.

$$\therefore \quad I_{s\,rms} = I_{L\,rms} = \frac{I_m}{2} \quad \text{...(11.3.12)}$$

$$\therefore \quad P_{ac} = \left(\frac{I_m}{2}\right)^2 (R_S + R_F + R_L) = \frac{I_m^2}{4} (R_S + R_F + R_L) \quad \text{...(11.3.13)}$$

11.3.11 Rectification Efficiency or Power Conversion Efficiency :

- Rectification efficiency is defined as,

$$\eta = \frac{\text{DC output power}}{\text{AC input power}} = \frac{P_{Ldc}}{P_{ac}}$$

- Substitute Equations (11.3.9) and (11.3.13) to get,

$$\eta = \frac{I_{Ldc}^2 R_L}{I_{s\,rms}^2 (R_S + R_F + R_L)}$$

$$= \frac{(I_m/\pi)^2 R_L}{(I_m/2)^2 (R_S + R_F + R_L)} = \frac{4}{\pi^2} \frac{R_L}{(R_S + R_F + R_L)}$$

- If $R_L >> (R_S + R_F)$, then we get the maximum rectification efficiency as,

$$\eta_{max} = \frac{4}{\pi^2} = 0.4 \text{ or } 40\% \quad \text{...(11.3.14)}$$

Rectification efficiency of a rectifier indicates the percentage of ac input power, actually converted into the average load power. Hence it should be as high as possible.

- Ideally the conversion efficiency should be 100 % and practically it should be as high as possible. But η_{max} for the half wave rectifier is too small. This is its biggest disadvantage.

11.3.12 Transformer Utilization Factor (TUF) :

- The transformer utilization factor (TUF) indicates how well the input transformer is being utilized.
- It is defined as the ratio of dc output power to the ac power ratings of the transformer.

TUF is defined as :

$$\text{TUF} = \frac{\text{DC output power } (P_{dc})}{\text{AC power rating of the transformer}} = \frac{V_{L\,dc}\, I_{L\,dc}}{V_{S\,rms}\, I_{S\,rms}}$$

Assuming $R_L >> (R_S + R_P)$ we get,

$$\text{TUF} = \frac{[V_m/\pi]\,[I_m/\pi]}{[V_m/\sqrt{2}]\,[I_m/2]} = \frac{2\sqrt{2}}{\pi^2}$$

$$\therefore \quad \text{TUF} = 0.287 \text{ or } 28.7\ \% \quad \text{...(11.3.15)}$$

- Ideal value of TUF is 100 % and practically it should be as high as possible.
- The value of TUF is too low for the HWR. This value of TUF indicates that the transformer is being utilized to only 28.7 % of its full capacity, which is gross underutilization.

11.3.13 Peak Inverse Voltage (PIV) :

- This is the maximum negative voltage which appears across a nonconducting reverse biased diode.
- As shown in Fig. 11.3.4 the maximum negative voltage across the diode is $-V_m$ Volt, when the diode is not conducting.

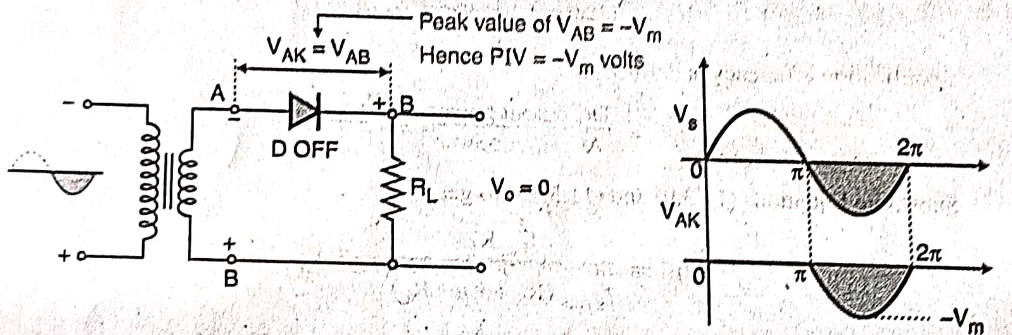


Fig. 11.3.4 : PIV of diode in HWR

- Strictly speaking the term PIV has been used to denote the maximum reverse voltage capability of a diode but commonly it is used to denote the maximum reverse voltage that occurs across a diode.

$$\therefore \quad \text{PIV} = V_m \text{ Volts} \quad \text{...(11.3.16)}$$

Diode selection based on PIV :

- We must select a diode which has a PIV rating, higher than the maximum possible negative voltage i.e. V_m to ensure safety of the diode.
- Otherwise the diode will enter into the breakdown region and get damaged.

Ripple frequency :

It is the frequency of the pulsating load voltage waveform. For a half wave rectifier, ripple frequency is 50 Hz. (Same as that of ac mains).

11.3.14 Voltage Regulation :

- Ideally the average rectifier output voltage should remain constant. But practically it varies with the changes in the load current. Voltage regulation is defined as :

$$\text{Voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\,\% \qquad ...(11.3.17)$$

where V_{NL} = Average load voltage at no load i.e. when $R_L = \infty$

$$\therefore\ V_{NL} = \frac{V_m}{\pi}$$

- No load voltage is the value of average output voltage at zero load current and V_{FL} i.e. the full load voltage is the value of average output voltage at the specified maximum load current.

and V_{FL} = Average load voltage at full load $= \frac{V_m}{\pi} \cdot \frac{R_L}{R_S + R_F + R_L}$

- Substituting the expressions for V_{NL} and V_{FL} in Equation (11.3.17) we get,

$$\text{load regulation} = \frac{\left(\frac{V_m}{\pi}\right) - \left(\frac{V_m}{\pi} \cdot \frac{R_L}{R_S + R_F + R_L}\right)}{\left(\frac{V_m}{\pi} \cdot \frac{R_L}{R_S + R_F + R_L}\right)}$$

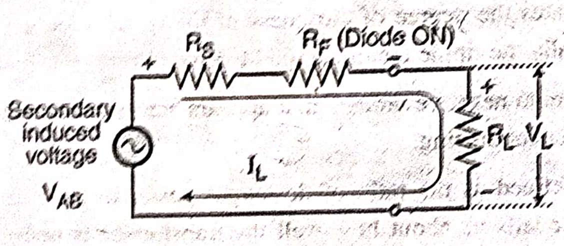
$$= \frac{\frac{V_m}{\pi}\left[R_S + R_F + R_L - R_L\right]}{\frac{V_m}{\pi} \cdot R_L}$$

$$\text{Voltage regulation} = \frac{(R_S + R_F)}{R_L} \times 100\,\% \qquad ...(11.3.18)$$

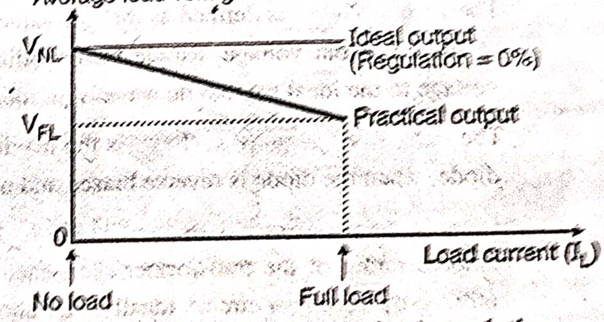
- Ideally the load regulation should be 0 % and practically it should be as low as possible. A rectifier with lowest value of regulation should be preferred.

Why does the output voltage change with change in I_L?

- Fig. 11.3.5(a) shows the equivalent circuit of the half wave rectifier.



(a) Equivalent circuit of HWR



(b) Characteristic showing the load regulation

Fig. 11.3.5

- Due to reduction in the load resistance R_L, load current I_L will increase. This will increase the voltage drop across $(R_S + R_F)$ as shown in Fig. 11.3.5(a).
- If the secondary voltage is constant, then V_{LDC} will decrease with increase in the load current, as shown in Fig. 11.3.5(b).

11.3.15 Disadvantages of Half Wave Rectifier :

1. Due to the unidirectional current flow through the transformer, there is a possibility of core saturation. To avoid it, transformer size must be increased.
2. Ripple factor is high (1.21).
3. Low rectification efficiency (40 %).
4. Low TUF (only 28 %) which indicates that the transformer is not being used effectively.
5. Low DC output voltage and current.
6. Larger filter components are required.

Because of these disadvantages, half wave rectifier is normally not used in practice.

11.3.16 Advantages of HWR :

1. Simple construction.
2. Less number of components are required to be used.
3. Small size.

11.3.17 Applications of HWR :

In the eliminators for pocket radios or eliminators for walkman or in the low cost power supplies.

11.3.18 Important Terms Related to Rectification :

- **Rectifier** is a circuit which converts ac voltage into a pulsating dc voltage. Pulsating dc voltage is not pure dc, it contains some ac part called ripple.
- The **Rectification efficiency** (η) is defined as the ratio of dc output power to the a.c. input power of a rectifier.
- The **Ripple factor** is defined as the rms value of the ripple voltage (a.c. component of the output) to the dc output voltage. Ripple factor indicates the degree of closeness of the rectifier output voltage to the ideal smooth dc waveform. Ideally the ripple factor should be zero.
- The **Peak inverse voltage (PIV)** is the maximum negative voltage that appears across a rectifier diode, when the diode is reverse biased and nonconducting.
- **Transformer utilization factor (TUF)** is defined as the ratio of dc output power to the volt ampere rating of the transformer. This factor tells us about how well the transformer is being utilized by a rectifier circuit. Ideally TUF should be 100%.

11.4 Full Wave Rectifier with Center Tapped Transformer :

➤➤➤ [Asked In Exam : Dec. 06, May 07 !!!]

- The full wave rectifier configuration is as shown in Fig. 11.4.1. It consists of a step down center tapped transformer T_1, two diodes and a purely resistive load R_L.
- In the HWR the load current flows in only one half cycle of the supply but in the full wave rectifier it flows in both the half cycles of ac supply.

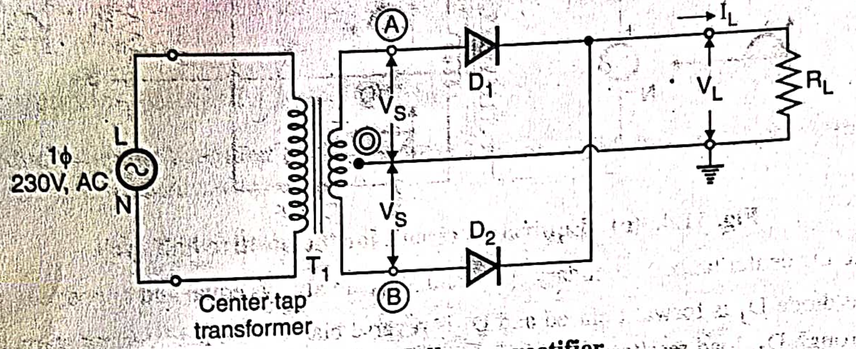


Fig. 11.4.1 : Full wave rectifier

Center tapped transformer :

- Before we analyze the full wave rectifier, let us refresh out concepts about the voltages induced on the secondary sides of a center tapped transformer. Refer Fig. 11.4.2 for the same.
- The induced voltages in the two halves of the secondary winding are always 180° out of phase with respect to each other.

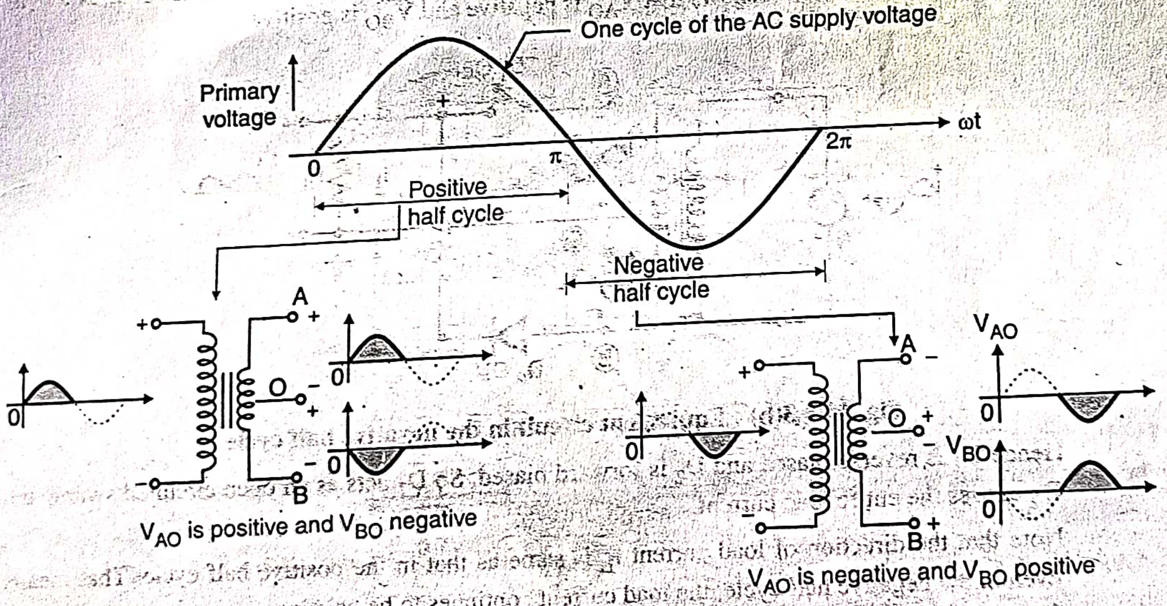


Fig. 11.4.2 : Secondary induced voltages for a center tapped transformer

11.4.1 Operation of FWR :

Let us understand the operation of FWR in the two half cycles of the ac supply.

Operation in the positive half cycle (0 – π) :

- In the positive half cycle of ac supply, the polarities of the secondary induced voltages are as shown in Fig. 11.4.3(a). It shows that V_{AO} is positive and V_{BO} is negative.

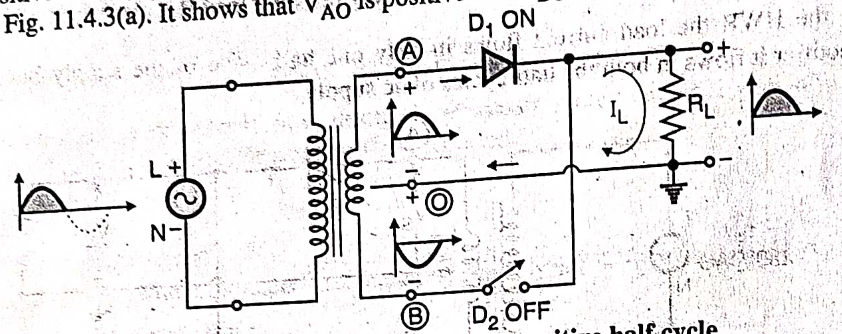


Fig. 11.4.3(a) : Equivalent circuit for the positive half cycle

- Due to the center tapped secondary, V_{AO} and V_{BO} are always equal and opposite to each other.
- Hence diode D_1 is forward biased and D_2 is reverse biased. The load current starts flowing from A, through D_1, load resistance R_L back to point O as shown in Fig. 11.4.3(a).
- The instantaneous load voltage is positive and approximately equal to V_{AO}. As the load is purely resistive, the load current i_L has the same shape as that of the load voltage. The voltage and current waveforms are as shown in Fig. 11.4.4.

Operation in the negative half cycle (π – 2 π) :

- In the negative half cycle of the ac supply, the polarities of secondary induced voltages are as shown in Fig. 11.4.3(b). It shows that V_{AO} is negative and V_{BO} is positive.

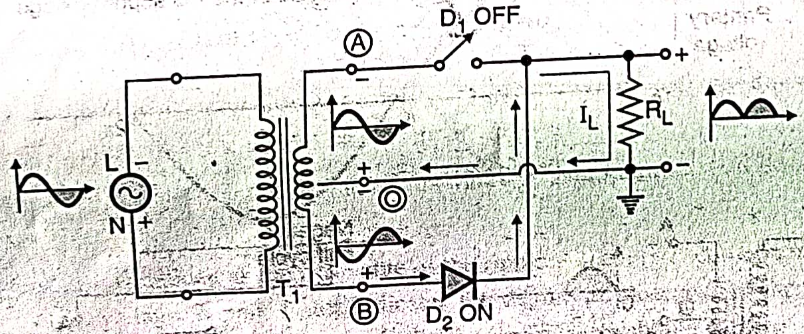


Fig. 11.4.3(b) : Equivalent circuit in the negative half cycle

- Hence D_1 is reverse biased and D_2 is forward biased. So D_1 acts as an open circuited switch and D_2 carries the entire load current.
- Note that the direction of load current i_L is same as that in the positive half cycle. That means even in the negative half cycle, the load current continues to be positive.
- The instantaneous load voltage v_L is positive and almost equal to V_{BO}.

Waveforms :

The voltage and current waveforms are as shown in Fig. 11.4.4.

Important points about the full wave rectifier :

1. Load voltage and load current both are positive in both the half cycles of the ac supply.
2. Output voltage is available in both the half cycles of the ac supply.
3. The full wave rectifier circuit consists of two half wave rectifiers, which work independently and feed the common load.

11.4.2 Analysis of the Full Wave Rectifier Circuit :

- After discussing the operation of the full wave rectifier circuit now let us obtain the expressions for various performance parameters.

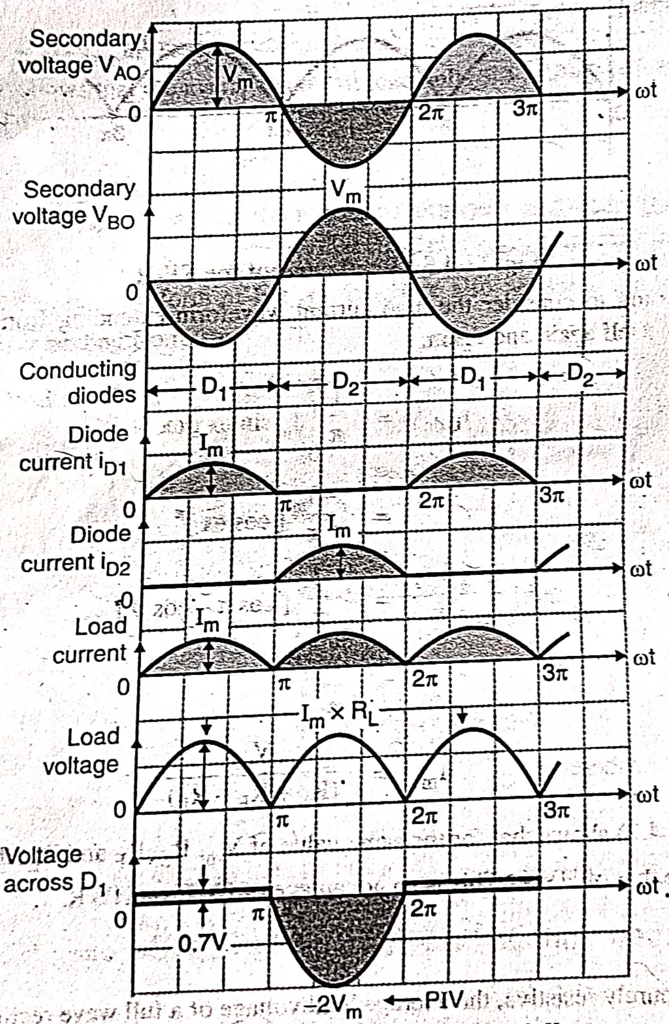


Fig. 11.4.4 : Voltage and current waveforms for a full wave rectifier

- This will help us to compare the performance of this circuit with that of a HWR. Before going further, let us obtain the expression for the peak load, current I_m.

$$\text{Peak load current,} \quad I_m = \frac{V_m}{(R_S + R_F + R_L)} \quad \text{...(11.4.1)}$$

where, V_m = Peak secondary voltage for half the secondary (OA or OB).
R_S = Resistance of half the secondary (OA or OB)
R_F = Forward resistance of a diode.

11.4.3 Average Load Current ($I_{L\,dc}$) :

➤➤➤ [Asked in Exam : Dec. 05 !!!]

Refer to the load current waveform of Fig. 11.4.5.

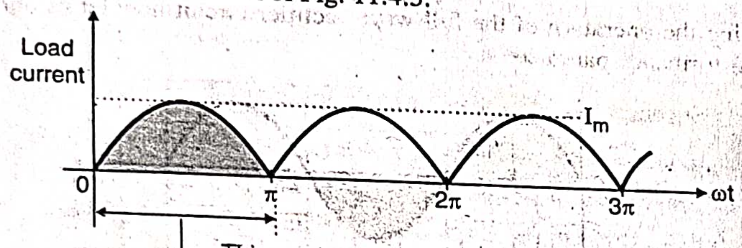


Fig. 11.4.5 : Load current for FWR

- Here we are going to consider the load current waveform extending from 0 to π because this portion repeats itself again and again.

$$\therefore \quad I_{L\,dc} = \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t \, d\omega t$$

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

$$= \frac{-I_m}{\pi}[\cos \pi - \cos 0]$$

$$\therefore \quad I_{L\,dc} = \frac{2 I_m}{\pi} \quad \text{...(11.4.2)}$$

$$\text{where,} \quad I_m = \frac{V_m}{(R_S + R_F + R_L)}$$

Equation (11.4.2) shows that for the same value of V_m, R_S, R_F and R_L, the average load current value of FWR is twice that of HWR. This is an advantage of FWR on HWR.

11.4.4 Average Load Voltage (V_{Ldc}) :

- As the load is purely resistive, the average load voltage of a full wave rectifier is given by,

$$V_{L\,dc} = I_{L\,dc} \times R_L$$

- Substituting the value of $I_{L\,dc}$ we get,

$$V_{L\,dc} = \frac{2\,I_m}{\pi} \times R_L$$

- Substitute the value of I_m to get,

$$V_{L\,dc} = \frac{2\,V_m}{\pi\,(R_S + R_F + R_L)} \times R_L \quad \text{...(Exact)} \qquad \text{...(11.4.3)}$$

$$= \frac{2\,V_m}{\pi\left[1 + \frac{(R_S + R_F)}{R_L}\right]}$$

- Assuming that $(R_S + R_F) << R_L$ we get,

$$V_{L\,dc} \approx \frac{2\,V_m}{\pi} \quad \text{... (Approximate)} \qquad \text{...(11.4.4)}$$

- Equation (11.4.4) shows that the average value of load voltage for FWR is twice the average load voltage for FWR.

11.4.5 RMS Load Current ($I_{L\,rms}$) :

➤➤➤ [Asked in Exam : Dec. 05 !!!]

- Refer to the load current waveform of Fig. 11.4.5. Here also we are going to consider the load current waveform extending from 0 to π.

- The rms value of load current is given by,

$$I_{L\,rms} = \left[\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2}$$

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

$$= \frac{I_m}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi - \frac{1}{2}\sin 2\pi\right)\right]^{1/2}$$

But $\sin 2\pi = 0$

$$\therefore \; I_{L\,rms} = \frac{I_m}{\sqrt{2}} \qquad \text{...(11.4.5)}$$

- Compared to HWR, the value of $I_{L\,rms}$ for FWR is higher by 20.7 %.

11.4.6 RMS Load Voltage ($V_{L\,rms}$) :

- The rms value of load voltage is given by,

$$V_{L\,rms} = I_{L\,rms} \times R_L$$

$$\therefore \quad V_{L\,rms} = \frac{I_m}{\sqrt{2}} \times R_L$$

- Substitute the value of I_m we get,

$$V_{L\,rms} = \frac{V_m}{\sqrt{2}\,(R_S + R_F + R_L)} \times R_L$$

$$= \frac{V_m}{\sqrt{2}\left[1 + \frac{(R_S + R_F)}{R_L}\right]} \quad \text{... (Exact)}$$

Assuming $(R_S + R_F) << R_L$,

$$V_{L\,rms} = \frac{V_m}{\sqrt{2}} \quad \text{...(Approximate)} \qquad \text{...(11.4.6)}$$

Thus the rms load voltage for the FWR is higher than that for the HWR.

11.4.7 Ripple Factor (RF) :

➤➤➤ [Asked in Exam : Dec. 05 !!!]

$$\text{Ripple factor (RF)} = \frac{\left[V_{L\,rms}^2 - V_{L\,dc}^2\right]^{1/2}}{V_{L\,dc}}$$

Substituting the values we get,

$$RF = \frac{\left[(V_m/\sqrt{2})^2 - (2V_m/\pi)^2\right]^{1/2}}{2\,V_m/\pi}$$

$$= \left[\frac{\pi^2}{8} - 1\right]^{1/2} = 0.48 \text{ or } 48\% \qquad \text{...(11.4.7)}$$

Note that this value is much less than the ripple factor of a half wave rectifier which is 1.21 or 121 %. Therefore the quality of the dc voltage at the full wave rectifier is much better than that of a HWR.

11.4.8 DC Output Power (P_{Ldc}) :

➤➤➤ [Asked in Exam : Dec. 05 !!!]

The dc output power is given by,

$$P_{L\,dc} = I_{L\,dc}^2 \times R_L$$

Substitute, $I_{L\,dc} = \frac{2\,I_m}{\pi}$ and $I_m = \frac{V_m}{R_S + R_F + R_L}$ we get,

$$\therefore \quad P_{L\,dc} = \frac{4\,V_m^2}{\pi^2\,(R_S + R_F + R_L)^2} \times R_L \qquad ...(11.4.8)$$

11.4.9 AC Input Power (P_{ac}) :

➤➤➤ [Asked In Exam : Dec. 05 !!!]

The ac input power is given by,

$$P_{ac} = I_{S\,rms}^2 \times (R_S + R_F + R_L) = \left[\frac{I_m}{\sqrt{2}}\right]^2 \times (R_S + R_F + R_L)$$

$$\therefore \quad P_{ac} = \frac{I_m^2\,(R_S + R_F + R_L)}{2}$$

Substituting the value of I_m we get,

$$P_{ac} = \frac{V_m^2\,(R_S + R_F + R_L)}{2\,(R_S + R_F + R_L)^2} = \frac{V_m^2}{2\,(R_S + R_F + R_L)} \qquad ...(11.4.9)$$

11.4.10 Rectifier Efficiency :

➤➤➤ [Asked In Exam : Dec. 05, May 06, May 07 !!!]

- As we have already defined,

$$\eta = \frac{P_{L\,dc}}{P_{ac}} = \frac{I_{L\,dc}^2 \times R_L}{(I_{S\,rms})^2\,(R_S + R_F + R_L)}$$

- Now substitute the values of $I_{L\,dc}$ and $I_{S\,rms}$ as,

$$I_{L\,dc} = \frac{2\,I_m}{\pi} \quad \text{and} \quad I_{S\,rms} = \frac{I_m}{\sqrt{2}}$$

$$\therefore \quad \eta = \frac{(2\,I_m/\pi)^2\,R_L}{(I_m/\sqrt{2})^2\,(R_S + R_F + R_L)}$$

$$\therefore \quad \eta = \frac{8\,R_L}{\pi^2\,(R_S + R_F + R_L)} \qquad ...(11.4.10)$$

- This is the required expression for rectifier efficiency.
- Assuming $(R_S + R_F) << R_L$ we get, the maximum value of efficiency to be,

$$\eta_{max} = \frac{8}{\pi^2} = 0.812 \text{ or } 81.2\ \% \qquad ...(11.4.11)$$

- This is the maximum theoretical value of rectifier efficiency. Note that the rectification efficiency of FWR is almost twice the rectifier efficiency of HWR.

11.4.11 Peak Inverse Voltage (PIV) :

- To obtain the value of PIV, refer Fig. 11.4.6, which is the equivalent circuit of FWR in the positive half cycle.
- Diode D_1 is conducting and it is assumed to be equivalent to a closed switch. Let us obtain the PIV of D_2 which is now OFF.
- Fig. 11.4.6 shows that in the positive half cycle $(0 - \pi)$ the instantaneous voltage across D_2 is V_{BA}. As shown in the waveforms the maximum negative value of V_{BA} is $-2V_m$.

$$\therefore \quad PIV = 2\,V_m \text{ Volts} \qquad ...(11.4.12)$$

- This is a disadvantage of FWR as compared to HWR where PIV = V_m volts. Due to higher PIV we have to select diodes of higher PIV ratings which are costly.

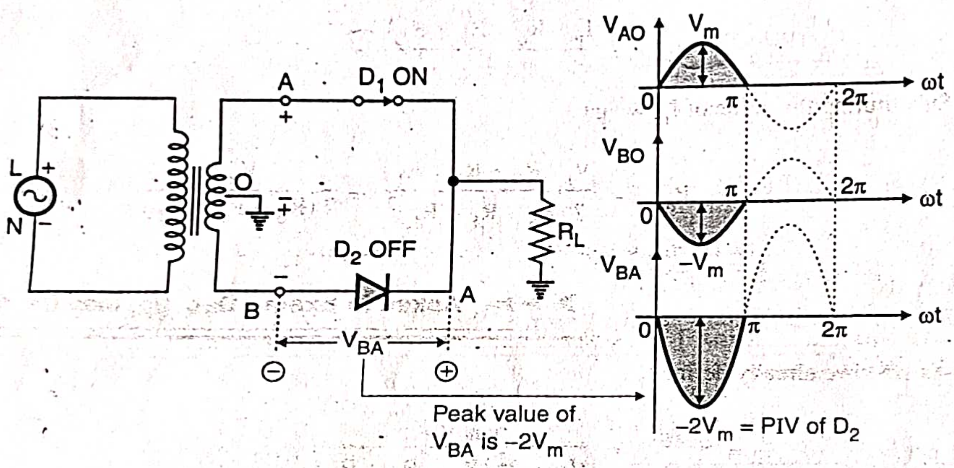


Fig. 11.4.6 : Peak inverse voltage for FWR

Ripple frequency :

The ripple frequency of FWR is twice that of the HWR i.e. 100 Hz. This is advantageous because the filter design becomes simpler as ripple frequency is increased.

11.4.12 Voltage Regulation :

$$\text{Voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\ \%$$

$$\text{But } V_{NL} = \frac{2V_m}{\pi}$$

$$\text{and } V_{FL} = \frac{2V_m}{\pi} \times \frac{R_L}{(R_S + R_F + R_L)}$$

$$\therefore \text{ Voltage regulation } = \frac{(2V_m/\pi) - [2V_m R_L/\pi (R_S + R_F + R_L)]}{2V_m R_L/\pi (R_S + R_F + R_L)} \times 100$$

$$= \frac{(2V_m/\pi)(R_s + R_f + R_L - R_L)}{(2V_m/\pi)\, R_L} \times 100$$

$$= \frac{R_s + R_f}{R_L} \times 100$$

This is same as the voltage regulation of a HWR.

11.4.13 Advantages of Full Wave Rectifier :

1. Low ripple factor as compared to HWR
2. Better rectification efficiency
3. Better TUF
4. Higher values of average load voltage and average load current
5. No possibility of transformer core saturation because transformer current flows equally in both the half cycles.

11.4.14 Disadvantages of Full Wave Rectifier :

1. Since PIV of the diodes is 2 V_m, size of the diodes is larger and they are more costly.
2. Cost of the center tapped transformer is high.

11.5 Applications of FWR :

1. Laboratory power supplies.
2. High current power supplies.
3. Battery chargers.
4. Power supplies for various electronic circuits.

11.5 Full Wave Bridge Rectifier :

>>> [Asked In Exam : Dec. 02, May 03, Dec. 03, Dec. 04 !!!]

- The disadvantages of the full wave rectifier such as high PIV and compulsory use of center tapped transformer are overcome in the bridge rectifier.
- The circuit configuration of bridge rectifier is as shown in Fig. 11.5.1. It consists of four diodes connected to form a bridge.
- The center tapped input transformer is not required. The input transformer T_1 shown in Fig. 11.5.1 is a step down transformer.

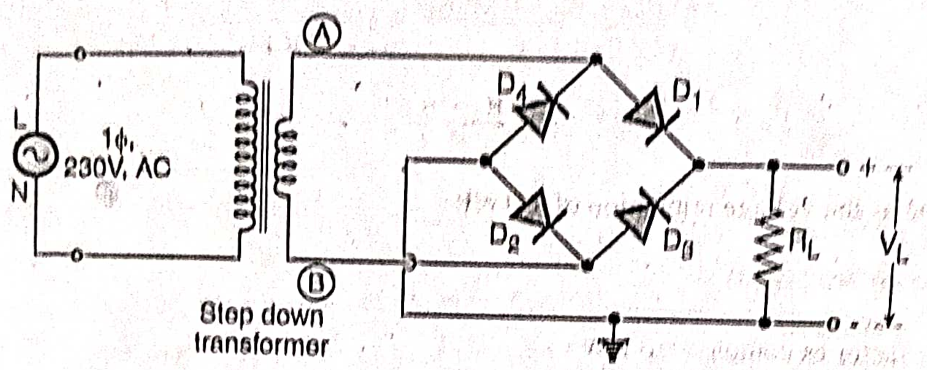


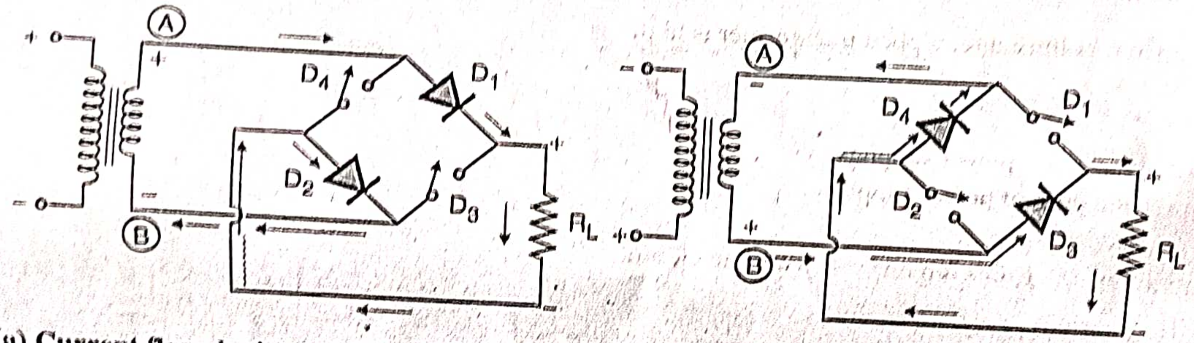
Fig. 11.5.1 : A bridge rectifier circuit

- Bridge rectifier offers full wave rectification. The diodes conduct in pairs i.e. at any given instant of time, one pair of diodes either D_1 D_2 or D_3 D_4 will be conducting.

11.5.1 Operation of the Bridge Rectifier :

➤➤➤ [Asked in Exam : May 03, Dec. 03, Dec. 04 !!!]

Operation of the bridge rectifier can be explained in two half cycles of the AC supply voltage as follows :



(a) Current flow during positive half cycle **(b) Current flow during negative half cycle**

Fig. 11.5.2

(i) Operation in the positive half cycle ($0 \leq \omega t \leq \pi$) :

- In the positive half cycle of the ac supply the secondary voltage V_{AB} is positive. Therefore diodes D_1 and D_2 are forward biased whereas D_3 and D_4 are reverse biased.
- The equivalent circuit for this interval is as shown in Fig. 11.5.2(a). Note that the reverse biased diodes D_3 and D_4 act as open switches.
- The load current and load voltage both are positive as shown in the waveforms in Fig. 11.5.3.

(ii) Operation in the negative half cycle ($\pi \le \omega t \le 2\pi$) :

- In the negative half cycle of the ac supply the secondary voltage V_{AB} becomes negative. Diodes D_3 and D_4 are forward biased and start conducting.
- D_1 and D_2 are reverse biased hence do not conduct. The equivalent circuit for this interval is as shown in Fig. 11.5.2(b).
- The waveforms of the bridge circuit are as shown in Fig. 11.5.3.

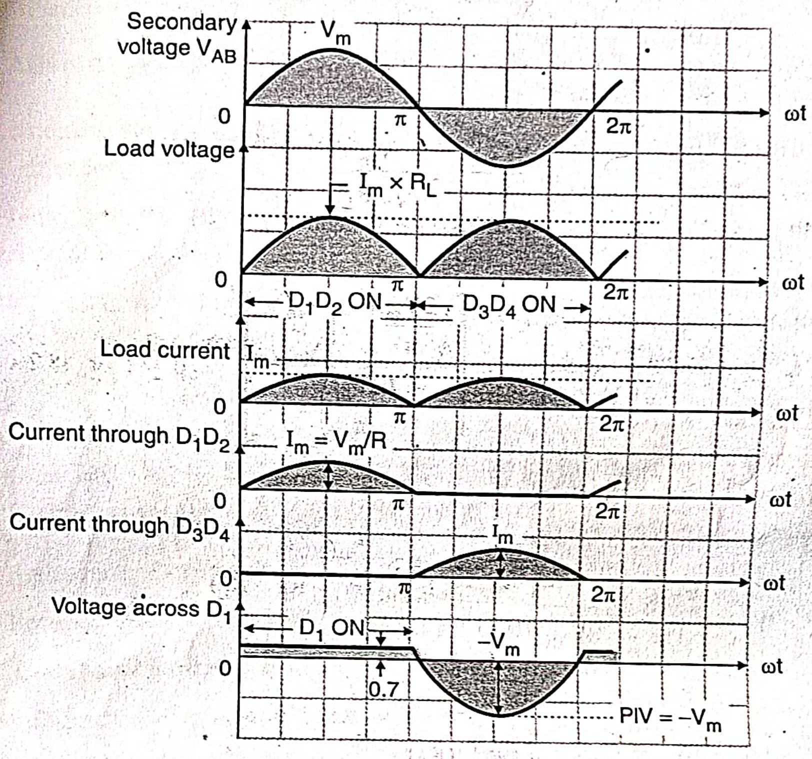


Fig. 11.5.3 : Waveforms for the bridge rectifier

11.5.2 Performance Parameter of a Bridge Rectifier :

- The bridge rectifier circuit is basically a full wave rectifier only. Therefore all the performance parameters such as $V_{L\ dc}$, $V_{L\ rms}$, $I_{L\ dc}$, $I_{L\ rms}$ etc. will have the same expressions as those derived for the FWR circuit earlier.
- However the expression for peak load current I_m gets modified slightly. In bridge circuit, as two diodes conduct simultaneously, the maximum value of load current is given by,

$$I_m = \frac{V_m}{(R_S + 2R_F + R_L)} \qquad \text{...(11.5.1)}$$

- Note that we have used 2 R_F instead of R_F in the denominator. The remaining expressions however remain same as those for the full wave rectifier.

- Some of the important performance parameters are as given below :

1. DC output voltage : It is same as that of the full wave rectifier with center tap.

$$\therefore \quad V_{L\,dc} = \frac{2V_m}{\pi} \text{... Approximate}$$

2. DC output current : DC output current is approximately given by,

$$I_{L\,dc} = \frac{V_{L\,dc}}{R_L} = \frac{2\,V_m}{\pi R_L} = \frac{2I_m}{\pi}$$

3. RMS output voltage : $V_{L\,rms} = \frac{V_m}{\sqrt{2}}$

4. RMS output current : $I_{L\,rms} = \frac{V_{L\,rms}}{R_L} = \frac{V_m}{\sqrt{2}\,R_L}$

5. Ripple factor :

$$r = \left[\frac{V_{L\,rms}^2 - V_{L\,dc}^2}{V_{L\,dc}^2}\right]^{1/2} = \left[\frac{\left(\frac{2V_m}{\pi}\right)^2 - \left(\frac{V_m}{\sqrt{2}}\right)^2}{\left(\frac{2V_m}{\pi}\right)^2}\right]^{1/2} = 0.482 \text{ or } 48.2\%$$

6. Rectification efficiency :

$$\eta = \frac{P_{L\,dc}}{P_{ac}} = \frac{I_{L\,dc}^2\,R_L}{I_{S\,rms}^2\,(R_S + R_F + R_L)}$$

$$\therefore \quad \eta_{max} = \frac{\left(\frac{2\,I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (R_L)} = 0.812 \text{ or } 81.2\%$$

7. Peak inverse voltage (PIV) :

Fig. 11.5.4 shows that the peak negative voltage across a non-conducting diode is $-V_m$ volts. This is its advantage over the full wave rectifier with center tap transformer.

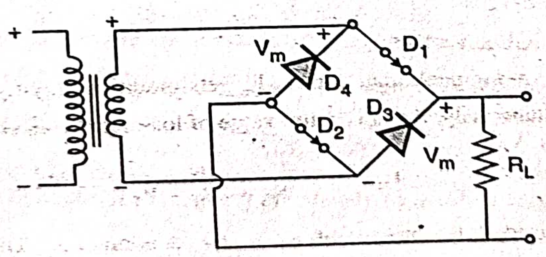


Fig. 11.5.4 : PIV of diodes in bridge rectifier

8. **Voltage regulation :**

The expression for voltage regulation of a bridge rectifier is as follows :

$$\text{Voltage regulation} = \frac{R_S + 2R_F}{R_L} \times 100$$

9. **Ripple frequency :**

As shown in waveforms of Fig. 11.5.3, two cycles of output appear for each cycle of input. Hence, the ripple frequency is twice the input frequency. So ripple frequency is 100 Hz.

11.5.3 Advantages of Bridge Rectifier :

1. It requires a small size transformer. Center tap transformer is not required. This makes the bridge rectifier cost effective.
2. The input transformer is not a must. It is possible to operate the bridge rectifier directly on the 230 V ac supply.
3. This circuit is most suitable for the high voltage applications. This is because the maximum negative voltage that appears across each diode is $-V_m$. Therefore the diodes with PIV rating of $-V_m$ Volts are required to be selected. (PIV in full wave rectifier is $-2V_m$).
4. Core saturation does not take place. Therefore transformer losses are reduced. Core saturation is avoided because equal and opposite currents flow through the transformer in each cycle.
5. The PIV is only V_m volts which is half the PIV of full wave rectifier with center tap.
6. High average output voltage
7. Rectifier efficiency η is high
8. Transformer utilization factor TUF is high.

11.5.4 Disadvantages of Bridge Rectifier :

1. The number of diodes used is four instead of two for FWR.
2. As two diodes conduct simultaneously, the voltage drop increases and the output voltage reduces.

11.5.5 Applications of Bridge Rectifier :

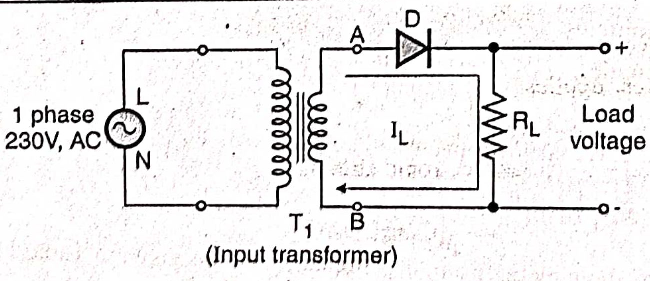
1. Laboratory dc power supplies.
2. High current power supplies.
3. Battery charger.
4. DC power supplies for various electronic circuits.

11.5.6 Comparison of Rectifying Circuits :

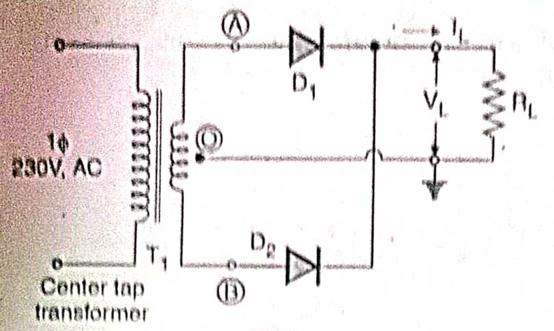
The comparison of the three rectifier circuits studied till now is given in Table 11.5.1.

Table 11.5.1 : Comparison of the rectifier circuits

Sr. No.	Parameter	HWR	FWR	Bridge rectifier
1.	DC or average load current ($I_{L\,dc}$)	$\frac{I_m}{\pi}$	$\frac{2\,I_m}{\pi}$	$\frac{2\,I_m}{\pi}$
2.	Maximum average load voltage $V_{L\,dc}$	$\frac{V_m}{\pi}$	$\frac{2\,V_m}{\pi}$	$\frac{2\,V_m}{\pi}$
3.	RMS load current $I_{L\,rms}$	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
4.	RMS load voltage $V_{L\,rms}$	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$
5.	DC load power P_{dc}	$\frac{I_m^2}{\pi^2}\,R_L$	$\frac{4I_m^2\,R_L}{\pi^2}$	$\frac{4I_m^2\,R_L}{\pi^2}$
6.	Maximum rectification efficiency (η)	40 %	81.2 %	81.2 %
7.	TUF	28.7 %	69.3 %	81.2 %
8.	Ripple factor	121 %	48 %	48 %
9.	Ripple frequency	50 Hz	100 Hz	100 Hz
10.	Number of diodes used	One	Two	Four
11.	Center tap transformer	Not required	Very much required	Not required
12.	Transformer core saturation	Possible	Not possible	Not possible
13.	PIV	V_m	$2\,V_m$	V_m
14.	Expression for the peak load current	$I_m = \frac{V_m}{(R_S + R_F + R_L)}$	$I_m = \frac{V_m}{(R_S + R_F + R_L)}$	$I_m = \frac{V_m}{(R_S + 2R_F + R_L)}$
15.	Circuit diagram	Refer Fig. A	Refer Fig. B	Refer Fig. C

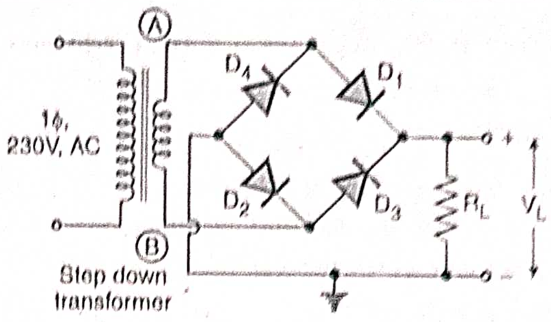


HWR
Fig. A



FWR

Fig. B



Bridge

Fig. C

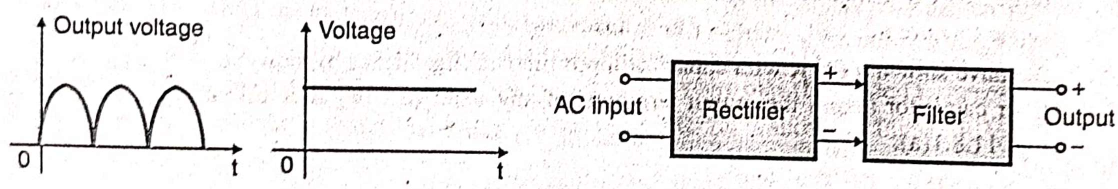
11.5.7 Specifications of Rectifiers :

The important specifications of rectifiers are as follows :

1. Average output voltage
2. Ripple factor
3. Peak inverse voltage (PIV)
4. Transformer utilization factor (TUF)
5. Average output current

11.6 Need of Filter Circuits :

- Filter is connected after the rectifier to obtain a ripple free or pure dc voltage whereas voltage regulators are used to deliver a constant d.c. voltage to the load.
- Filters are the electronic circuits used alongwith rectifiers in order to get a pure ripple free dc voltage.
- Till now we have seen that from all the rectifiers we get a "pulsating" dc voltage as shown in Fig. 11.6.1(a).
- But this is not what we want. What we want is a pure dc waveform as shown in Fig. 11.6.1(b).
- In order to obtain it we use filters. A filter is connected at the output of the rectifier as shown in Fig. 11.6.1(c).
- We can connect a filter at the output of any type of rectifier. (HWR, FWR or bridge).



(a) Pulsating dc at rectifier output (b) Ideal pure dc voltage (c) Rectifier to filter connection

Fig. 11.6.1

- The filter circuits use resistors, capacitors and inductors. Therefore they are called as passive filters.

11.7 Types of Filters (Classification of Filters) :

Filters are classified depending on the components used and depending on the configuration in which they are connected.

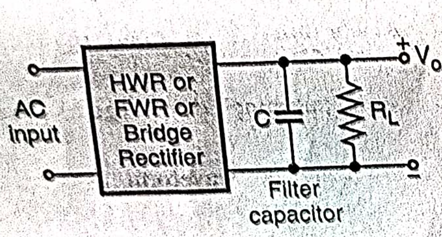
Some of the important filter types are as follows :

1. Capacitor input filter (shunt capacitor filter)
2. Choke input filter (series inductor filter)
3. LC filter
4. π type filter.
5. RC filter

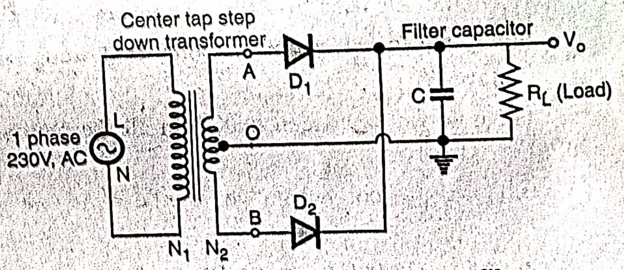
11.8 Capacitor Input Filter (Shunt Capacitor Filter) or C Filter :

➤➤➤ [Asked in Exam : Dec. 05 !!!]

- The capacitor input filter is used to reduce the ripple contents in the output of a rectifier to obtain a pure dc voltage.
- A full wave rectifier alongwith a capacitor input filter is as shown in Fig. 11.8.1(b).



(a) Connection of filter capacitor



(b) FWR with capacitor input filter

Fig. 11.8.1

- "C" is the filter capacitor which is connected across the load resistance R. The value of C is very large i.e. a few hundred microfarads in order to reduce the ripple successfully. The electrolytic capacitors are normally used as filter capacitors.
- We have shown a FWR with capacitor input filter in Fig. 11.8.1(b), however we can connect the filter capacitor across the output terminals of any other rectifier in a similar way, as shown in Fig. 11.8.1(a).

Why the name shunt capacitor filter ?

The filter capacitor is connected across (in shunt with) the load, this filter is called as shunt capacitor filter.

11.8.1 Operation of FWR with a Shunt Capacitor Filter :

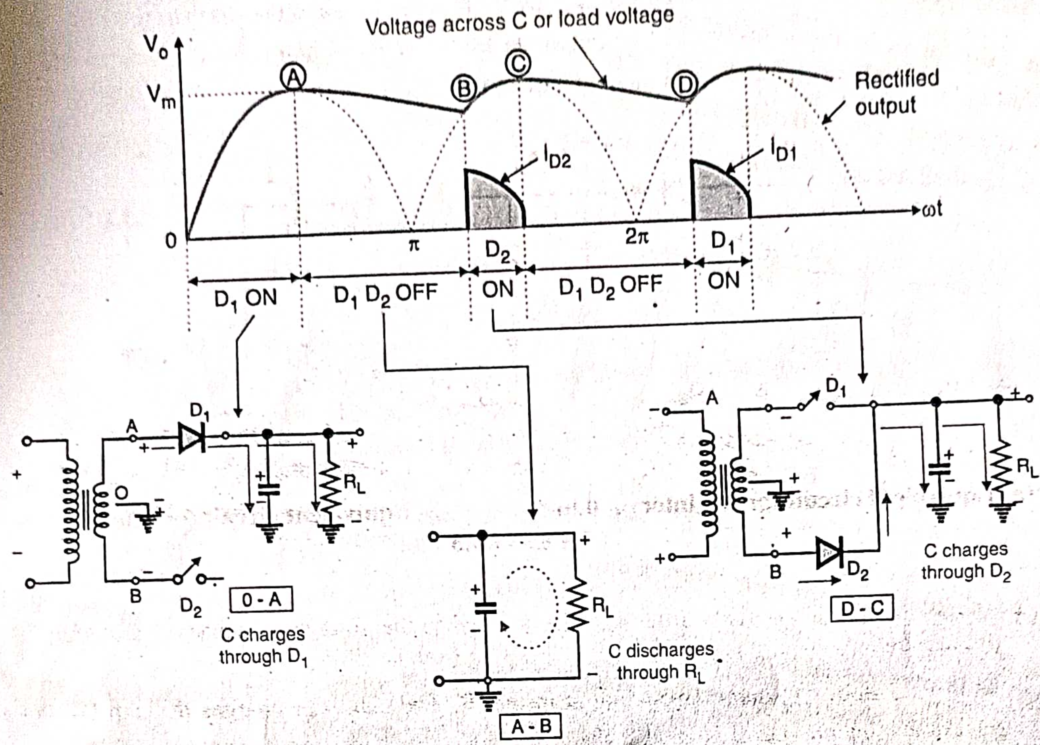


Fig. 11.8.2 : Load voltage waveform and equivalent circuits of FWR with a capacitor filter

- Fig. 11.8.2 shows the waveform of load voltage with the capacitor filter. Alongwith the waveforms the equivalent circuits for various intervals have been shown.
- Operation of the FWR with capacitor filter can be explained in four different intervals.

Operation in the interval 0 to A :

- The initial voltage on capacitor "C" is assumed to be zero. In the first positive half cycle of the supply, D_1 is forward biased and starts conducting. D_2 is reverse biased and acts as an open switch. Diode D_1 supplies for the charging current of the capacitor and the load current.
- Capacitor starts charging through D_1 and at the end of this interval i.e. at "A" it charges to the peak value of secondary voltage i.e. "V_m".

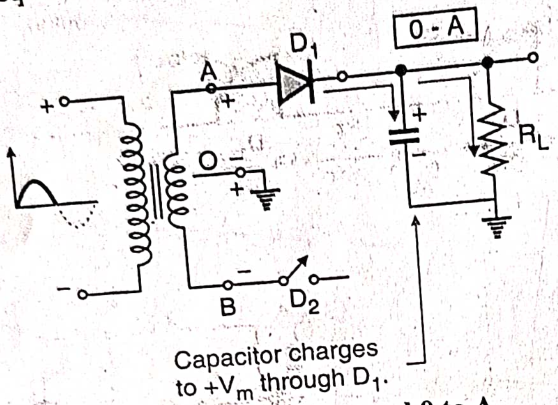
$\therefore$ **At "A", voltage on C i.e. $V_C = V_m$**

- After point "A" the instantaneous secondary voltage starts reducing as shown by the dotted waveform of rectifier output in Fig. 11.8.2. This will reverse bias the diode D_1, hence at "A", the diode D_1 is turned off. The equivalent circuit for this interval is shown in Fig. 11.8.3(a).

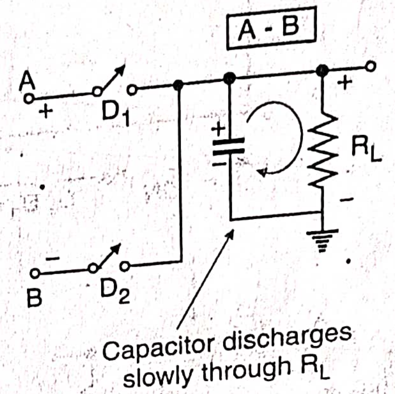
Operation in the interval A to B :

- During this interval, voltage on the capacitor is higher than rectifier output (shown by dotted lines). Hence D_1 and D_2 both remain off. The capacitor discharges exponentially through the load resistance R_L.

- As the value of R_L is much higher than R_F, the capacitor discharges slowly. Discharging time constant is "$R_L C$". Value of C is very large in order to make the discharging time constant as large as possible. This will reduce the ripple content in the output voltage.
- The equivalent circuit for this interval is shown in Fig. 11.8.3(b).



(a) Equivalent circuit for the interval 0 to A



(b) Equivalent circuit for interval A to B

Fig. 11.8.3

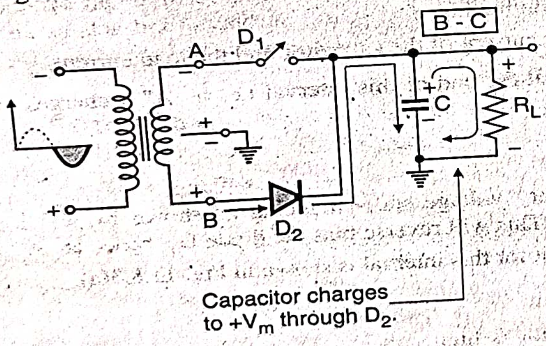
Operation in the interval B to C :

- At "B" the instantaneous rectified voltage is equal to the voltage on capacitor and after "B" it is greater than V_C.
- Therefore diode D_2 starts conducting at instant B. The capacitor charges through D_2 and at the end of this interval i.e. at point "C", the voltage on capacitor is again equal to $+V_m$.
- Due to this D_2 is reverse biased and stops conducting at point "C" as shown in Fig. 11.8.2. The equivalent circuit for this interval is shown in Fig. 11.8.4(a).

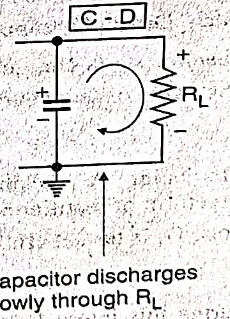
Operation in the interval C to D :

The operation in this interval is identical to that in the interval A to B.

The load voltage waveform of Fig. 11.8.2 with filter capacitor is very close to the pure dc voltage waveform.



(a) Equivalent circuit for the interval B to C



(b) Equivalent circuit for the interval C to D

Fig. 11.8.4

11.8.2 Ripple Factor with the Shunt Capacitor Filter :

[Asked In Exam : May 07 !!!]

- The expressions for the ripple factor of HWR and FWR with center tap or bridge rectifier are as follows :

(i) Ripple factor for C filter with FWR or bridge rectifier, $r = \frac{1}{4\sqrt{3}\, f\, CR_L}$ ...(11.8.1)

(ii) Ripple factor for C filter with HWR is $r = \frac{1}{2\sqrt{3}\, f\, CR_L}$ ...(11.8.2)

where, f = Supply frequency in Hz.

C = Value of filter capacitor in farad.

R_L = Load resistance.

- As the load voltage waveform with capacitor filter is very close to the ideal dc voltage waveform, the ripple factor is lower than the ripple factor of a rectifier.
- The value of ripple factor should be as low as possible.
- **How to reduce the ripple factor ?**
  The expressions for ripple factor stated in Equations (11.8.1) and (11.8.2) show that the value of ripple factor can be reduced by,
  - Increasing the value of filter capacitor C or
  - Increasing the load resistance R_L.

11.8.3 Dependence of Ripple Factor on the Value of Load :

- The ripple factor is low (good) for large values of R_L but the ripple factor increases (becomes poor) with decrease in the value of R_L.
- Thus capacitor filter performs well for lighter loads (i.e. larger R_L).

11.8.4 D.C. Output Voltage of Capacitor Filter :

- The D.C. load voltage at the output of capacitor input filter along with a full wave or bridge rectifier is given by :

$$V_{L\,dc} = V_m - \frac{I_{L\,dc}}{4\,fC} \quad ...(11.8.3(a))$$

- The dc output voltage of a shunt capacitor filter with a half wave rectifier is given by,

$$V_{L\,dc} = V_m - \frac{I_{L\,dc}}{2\,fC} \quad ...(11.8.3(b))$$

where V_m = Peak output voltage of the rectifier

f = Supply frequency = 50 Hz

C = Value of the filter capacitor

$I_{L\,dc}$ = Average load current

- Equations 11.8.3 (a) and (b) show that for the same values of V_m, $I_{L\,dc}$, f and C, the average output voltage of a full wave rectifier with shunt capacitor filter is always higher than that for a HWR with shunt capacitor filter.

The conclusions from Equation 11.8.3 (a) :

1. The D.C. load voltage at zero load current i.e. at no load is equal to the peak secondary voltage.

$$\therefore \quad V_{L\,dc\,(N.L.)} = V_m \qquad ...(11.8.4)$$

2. If C is constant then $V_{L\ dc}$ decreases with increase in load current. The second term in Equation (11.8.3 (a)) represents drop in voltage. The variation in $V_{L\ dc}$ with change in load current is as shown in Fig. 11.8.5.
3. The load regulation can be calculated from the characteristics of Fig. 11.8.5. The regulation will be better with increase in the value of "C" or with reduction in the value of full load current.

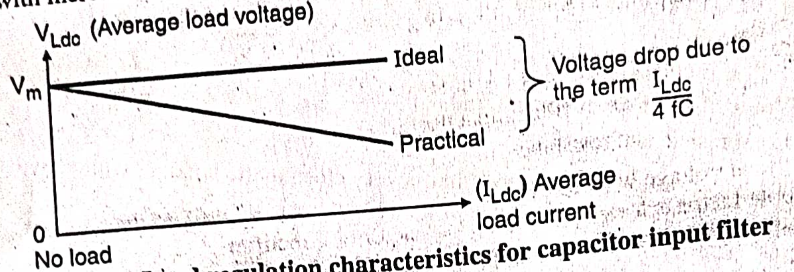


Fig. 11.8.5 : Load regulation characteristics for capacitor input filter

11.8.5 Surge Currents in Capacitor Input Filter :

- When the value of load resistance R_L is very large, the filter capacitor takes a longer time to discharge as compared to the time it takes for charging.

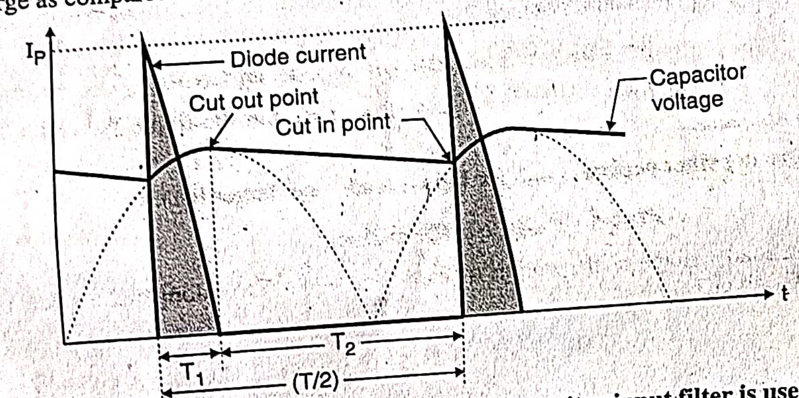


Fig. 11.8.6 : Surge current in diodes when capacitor input filter is used

- Thus the diodes will conduct for a very short time T_1 and discharge for a long time T_2 as shown in Fig. 11.8.6.
- Therefore the diode current flows in the form of pulses of very short duration and large peak values as shown in Fig. 11.8.6.
- The surge current can be limited by connecting a resistor R_S in series with the filter capacitor as shown in Fig. 11.8.7. R_S is a small resistor.

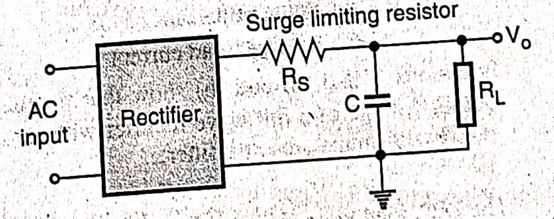


Fig. 11.8.7 : Surge current limiting by including resistor R_S

11.8.6 Advantages of Capacitor Input Filter :

The advantages of a capacitor input filter are as follows :

1. Easy to design
2. Reduction in the ripple content of the output voltage waveform
3. Increase in the average load voltage.
4. Small size and low cost

11.8.7 Disadvantages (Limitations) :

The disadvantages of a capacitor input filter are :

1. Ripple factor is dependent on the load. (See Equation (11.8.1)).
2. Regulation is relatively poor.
3. Diodes have to handle large peak currents.

Ex. 11.8.1 : Draw the circuit diagram of FWCT rectifier with capacitor shunt filter. If input of the rectifier is sine wave, draw the nature of the output waveforms for the following :

(i) Filter capacitance only without load resistance.
(ii) Capacitor filter with load resistance.
(iii) Rectifier without filter.

Soln. :

FWCT means full wave rectifier with center tapped transformer. For the circuit diagram of FWCT rectifier with capacitor shunt filter, refer to Fig. 11.8.1. The waveforms are as shown in Fig. P. 11.8.1.

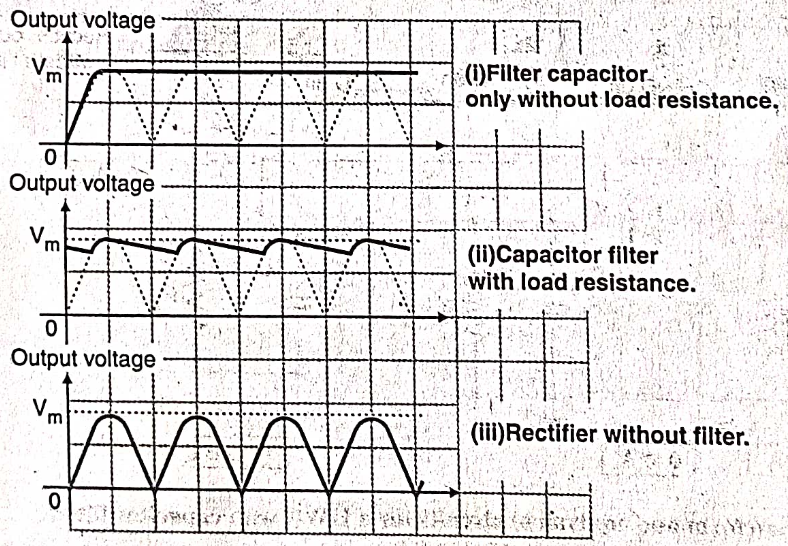


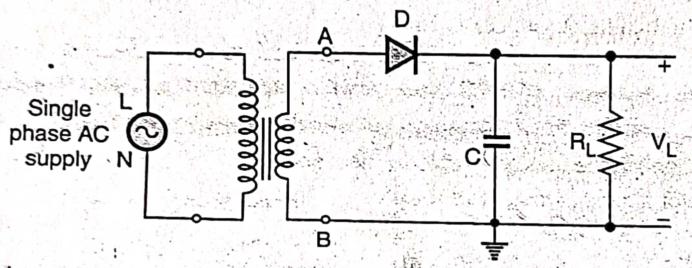
Fig. P. 11.8.1

11.8.8 HWR with Shunt Capacitor Filter :

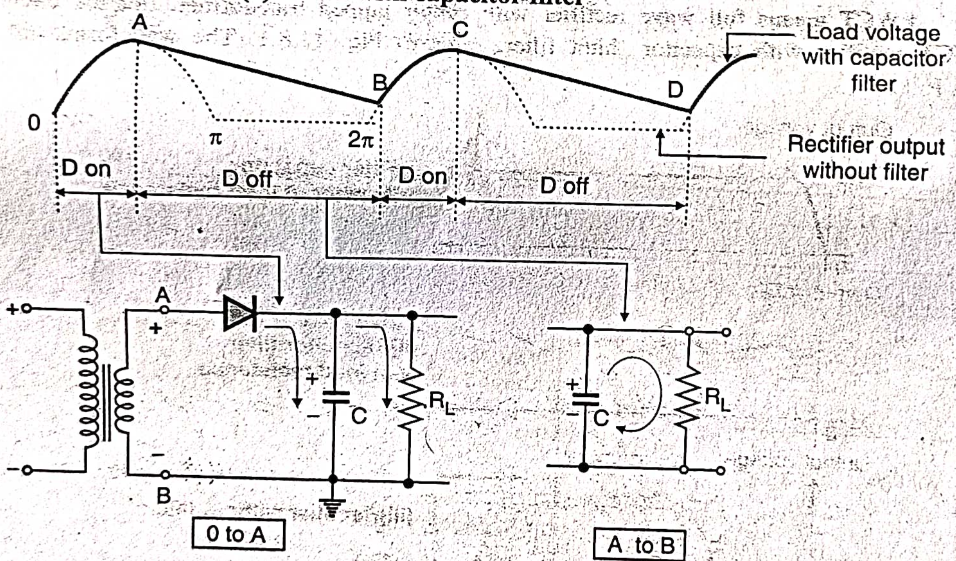
The circuit diagram of a HWR with capacitor filter is as shown in Fig. 11.8.8(a) and the load voltage waveform alongwith the equivalent circuits is shown in Fig. 11.8.8(b).

Operation and waveforms :

- For the intervals 0 to A, B to C the diode is forward biased and the capacitor charges through the diode almost instantly.
- For the intervals A to B, C to D etc. the capacitor voltage is higher than the instantaneous secondary voltage. Hence the diode is off and the capacitor discharges through R_L slowly.
- Note that the discharging time with HWR is longer than that with the FWR. Hence the capacitor discharges to a lower voltage [point B or D in Fig. 11.8.8(b)]. Hence the ripple increases. So the ripple factor of this circuit is higher than that of the capacitor filter with FWR.



(a) HWR with capacitor filter

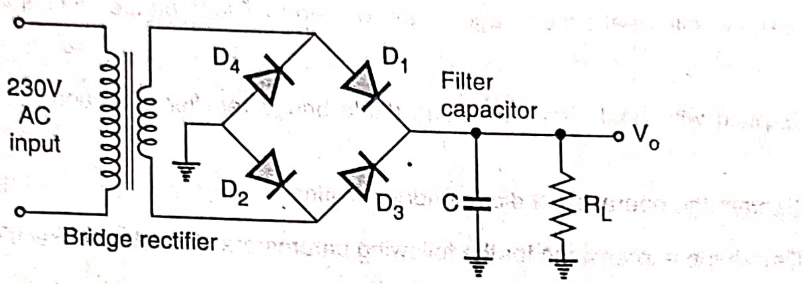


(b) Waveform and equivalent circuits for a HWR with capacitor filter

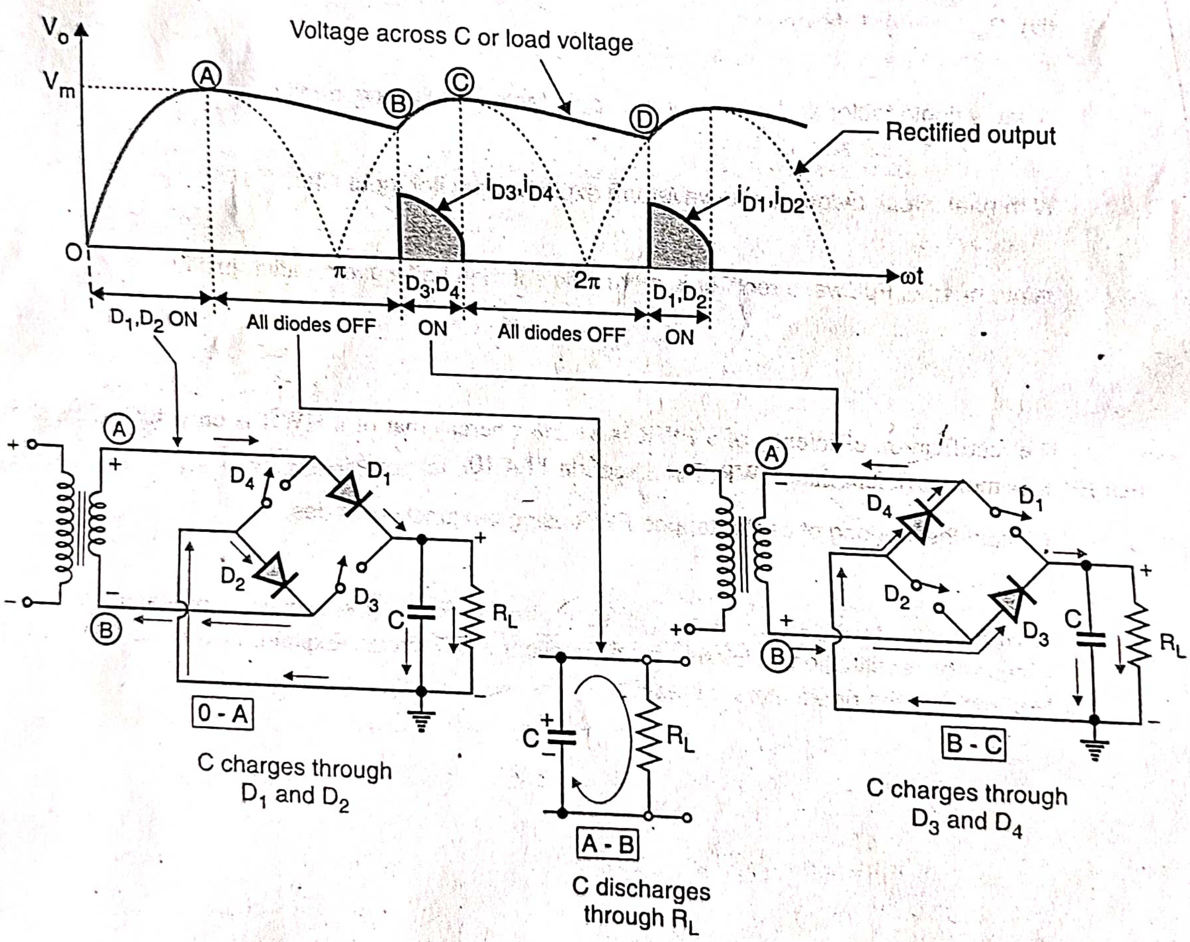
Fig. 11.8.8

11.8.9 Bridge Rectifier with Shunt Capacitor Filter :

- The bridge rectifier with capacitor filter is shown in Fig. 11.8.9(a) and the load voltage wavef alongwith the equivalent circuits is shown in Fig. 11.8.9(b).



(a) Bridge rectifier with capacitor filter



(b) Waveform and equivalent circuits

Fig. 11.8.9

- Note that the load voltage waveform is exactly same as that for a FWR with capacitor filter. The only change is that here two diodes conduct simultaneously instead of one in FWR.