MODULE 1
Semiconductor Diodes and Applications

Semiconductor Diodes and Applications (Text-1)**:** p-n junction diode, Characteristics and Parameters, Diode approximations, DC load line analysis, Half-wave rectifier, Two-diode Full-wave rectifier, Bridge rectifier, Capacitor filter circuit (only qualitative approach), Zener diode voltage regulators: Regulator circuit with no load, Loaded Regulator. Numerical examples as applicable. 06 Hours

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Introduction

Semiconductor diode is a p-n junction device. It has two terminals namely Anode and Cathode. The diode can be manufactured by using semiconductor materials like either doped silicon or doped germanium. It is a unidirectional device (one way direction) .it has very low resistance during the forward biased i.e. current flows from p to n material and it behaves like **closed switch**. And it has infinite resistance during reverse biased condition and it behaves like **open switch**.

P-N junction diode

The p-n junction diode is formed by combining a p-type material and an n-type material. On either side metal contacts along with copper connecting leads are provided for external connections, as shown below fig 1. These contacts are called **Ohmic contact**. At these contacts there is potential due to the flow of current. **This potential is independent of direction of current**.

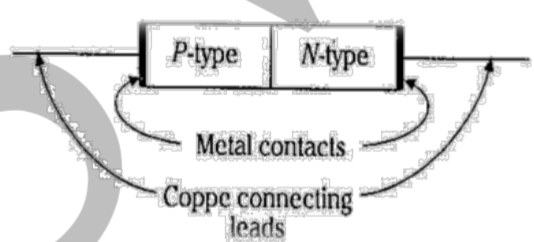


Fig1. P-N junction diode

A p-n junction provided with copper wire connecting leads becomes an electronic device known as diode**.** The symbol for the p n junction is shown fig 2. The arrow head in the diode symbol indicates conventional current flow. P type material is known as 'anode', N type material is known as 'cathode'. The Michael faraday was the first to use the terms anode and cathode. They came from the greek, "ana" – means up, "kata"- means down and "hodes"- means route, sometimes anode is abbreviated to A and the cathode to K.

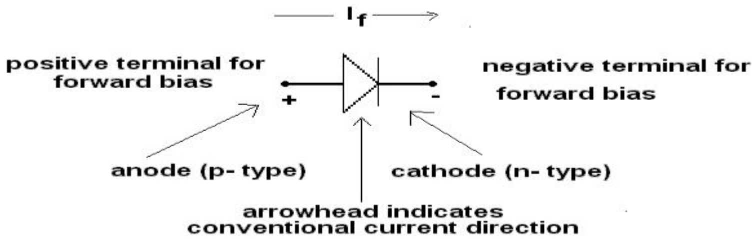


Fig 2: P-N semiconductor diode symbol.

P-type: The p-type semiconductor is formed by doping the intrinsic semiconductor with acceptor impurity atoms. The acceptor impurity atom is trivalent, has three valence electrons. Therefore, among the four covalent bonds formed by the impurity atom, one of the covalent bond will incomplete. The incomplete covalent bond is a deficiency of electron. This is seen as a hole. The result thus is every impurity atom added results in creation of positive ion, which increases the conductivity of the semiconductor.

So for p-type semiconductor positive charges (also called **holes)** are large in number and are called **majority charge carriers**. Negatively charged **electrons** which are less in number are called **minority charge carriers.**

N-type: The n-type semi conductor is formed by doping the intrinsic semiconductor with donor impurity atoms. The donor impurity atom is pentavalent, has five valence electrons. Each impurity atom creates four covalent bonds with the adjacent semiconductor atoms. The fifth valence electron is left as an excess electron, and is available for conduction. Thus every impurity atom added results in creation of negative ion, which increases the conductivity of the semiconductor. For a n-type semiconductor negative charges (**electrons**) are large in number and are called **majority charge carriers** positively charged **holes** which are less in number are called **minority charge carriers.**

The PN Junction: Junction of P type and N type

When P type semiconductor- having uniformly distributed holes and n type semiconductor- having uniformly distributed electrons brought together, diffusion takes place.

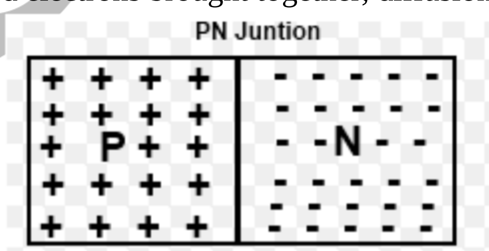


Fig 3: PN junction

Diffusion: fig 3 shows the p-n junction. Diffusion is the movement of charge carriers from high concentration to low concentration, due to the force of attraction among free electrons and holes adjacent to junction. This is shown in fig 4. In a p-n junction diode, free electrons (majority charge carriers) on the n-side will move to p-side and free holes (majority charge carriers) on p-side will cross the junction to the n-side.

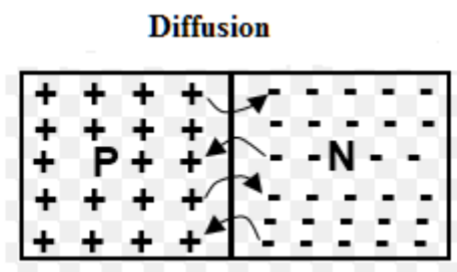


Fig 4: diffusion process

Recombination: Due to diffusion the charge carriers crossing the junction will meet opposite charge carrier and gets neutralized. (The free electron which is majority charge on n side is an excess electron and the hole on the p-side is deficiency of electron. Thus when an excess electron meets a hole, the electron will fill shortage of electron hence both the free electron and the hole are lost).When a electron combines with a hole free carriers recombine to form ions(these are charged particles but are not free carriers) This process is called '**Recombination'.**

Depletion region: Owing to recombination, many charges on either side of the junction will get neutralized resulting in a space which doesn't contain any charges. This region around the junction which doesn't have any charges is called **'depletion region'** is shown in fig 5. The region that is depleted of free charge carriers is called as depletion region

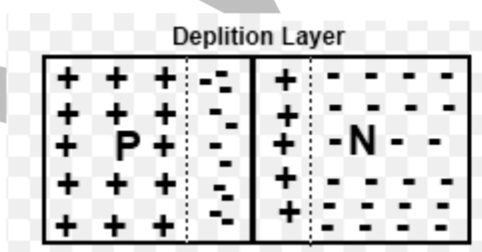


Fig 5: depletion region

Potential barrier: The presence of neutralized ions (depletion region) will oppose further diffusion process. The ions results in an electric field being created around the junction. To move the majority charge carrier against the electric field of the ions (depletion region) an external voltage is required. **The minimum voltage required for moving majority charge carrier across the junction is called 'potential barrier'.**

Diode Parameters

The diode has the following properties:

- It is unidirectional device.
- Conducts in forward biased condition and offers very low resistance, ideally this resistance is zero. But a practical device will have a very low resistance.
- Under reverse biased condition the diode doesn't conduct. That is it offers a very large resistance for the flow of current. Ideally the reverse resistance is infinite.

Types of Diodes

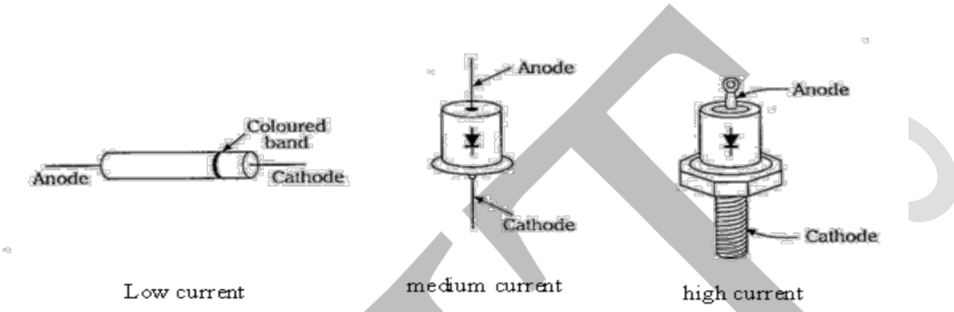


Fig 6: Various types of diodes

One of the classifications of the diode is based on the forward current carrying capacity and reverse voltage withstanding capacity. There are broadly three types of diodes, as explained below and shown in fig 6.

SL No.	Diode	forward current carrying capacity	Reverse voltage withstanding capacity
1	Low current	up to 100mA	up to 75v
2	medium current	up to 400mA	up to 200v
3	large current	few amperes	several 100 volts

- **Low current diodes*:*** These diodes are capable of carrying current magnitude of the order of few hundreds of mili -amperes (about 100mA). The breakdown voltage is about few tens of volts (typically about 100V).
- **Medium current diodes:** These diodes can carry a current little higher than that of low current diodes. These diodes have higher cross section of the junction to be able to dissipate the heat generated due the increased current. The breakdown voltage is about few hundreds of volts (typically 400V).
- **High current diodes**: These are also called power diodes. These diodes are meant for application where the current and hence the power dissipation is very high. For these diodes suitable **heat sinks** made up of metals like copper or aluminum are provided to dissipate the heat effectively. The heat sink increases the surface area so that the heat is radiated to the surrounding. The current rating of the power diodes is of the order of few amperes. The reverse breakdown voltage is also very high.

The size and appearance of a diode depends upon the level of forward current that the device is required.

Biasing of a Diode

Forward Bias:

Device formed by the formation of the PN junction is called Diode. Diodes are single junction and two terminal electronic components. The forward bias PN junction is shown in figure 7(a).

The two terminal of the diode are Anode and Cathode. When external bias is applied to the PN junction such that the anode is made positive with respect of cathode the diode is said to be 'forward biased'.

Under forward biased condition of the diode the majority charge carriers from either side of the junction are pushed towards the junction and hence the width of the depletion layer decreases. Due to the external bias connected, the charge carriers gain sufficient potential energy to overcome the barrier potential. The current conduction does not occur until the supply potential rises beyond barrier potential (or cut-in voltage). The current flows through the diode when the supply voltage increased beyond barrier potential, and diode said to be conducting. Forward and Reverse characterstics curve for Ge diode is shown in figure 1a.

Reverse Bias:

When the anode terminal is made negative with respect to cathode the diode is said to be reverse biased. The reverse bias PN junction is shown in figure 7(b). When an external bias voltage is applied to a PN junction, i.e., positive terminal to n side and negative terminal to P side, the electrons from N side are attracted to positive terminal and holes from p side are attracted to negative terminal. So the majority charge carriers on either side of the junction are pulled away from the junction. Due to movement of majority charges away from the junction, the width of the depletion layer increases. With the increase in the width of the depletion layer, the ions also increase.

Hence the electrical field also increases. Since the majority charge carriers are not crossing the junction, there is no current through the junction due to majority charge carriers.

Diode Characteristics

Forward Characteristics

When external bias is applied to the junction such that the anode is made positive with respect of cathode the diode is said to be **'forward biased'.**

Fig 7(a). Forward biasing of a diode Fig 7(b). Reverse Biasing of a diode

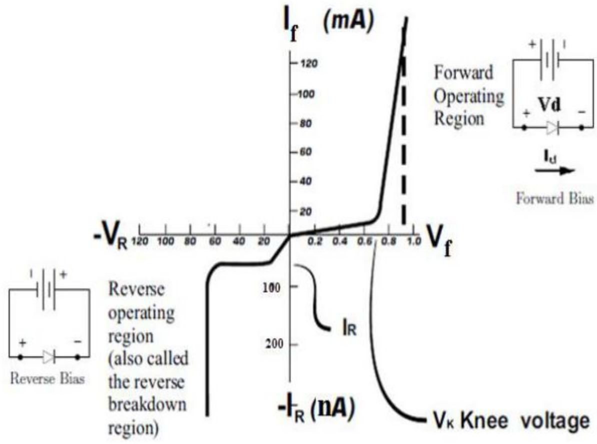


Fig 8(a) Forward and Reverse V-I characterstics curve for Si diode

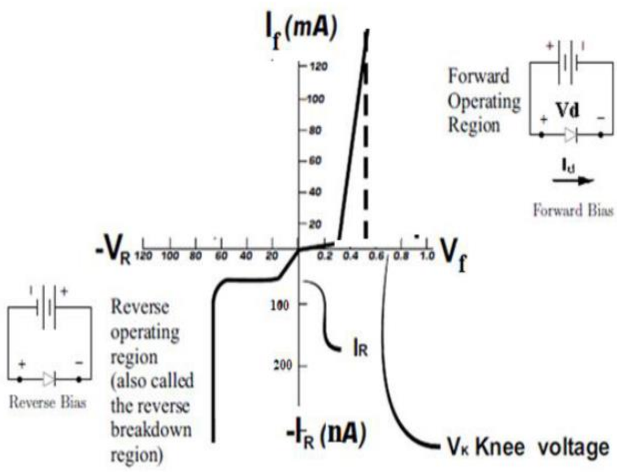


Fig 8(b) Forward and Reverse characterstics curve for Ge diode.

1. Forward V-I characteristics of a diode.

When a positive terminal of the external dc voltage is connected to the p-region and negative terminal of the external dc voltage is connected n-region of the diode then the diode is said to forward biased. In forward biasing V_f is the voltage across the p-n junction and I_f is the forward current hence the graph of I_f against V_f is called forward characteristics.

The forward current is the conventional current, hence it is treated as positive and Voltage also positive hence the graph is plotted in the first quadrant.

2. Reverse V-I characteristics:

The reverse voltage across the diode is Vr and reverse current through the diode is Ir. hence the graph of Ir against Vr is called reverse V-I characteristics of P-n junction. The Vr and Ir are treated as negative hence the graph is plotted in the third quadrant. The V-I characterstics curve for Si and Ge diodes are shown in fig 7 and 8 respectively.

Diode Current Equations:

The movement of charge carriers results in flow of current. The current increases exponentially with voltage across the diode after cut-in voltage. The current through the diode can be expressed by the equation

- 1]………………………………….(1)

Where: I is the current through the diode.

I_0 is the reverse saturation current.

V is the voltage across the diode.

η is a constant 1 for germanium, Si and 2 for silicon for lower range of current

V_T is the voltage equivalent of temperature.

, t is the temperature in ^{0}C.

(OR)

Where K (Boltzmann Constant) =1.38x J/K and T (Temperature in degree Kelvin) =273+ t ^{0}C and q (Charge in Columbs) =1.6x

Diode Parameters

The various parameters that indicate the performance of the diode are listed as follows. These parameters are to be considered before selecting the diode for a particular application.

1). Forward Resistance

When the diode is forward biased the resistance offered to the flow of current is called forward resistance. There are two types of forward resistances:

- Static resistance or dc resistance.
- Dynamic resistance or ac resistance.

a). Static Resistance or Dc Resistance:

At any point, called operating point, the ratio of voltage at that point to the current through the diode is called the forward resistance of the diode

This resistance will be useful for analysis when the diode is connected to the dc source. The static resistance is shown in fig 9.

$$\text{i.e. } R_f = \frac{V_f}{I_f}$$

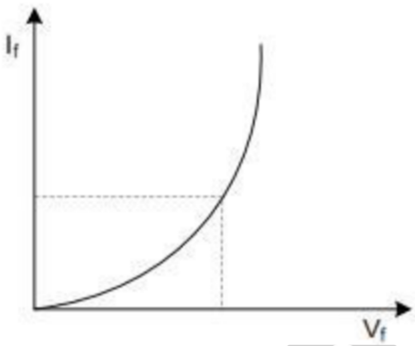


Fig 9. Static resistance

b). Dynamic Resistance or Ac Resistance:

Dynamic Resistance

The dynamic resistance of the diode can be defined as the forward resistance of the diode when alternating voltage applied to the diode. Consider the V-I characteristics of a diode under forward biased condition as shown in fig 10. At point Q draw a tangent to the characteristics curve.

The dynamic resistance can be given as the reciprocal of the slope of the tangent at the Q point or Operating point or quiescent point.

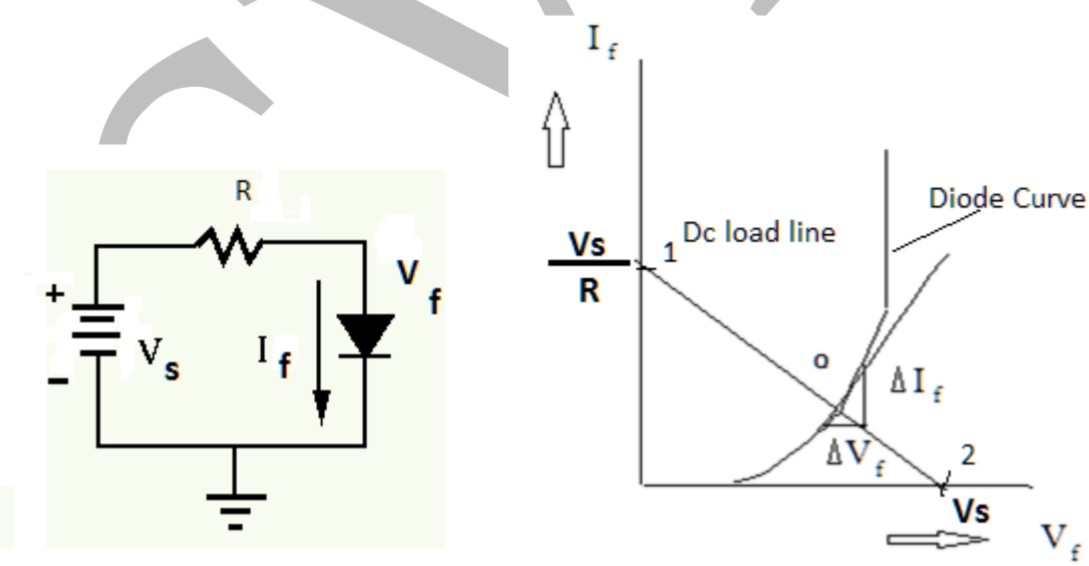


Fig 10. The forward characteristics of Diode and slope of the tangent

To find the expression for the dynamic resistance

<u>Apply KVL to the diode circuit shown above in figure 1b.</u>

Then,

R)

Substitute V_f =0, then =

Point 1 = (0, =),

Substitute I_f=0, then

Point 2 = (Vs, 0)

At point Q draw a tangent to the curve. The . The dynamic resistance is the reciprocal of the slope.

By definition, Dynamic resistance ………………………………… (1)

- 1]

In the above expression the value is very large in comparison with '1'. Therefore equation (1) reduces as shown below

]…………………………………(2)

Differentiating Equation (1.2) with respect to V

For η=1 and temperature t=27°C

r_d =

2). Static Forward Voltage (V_f)

This is the voltage across the diode when the diode is forward biased and conducting. This is due to the voltage drop across the internal resistance of the diode. This value of voltage depends on the forward resistance R_f of the diode and the forward current I_f.

3). Reverse Breakdown Voltage (V_{BR}):

At increased reverse voltage, the p-n junction breaks down due Zener and avalanche mechanism. Under this condition the current suddenly increases to a very large value limited only by external circuit. This is an irreversible mechanism leading to permanent damage of the junction. The reverse voltage at which the junction breaks down is called Reverse Breakdown Voltage. Therefore, the reverse applied voltage must be always less than the breakdown voltage for safe operation.

4). Reverse Saturation Current (I_o):

The minority charges present on either side of the junction can cross the junction due to applied potential. This results in flow of current in the reverse direction. This is called **reverse saturation current.** Since minority charge carriers are less in number the corresponding current is very low in magnitude. The reverse current remains almost constant with respect to the applied voltage. This is so because the number of minority charges is a constant. But the reverse current increases slightly due to increased velocity of the minority charge carriers.

5). Maximum Forward Current ($I_{F(max)}$):

Due to the flow of current when the diode is forward biased, the power is dissipated in the internal resistance of the diode. This leads to heating of the diode and hence the damage to the junction. To prevent such damage, the maximum current must be limited to a safe value specified by data sheet.

The maximum forward current is defines as the current that can flow through the diode continuously without causing damage

6). Knee voltage: Knee Voltage is defined as the minimum voltage under the forward biased condition, at which diode start conducting. Connecting positive terminal of the supply to the anode and negative terminal of the supply to the Cathode is called as forward biasing of a diode.

When we start apply the voltage at one voltage value the diode current increase exponentially. This voltage is called as the knee voltage.

It is also called as cut-in voltage or barrier potential. The knee voltage value for Si diode is 0.7 V and Germanium diode is 0.3V. The Knee voltage and Peak inverse voltage is shown in figure 11.

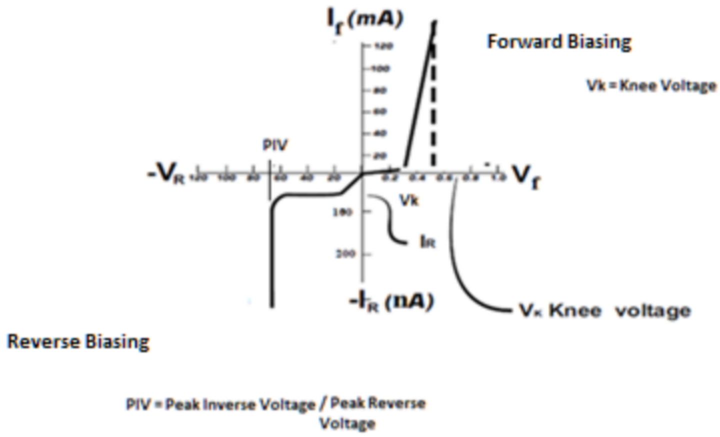


Fig 11. V-I Characteristics of diode showing Knee voltage and PIV (Peak Inverse Voltage)

7). Reverse breakdown load

The load resistance is connected across the diode during the reverse biasing of the diode is called as the reverse breakdown load.

8). Maximum power rating:

The Maximum power rating is defined as the maximum power that a p-n junction or diode can dissipate without damaging the device itself. The power dissipated at the junction is equal to the product of junction current the voltage across the junction.

$$P=V*I$$

9). PIV:

PIV refers to peak inverse voltage. It occurs when diode is connected in reverse biasing method. Applying negative voltage to the Anode terminal and positive voltage to cathode terminal is called as reverse biasing of a diode.

Peak Inverse Voltage is defined as the reverse (or inverse) voltage at which the PN junction breaks down and the diode starts conducting heavily. Once PN junction breaks down the device gets damaged. Therefore, the breakdown is said to be irreversible.

The Peak Inverse Voltage rating of the diode is the maximum voltage that a diode can withstand in the reverse direction without breaking down or avalanching.

If this voltage is exceeded the diode may be destroyed or damaged. The Peak Inverse Voltage is shown in VI characteristics curve of a diode as in fig 9.

Diode Approximations

Diode approximation is useful in analyzing the circuits containing diode. This provides suitable mathematical method for understanding the circuits. There are three levels of approximations depending on the required degree of accuracy.

i) Ideal Diode characteristics:

The following are the features assumed for an ideal diode: the following fig

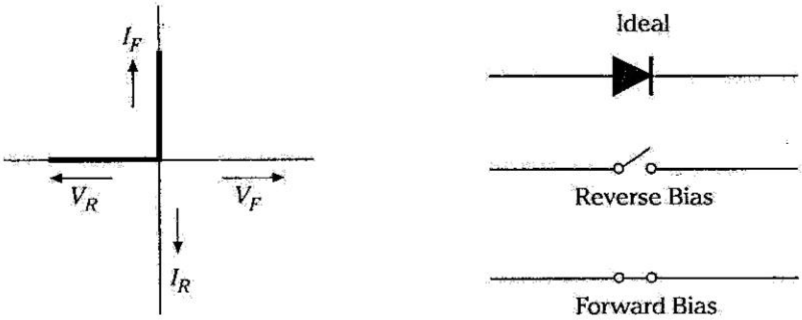


Fig 12. Ideal diode approximations

The reverse resistance is infinite

This assumption results in reverse current are zero. Therefore, the reverse characteristics coincide with X-axis.

The forward resistance of the diode is zero

r_d = ————————————————————

Zero forward resistance indicates that the slope is infinite, or the characteristics are a vertical line.

The cut-in voltage is zero.

The barrier potential is neglected. Therefore, the diode conducts readily from zero voltage.

ii) Ideal diode with cut-in voltage considered or Second approximation This is the second approximation

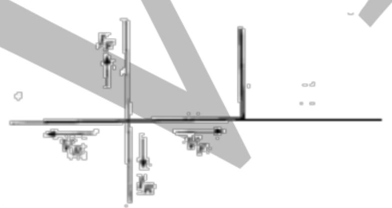


Fig 13: showing the second approximations The reverse resistance is infinite

This assumption results in reverse current are zero. Therefore, the reverse characteristics coincide with X-axis.

The forward resistance of the diode is zero

r_d = ————————————————————

Zero forward resistance indicates that the slope is infinite, or the characteristic is a vertical line.

The cut-in voltage is finite.

The barrier potential due to the stored charges is considered, therefore, the diode conducts only when the forward voltage is greater than the cut-in voltage. The value of cut-in voltage is 0.7 for silicon and 0.3 for germanium diode. For any forward voltage less than the cut-in voltage, the characteristics lies on the X-axis

iii)The piecewise linear approximation:
This is the third approximation. Fig 14.

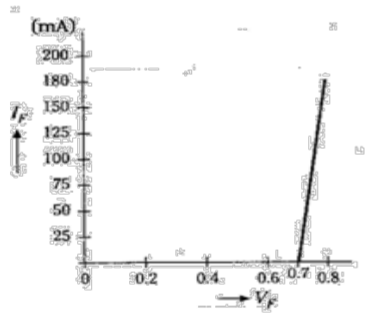


Fig 14. piecewise linear approximation

The reverse resistance is finite

These results non-zero reverse curre*nt*. The reverse current is due to the movement of minority charge carriers across the junction. The minority charge carriers are less in number and hence the current is very small. The number of minority charge carriers is constant; therefore the current is almost constant with respect to applied voltage.

The forward resistance of the diode is finite

r_d = ———————————————

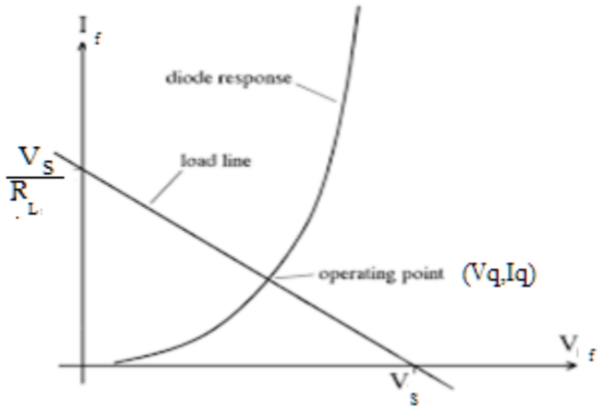
Finite forward resistance indicates that the slope is finite, or the characteristic is not a vertical line.

The cut-in voltage is finite.

The barrier potential due to the stored charges is considered, therefore, the diode conducts only when the forward voltage is greater than the cut-in voltage. The value of cut-in voltage is 0.7 for silicon and 0.3 for germanium diode. For any forward voltage less than the cut-in voltage, the characteristics lies on the X-axis

D.C Load line

The dc load line is straight line drawn on the V-I characteristics joining two points one on the X-axis and the other on the Y-axis and is shown in fig 15. The reciprocal of slope of the dc load line is equal to the resistance in series with the diode. The series resistance is also called load resistance; hence the line is called load resistance. Fig. shows the circuit diagram to analyze the DC load line.



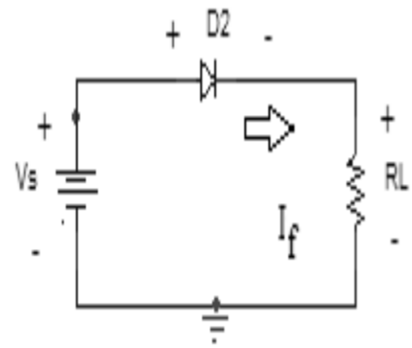


Fig 15: DC load line Analysis

In any diode circuit the current through the diode and the voltage across the diode is indicated by the Q point.

The Q point is a point at the intersection of dc load line and forward characteristics of a diode. The dc load line is a graphical method of locating the Q point of the diode. The Q point is also called operating point or quiescent point.

To draw the load line:

For the circuit shown fig , apply KVL

V_S- I_F - V_F= 0 ----- (1)

Where I_F is the current through the circuit and V_F is voltage across the diode.

To locate the point of the load line on X-axis, put I_F=0 in equation (1).

Then = V_F

The corresponding point is (V_F, 0) and it lies on the x-axis since Y-coordinate is zero. To locate the point of the load line on Y-axis, put V_F = 0 in equation (1)

Then —. The corresponding point of the load line is (0, —) and it lies on Y-axis since the X- coordinate is zero.

The dc load line and the corresponding Q point is as shown in the figure above fig.

Problem on DC load line:

For the circuit shown in fig 16. Draw the DC load line and locate the Q-point.

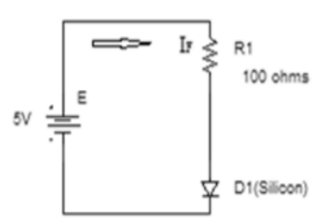


Fig 16.Diode circuit

Apply the KVL to the above circuit shown

--------------------------- (1)

—— —— , and

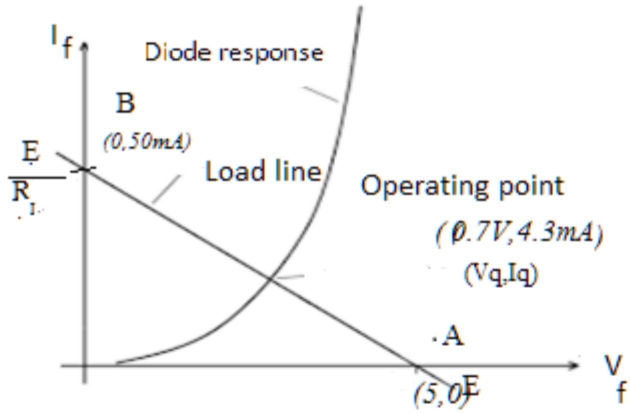


Fig 16a. DC load line with operating point or Q-point)

To draw the DC load line substitute =0, in equation (1), then

The Point A= (,) = (E,0) = (5,0) and

Substitute in equation (1), then

Point B= (,) = (0, E/R_1) = (0,50mA)

The DC load line with operating point is shown above in fig 16a.

Applications of Diode

Rectifier

The rectifier is a circuit that converts bi-directional ac voltage into unidirectional pulsating dc. Since the diode is a unilateral device, the diode can be used as rectifier.
The transformer is used to: 1.Alter the magnitude of voltage 2. Provide electrical isolation

There are two types of rectifiers.
1. Half wave rectifier.
2. Full wave rectifier.

1. Half wave rectifier

The Half wave rectifier circuit consists of transformer, resistive load, rectifying element i.e., p-n junction diode. and the source of ac voltage all are connected in series. To get the desired d.c. voltage across the load the a.c. voltage is applied to the rectifier circuit using suitable step-up or step-down transformer, mostly a step down one with necessary transformer turns ratio.

The input voltage is sinusoidal a.c. voltage having frequency 50Hz and 230 V.
Transformer decides the peak value of the secondary voltage. If N1 are the primary number of turns and N2 are the secondary number of turns and is the rms value of the secondary voltage and is the primary voltage then,

Note: the input can be a

Working: The circuit of half wave rectifier and waveform is shown in fig 17a. Half wave rectifier is a circuit which provides an output during positive half cycle of the input and zero output for the negative half cycle.

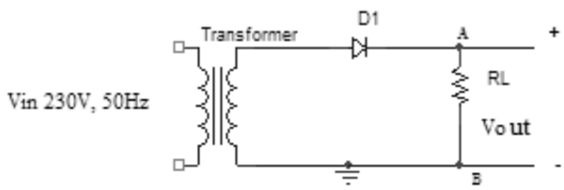


Fig 17a. Half wave rectifier circuit

- The transformer is used to either step down or step up the ac input voltage. A single diode D_1 is connected in series with the transformer and load. V_{in} is the secondary induced voltage which is also the source voltage for the rectifier circuit.
- During the positive half cycle of the input signal, the anode terminal becomes positive. Then, the diode is forward biased and hence conducts. Current flows through the load resistor and we get output voltage across the load resistance R_L. The current flows from the terminal A to terminal B. The polarity of the load voltage is as shown in the figure 17a.
- During the negative half cycle, the diode is reverse biased. The reverse biased diode behaves like open circuit, hence no current flows through the load resistor and load voltage is zero. Thus the current flows through the load only in one direction therefore, load current and hence output voltage is unidirectional. Therefore, the output is said to be rectified. The input and output waveform of half wave rectifier circuit is shown in figure 17b.

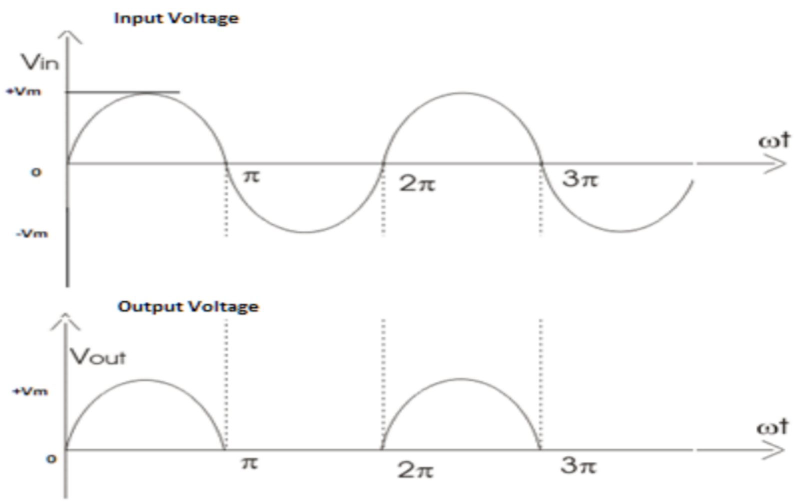


Fig 17b. Input and output waveforms of Half wave rectifier

The peak value of the load current is given by

where - secondary transformer resistance
- forward resistance of the diode
- load resistance of the diode.

Analysis parameters of Half Wave Rectifier

1). Average or d.c. value of the load current
2). Average or d.c. value of the load voltage
3) r.m.s value of the load current
4) r.m.s value of the load volatge
5) d.c. power output
6) a.c power input
7) Rectifier efficiency
8) ripple factor
9) Regulation
10) PIV-Peak Inverse Voltage

1). Average or d.c. value of the load current

Mathematically, current waveforms can be described as

$i_{L} = I_m$ * sin wt for $0 \leq wt \leq$ and $i_L = 0$ for $\leq wt \leq 2$*

is the Average value or the dc value.

2). Average or d.c. value of the load voltage

It is the product of the average d.c load current and the load resistance.

= — *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

3) r.m.s value of the load current

4) r.m.s value of the load volatge

It is the product of the average d.c load current and the load resistance.

= — *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

5) d.c. power output

6) a.c power input

+ but we know that

+

7) Rectifier efficiency

The rectifier efficiency is defined as the ration of output dc power to input ac power.

if are very small then, =0.406

% = 40.52%

Note: more the rectifier efficiency, les are the ripple content in the output.

8) ripple factor

The output of HWR circuit is not a complete dc bur it is a pulsating dc and it contains pulsating component called ripple. The measure of ripples present in the output is with the help of a factor called as ripple factor denoted as . It tells how smooth is the output.. smaller the ripple factor closer is the output to a pure dc.

Mathematically ripple factor is defined as the ratio of rms, value of the ac component in the output to the average or dc component present in the output.

ripple factor =

the output volatge composed of a.c component as well as dc component

Let -->is the rms value of the ac component in the output of rectifier

--> is the dc value of output of the rectifier

--> is the rms value of the combined waveform. (It includes both ac and dc value) ripple factor =

Substitute

and

9) Regulation

Where NL---No load and
FL Full load

R= =

% R= *100

10) PIV-Peak Inverse Voltage

Peak inverse voltage for half wave rectifier is

Problems on Rectifiers

1) The input to the Half wave rectifier is v(t) = 100 sin50t. If R_L is 1kΩ and forward resistance of diode is 50Ω, find

i) D.C current through the circuit
ii) The A.C (rms) value of current through the circuit
iii) The D.C output voltage
iv) The A.C power input
v) The D.C power output
vi) Rectifier efficiency. (06 Marks)

The equation v(t) = 100 sin50t is similar to equation V_o=V_m*sinwt hence V_m=100V

D.C current through the circuit, —=0.03033A

The A.C (rms) value of current through the circuit, —=0.04762A

The D.C output voltage, =0.03033*1000=30.33V

The A.C power input

The D.C power output

Rectifier efficiency — —

2). The input to a half wave rectifier is given through a transformer from supply given by 230 sin 314t V. If R_f=50Ω and R_L=500Ω. Determine DC load voltage, RMS load voltage, rectification efficiency, DC power delivered to the load.

The equation v(t) = 100 sin50t is similar to equation V_o=V_m*sinwt hence V_m=230V

D.C current through the circuit, —=0.133A

The A.C (rms) value of current through the circuit, —=0.2091A

The D.C output voltage, =0.133 *500=66.5V

The A.C power input

The D.C power output

Rectifier efficiency — ——

2. Full Wave Rectifier

Two diode Center-tapped full wave rectifier

Center-tapped full wave rectifier circuit and input output waveforms is in figure 18.

The rectifier is a circuit that converts bi-directional ac voltage into unidirectional pulsating dc voltage. Since the diode is a unilateral device, the diode can be used as rectifier.

Working:

The polarities of voltage at the terminal ‘A’ and ‘B’ always are opposite because these two terminals are the two ends of the transformer secondary.

During the positive half cycle of the input signal, let the terminal A becomes positive and the terminal ‘B’ becomes negative. For these polarities, the diodes D_1 is forward biased and the diode D2 is reverse biased. The current I_1 flows through the diode D1 from A to B through the load. The polarity of load voltage is shown in figure 18.

During the negative half cycle of the input signal, the terminal ‘A’ becomes negative and terminal B becomes positive the diode D_2 is forward biased and the diode D_1 reverse biased. The current I_2 flows through the diode D_2 from A to B through the load. The polarity of output voltage is as shown in figure 18.

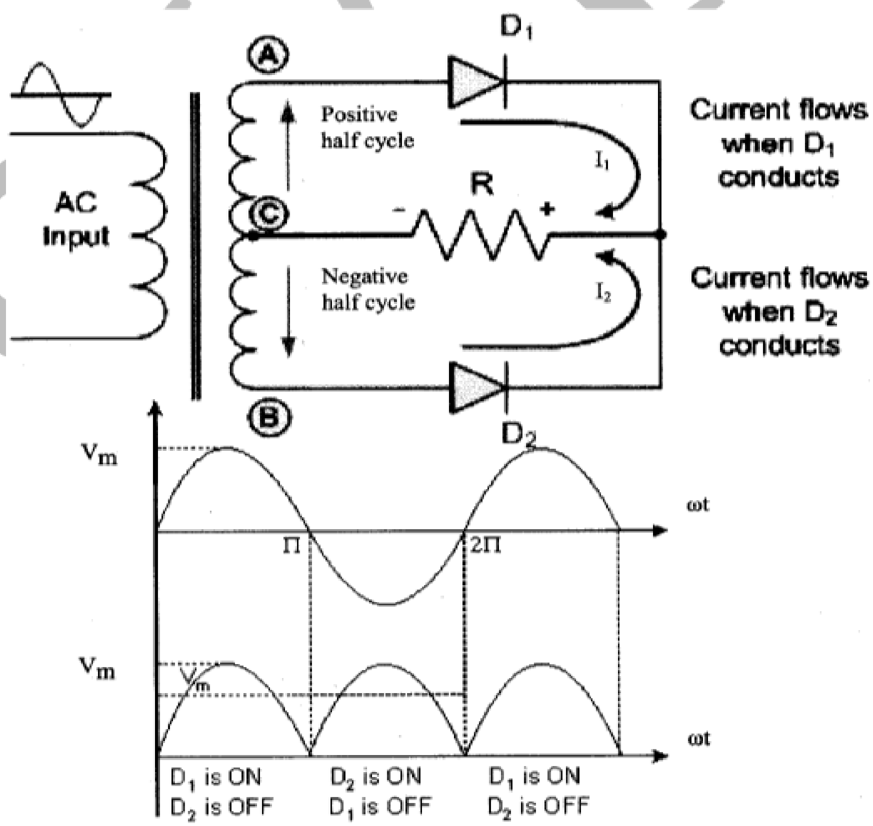


Fig. 18 Center-tapped full wave rectifier with input and output waveforms.

Thus during the both the half cycles the load current flows through the load in the same Direction and hence the output voltage is always positive.

Analysis parameters of Full wave Rectifier with centre tapped transformer

1). Average or d.c. value of the load current
2). Average or d.c. value of the load voltage
3) r.m.s value of the load current
4) r.m.s value of the load volatge
5) d.c. power output
6) a.c power input
7) Rectifier efficiency
8) ripple factor
9) Regulation
10) PIV-Peak Inverse Voltage

1). Average or d.c. value of the load current
Mathematically, current waveforms can be described
as $i_{L=}$ I_m * sin wt for 0 ≤ wt ≤

is the Average value or the dc value.

2). Average or d.c. value of the load voltage

It is the product of the average d.c load current and the load resistance.

= *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

3) r.m.s value of the load current

4) r.m.s value of the load volatge
It is the product of the average d.c load current and the load resistance.

= *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

5) d.c. power output

6) a.c power input

\+ but we know that

\+

7) Rectifier efficiency
The rectifier efficiency is defined as the ration of output dc power to input ac power.

if are very small then, =0.812

% = 81.2%

Note: more the rectifier efficiency, les are the ripple content in the output.

8) ripple factor

The output of HWR circuit is not a complete dc bur it is a pulsating dc and it contains pulsating component called ripple. The measure of ripples present in the output is with the help of a factor called as ripple factor denoted as . It tells how smooth is the output.. smaller the ripple factor closer is the output to a pure dc.

Mathematically ripple factor is defined as the ratio of rms, value of the ac component in the output to the average or dc component present in the output.

ripple factor =

the output volatge composed of a.c component as well as dc component

Let -->is the rms value of the ac component in the output of rectifier

--> is the dc value of output of the rectifier

--> is the rms value of the combined waveform. (It includes both ac and dc value)

ripple factor =

Substitute

and =

9) Regulation

Where NL---No load and
FL Full load

R= =

% R= *100

10) PIV-Peak Inverse Voltage

Peak inverse voltage for half wave rectifier is

1. A single phase full — wave rectifier supplies power to a 1 KΩ load. The AC voltage applied to the diode is 300-0-300 V. If diode resistance is 25Ω and that of the transformer secondary negligible. Determine average load current, average load voltage and rectification efficiency.

V_S=300V, Vm= * V_S= 424V

D.C current through the circuit, = 0.263A

The D.C output voltage, =0.263*1000=263V

The A.C (rms) value of current through the circuit, = 0.292A

The A.C power input

The D.C power output

Rectifier efficiency

2. In a full wave rectifier, the input is from 50-0-50V transformer. The load and diode forward resistances are 1000Ω and 20Ω respectively. Calculate the average voltage, dc output power, ac input power, rectification efficiency and percentage regulation.

V_m= * 50= 70.7V

D.C current through the circuit, = 44.12mA

The D.C output voltage, =44.12mA*1000=44.12V

Peak inverse voltage across the non conducting diodes = 2* V_m=2*70.7 = 141.4 Volts

3. In a full wave bridge rectifier, the transformer secondary voltage is 100 sin 50t. The forward Resistance of each diode is 50 Ω and the load resistance is 950Ω. Calculate

i) DC output voltage and Rms output voltage

ii) Ripple factor

iii) Efficiency of rectification

iv) DC output power and ac power

v) Peak inverse voltage of the diode

The equation v(t) = 100 sin50t is similar to equation V_o=V_m*sinwt hence V_m=100V

D.C current through the circuit, =0.0637A

The A.C (rms) value of current through the circuit, =0.0707A

The D.C output voltage, =0.0637*950=60.52V

The A.C power input

The D.C power output

Rectifier efficiency

Bridge Rectifier

The bridge rectifier is a circuit which provides output during both the half cycle of the input. The rectifier circuit is shown in figure 2a. The input and output waveform is shown in figure 2b.

The bridge rectifier using four diodes and a transformer is shown figure 19a. The transformer in the given circuit is used to either step up or step down the ac input voltage. the input and output waveform are shown in figure 19b.

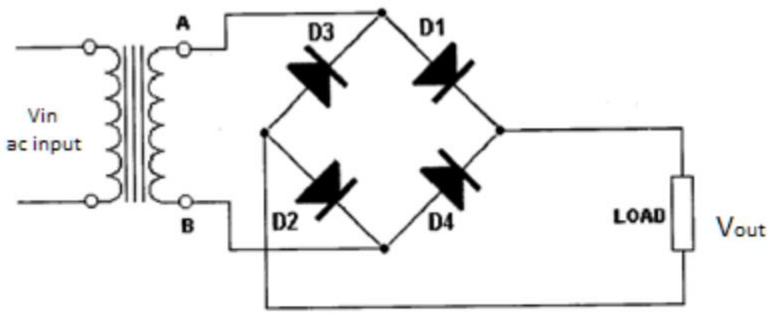


Fig.19a. Circuit diagram of bridge rectifier

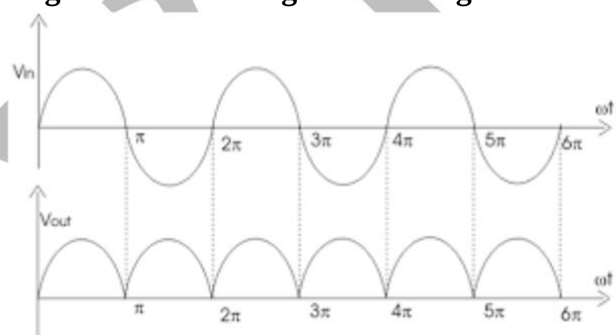


Fig.19b. Input and Output waveforms of bridge rectifier

Working:

During the positive half cycle of the input signal, the diodes D_1 and D_2 are forward biased and diodes $D_3$and $D_4$are reverse biased. The current flows through the diodes D_1 and D_2 from A to B through the load. The polarity of output voltage is the terminal A is positive with respect to terminal B as shown in figure 19c.

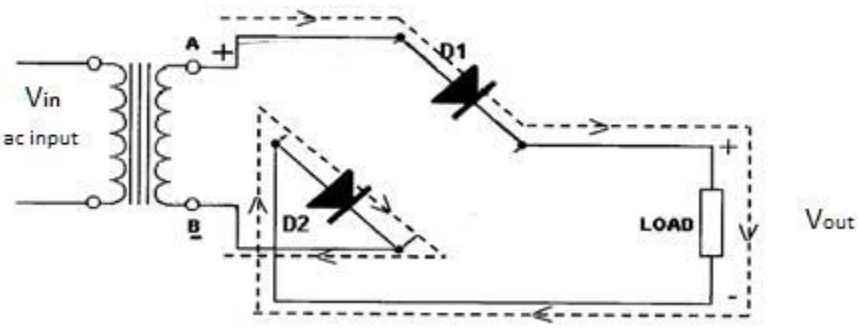


Fig. 19c bridge rectifier Circuit during positive half cycle

During the negative half cycle of the input signal, the diodes D_3 and D_4 are forward biased and D_1 and D_2 are reverse biased the current flows from A to B through the load.
Thus during the both the half cycles the load current flows through the load in the same direction and hence the output voltage is always positive. The polarity of the output voltage is shown in figure 19d..

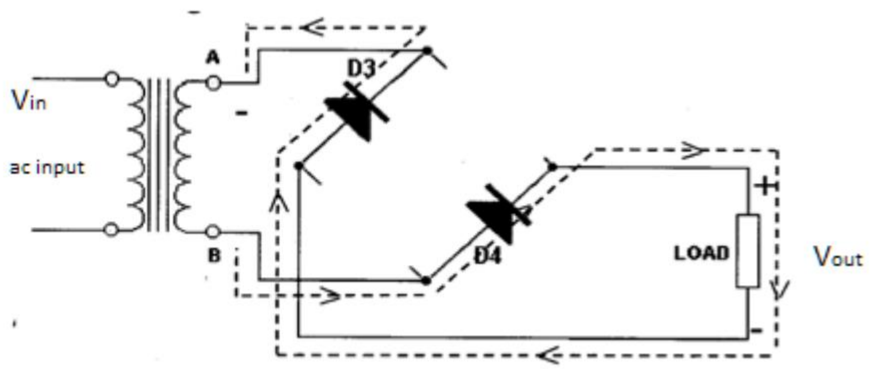


Fig. 19d. Bridge rectifier circuit during the negative half cycle

Thus the load voltage exits during positive and negative half cycles of input signal. The polarity of the output voltage remains same during both half cycle hence the circuit is called as full wave rectifier.

Analysis parameters of Bridge Rectifier.

1). Average or d.c. value of the load current
2). Average or d.c. value of the load voltage
3) r.m.s value of the load current
4) r.m.s value of the load volatge
5) d.c. power output
6) a.c power input
7) Rectifier efficiency
8) ripple factor

9) Regulation
10) PIV-Peak Inverse Voltage

1). Average or d.c. value of the load current
Mathematically, current waveforms can be described
as $i_{L=}$ I_m * sin wt for $0 \leq wt \leq$

is the Average value or the dc value.

2). Average or d.c. value of the load voltage

It is the product of the average d.c load current and the load resistance.

= *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

3) r.m.s value of the load current

4) r.m.s value of the load voltage

It is the product of the average d.c load current and the load resistance.

= *

we know that

then =

The secondary transformer resistance and forward resistance of the diode are practically very small hence neglecting them,

5) d.c. power output

6) a.c power input

\+ but we know that

\+

7) Rectifier efficiency

The rectifier efficiency is defined as the ration of output dc power to input ac power.

if are very small then, =0.812

% = 81.2%

Note: more the rectifier efficiency, les are the ripple content in the output.

8) ripple factor

The output of HWR circuit is not a complete dc bur it is a pulsating dc and it contains pulsating component called ripple. The measure of ripples present in the output is with the help of a factor called as ripple factor denoted as . It tells how smooth is the output.. smaller the ripple factor closer is the output to a pure dc.

Mathematically ripple factor is defined as the ratio of rms, value of the ac component in the output to the average or dc component present in the output.

ripple factor =

the output volatge composed of a.c component as well as dc component
Let -->is the rms value of the ac component in the output of rectifier
--> is the dc value of output of the rectifier
--> is the rms value of the combined waveform. (It includes both ac and dc value)

ripple factor =

Substitute

and =

9) Regulation

Where NL---No load and
FL Full load

R= =

% R= ——— *100

10) PIV-Peak Inverse Voltage

Peak inverse voltage for half wave rectifier is

1.9 Filter

The output of a rectifier circuit is a pulsating D.C. That is, the output of the rectifier circuit contains both D.C and A.C components. The ripple factor is a measure of A.C component in the output of the rectifier. To obtain a smooth D.C, filters circuits are used.

The filter circuits remove the A.C component so that the resulting output contains only D.C. thus, ***filter circuits are for converting pulsating D.C into smooth D.C***. one of simple form of filter is a parallel connected capacitor across the load.

Half-wave rectifier with a filter

Need for the capacitor filter:
Capacitor filters are used to remove the unwanted or undesired frequency component from the output of the half wave rectifier circuit. A capacitor is connected across the load resistance. Capacitors are used to smooth (filter) the pulsating DC.

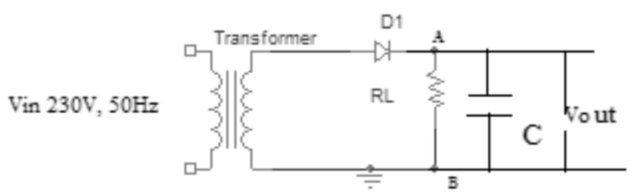


Fig. 20a. the half wave rectifier with Capacitor filter

The half wave rectifier with Capacitor filter is shown in figure 20a. The output of the rectifier is the input to the filter. The operation of filter circuit can be explained in two cases.

When V_i V_C i.e. input voltage is greater than the capacitor voltage.

The diode is in forward bias condition and conducts currents through the load resistor R_L, which has the same shape as the initial positive half cycle of the input voltage.
At the same time the capacitor is charged. At the end of quarter cycle, when the input voltage reaches the maximum value, the Capacitor will do charged to the maximum value of the input voltage.

When V_i V_c, i.e. when the input voltage is less than peak value.

The diode is reverse biased, anode voltage becomes less than the cathode voltage (capacitor voltage) therefore no current flows through the diode. The capacitor which has been already charged when diode was forward biased will discharge through the load resistor R_L. This process repeats for all the cycles of the input. The input and output waveform is shown in figure 20b.

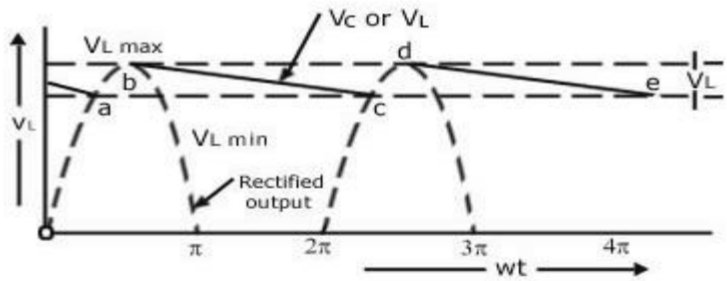


Fig. 20b Rectified and filtered output waveforms.

Full-wave rectifier with a filter:

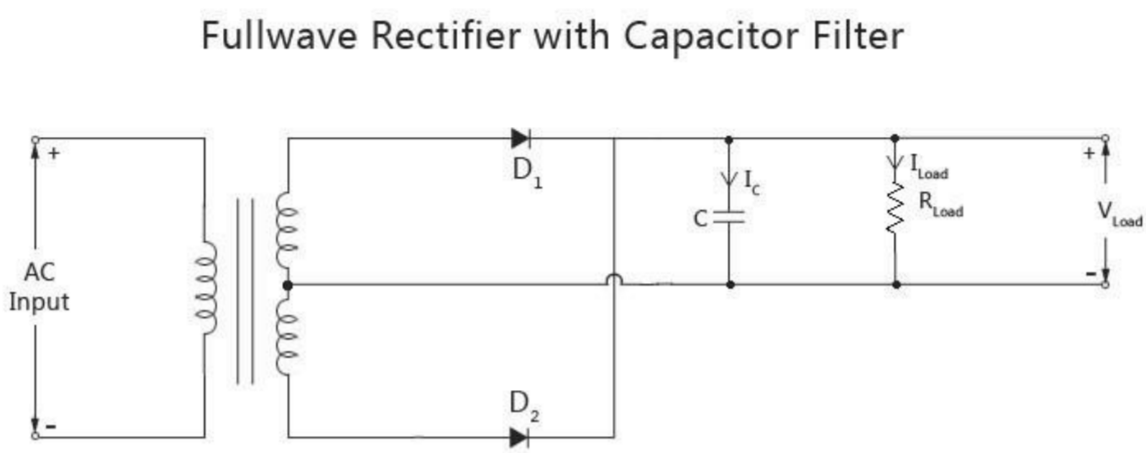


Fig. 21a. Full wave rectifier with capacitor filter

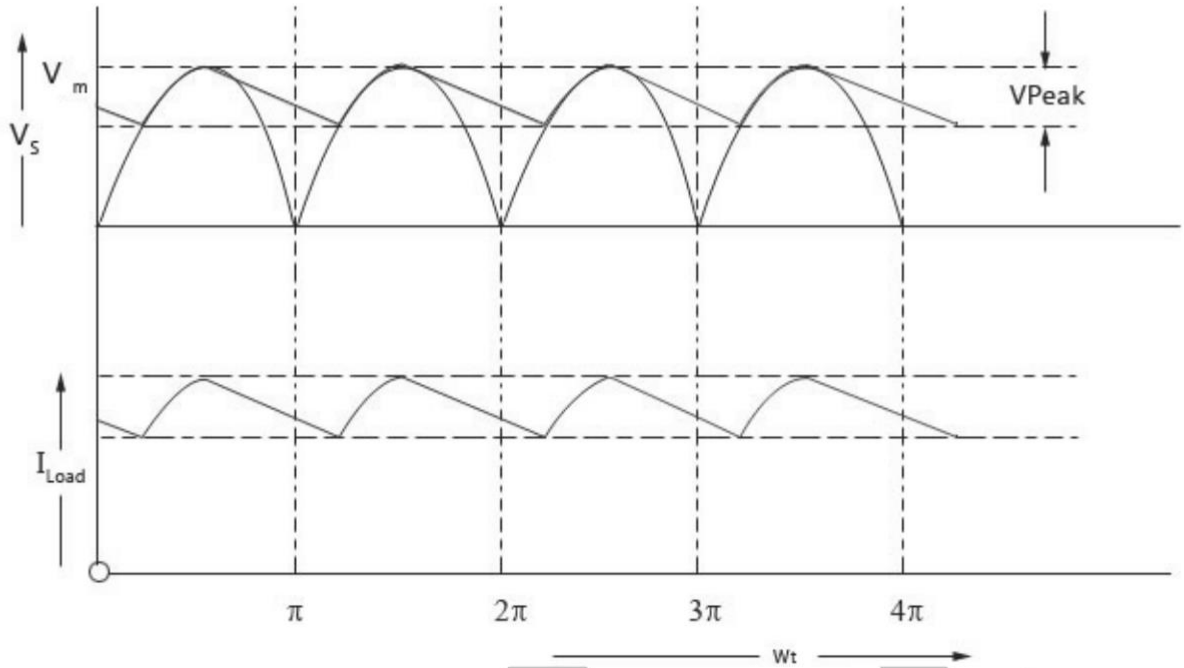


Fig. 21b. Output waveforms of full wave rectifier with Capacitor filter.

Assuming the capacitor to be initially discharged the diode D1 gets forward biased during the positive half cycle and the diode conducts. The current flows through the load and the capacitor. Due to this current, the capacitor charges and the output voltage increases. When the secondary voltage of the transformer reaches the maximum value the output voltage also reaches the maximum value.

Further, when the secondary voltage reduces below the maximum value, the capacitor discharges. The discharge of the capacitor flows in the opposite direction and the diode blocks the flow of the current in the opposite direction and hence gets reverse biased. The discharge of the capacitor takes place through the load resistor.

Since, the capacitor is in parallel with the output terminals the output voltage is equal to the capacitor voltage. The rate of discharge of the capacitor is determined the values of R_L and C.

In the next positive half cycle of the output the diode D2 gets forward biased when the source voltage v_s becomes greater than the capacitor voltage. Then the capacitor starts charging with a time constant of zero. The capacitor charges to the maximum value of the peak voltage of the input supply.

Thus, the output voltage will fluctuate between V_m and a minimum value decided by the discharging rate of the capacitor. Therefore, with the capacitor present the fluctuation of output voltage is less than that without capacitor. This reduces the ac component and hence the ripple factor reduces. The circuit and waveforms are shown in figure 21a and 21b.

Bridge rectifier with a filter:

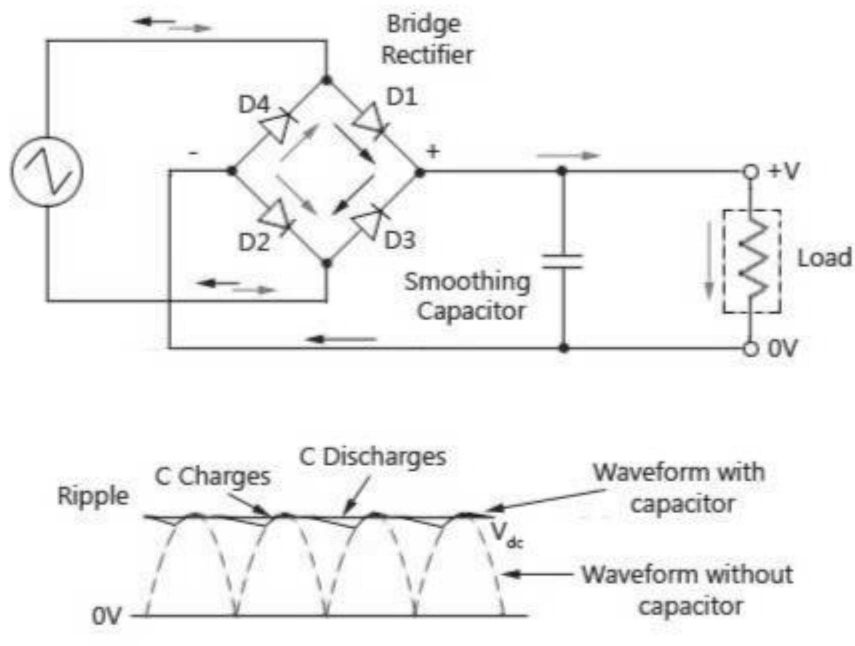


Fig 22 Bridge Rectifier with C- filter

Assuming the capacitor to be initially discharged, the diode D1, D2 gets forward biased during the positive half cycle and the diode conducts. The current flows through the load and the capacitor. Due to this current, the capacitor charges and the output voltage increases. When the secondary voltage of the transformer reaches the maximum value the output voltage also reaches the maximum value.

Further, when the secondary voltage reduces below the maximum value, the capacitor discharges. The discharge of the capacitor flows in the opposite direction and the diodes blocks the flow of the current in the opposite direction and hence gets reverse biased. The discharge of the capacitor takes place through the load resistor.

Since, the capacitor is in parallel with the output terminals the output voltage is equal to the capacitor voltage. The rate of discharge of the capacitor is determined the values of R_L and C.

In the next positive half cycle of the output the diodes D3, D4 gets forward biased when the source voltage v_s. becomes greater than the capacitor voltage. Then the capacitor starts charging with a time constant of zero. The capacitor charges to the maximum value of the peak voltage of the input supply.

Thus, the output voltage will fluctuate between V_m and a minimum value decided by the discharging rate of the capacitor. Therefore, with the capacitor present the fluctuation of output voltage is less than that without capacitor. This reduces the ac component and hence the ripple factor reduces.

Breakdown mechanism in diode:

When the p-n junction is reverse-biased the current through the p-n junction is negligible and the p-n junction is said to be not conducting. As the reverse voltage is increased at a suitable high voltage, the device starts conducting heavily and current becomes very large and is limited only by the external resist acnes. The reason for this is the breakdown of the p-n junction.

There are two types of breakdown mechanisms,

1. **Avalanche breakdown.**
2. **Zener breakdown.**

In a p-n junction any one of the breakdown mechanism or both may occur. The doping level of the p-n will decide the type of breakdown mechanism. In certain devices the doping level is adjusted such that the this breakdown is made to be a reversible process, that is, after the breakdown if the reverse voltage is disconnected the p-n junction will return to the normal state without any damage.

The breakdown mechanisms are explained as follows:

- **Avalanche breakdown:**

When higher reverse voltage is applied, the electrons are accelerated and move at higher velocity and hence acquire higher kinetic energy. The high energy electron when collides with a neutral atom will dislodge an electron from the atom. This process continues cumulatively leading to large number of electrons the region surrounding the junction. This phenomenon is called avalanche multiplication. As a result of this, all atoms of the depletion layer will be neutralized. Then the device is said to in the breakdown condition and conducts heavily due to the presence of large number of electrons

- **Zener breakdown.**

Zener breakdown occurs in a p-n junction diode which is heavily doped, the width of the depletion layer decreases and the electric field becomes very intense.

—

Where v is the applied voltage and the d is the width of the depletion layer. As doping is increased, d decreases and E increases. Due to high value of E, the electron in the valence band will be dislodged and hence an additional charge carrier is created. At a suitable value of E large number of electrons may be released and depletion layer vanishes consequently the p-n junction starts conducting. This is called **Zener breakdown** or **Zener effect**.

1.10 Zener Diode

In a p-n junction under reverse bias condition, the p-n junction may breakdown. The breakdown may be caused by:

- Zener breakdown
- Avalanche breakdown

In a device any one of the breakdown mechanism or both may occur. The doping level of the p-n will decide the type of breakdown mechanism. The doping level is adjusted such that the this breakdown is made to be a reversible process, that is, after the breakdown if the reverse voltage is disconnected the p-n junction will return to the normal state without any damage. Such a device is called a Zener diode.

One of the usual applications of Zener diodes is voltage regulator. The voltage is a circuit that produces a constant output voltage irrespective of the supply voltage and load conditions

Forward Characteristics:

Zener diode is p-n junction diode that has similar characteristics as a normal p-n junction diode under forward biased conditions.

Reverse Characteristics:

Under reverse bias condition, a small current called reverse leakage current flows through the diode. This current is due to the movement of minority charge carriers. The reverse leakage current is constant with respect to the reverse voltage. For all practical purposes the reverse current can be neglected and the zener diode can be treated like an open circuit.

As the reverse voltage is increased, the Zener diode is subjected to breakdown at suitable voltage called breakdown voltage V_Z. After breakdown, the current becomes large and is controlled only by the external circuit. The voltage across the zener diode remains almost constant. Hence, the zener diode in the breakdown region can be seen as constant voltage source. The device is then said to be in the breakdown region. As a regulator the Zener diode is always operated in the breakdown region.

For a p-n junction subjected to breakdown either zener or avalanche breakdown or both may occur. Based on the value of breakdown voltage the breakdown mechanism can be listed as follows.

Sl.no.	Breakdown Voltage range	Breakdown mechanism
1	Less than 4V	Zener breakdown
2	More than 6V	Avalanche breakdown
3	In between 4V and 6V	Both Zener and Avalanche Breakdown

In all the above cases, the p-n junction undergoing breakdown is referred to as Zener diode only.

Voltage regulators

What is a voltage regulator?

A voltage regulator is a circuit that maintains a constant output voltage irrespective of magnitude of input voltage and the load current.

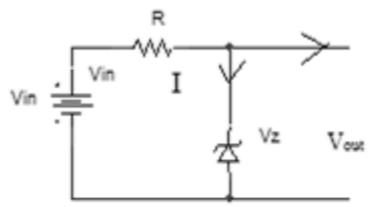
What is the need for a voltage regulator?

The available DC supply may be a fluctuating DC. An example of fluctuating DC is a rectifier. The output of a rectifier is unidirectional but not a constant value. Such a voltage can be connected to a voltage regulator which provides constant output voltage. Most of the electronic circuits require a constant DC as the source. Hence a voltage regulator can be used as source of DC supply to many electronic circuits.

A Zener diode voltage regulator is defined as a circuit that provides constant output voltage when the input of the circuit and the load resistance is varied.

Concept: The Zener diode when operated in the breakdown region provides a constant voltage across the terminals of the Zener diode and hence can be used as a voltage regulator. The Zener diode works as normal diode during forward biasing of the circuit.

Implementation of the circuit: the Zener diode is connected such that it is reverse biased and if the magnitude of the input voltage is greater than the Zener breakdown value, the Zener diode operates in the breakdown region.



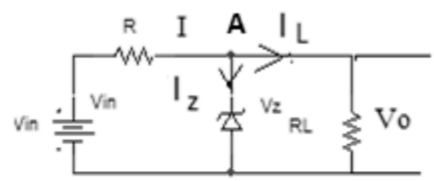


Fig.23a. Zener Diode Voltage regulator without load Fig. 23b .Zener Diode Voltage regulator with load

Figure 23a shows the Zener Diode Voltage regulator without R_L and Figure 23b .shows the Zener Diode Voltage regulator with R_L.

Apply KVL (Kirchhoff's Voltage Law) to Figure 23a

—— or

R ——

Apply KVL ((Kirchhoff's Voltage Law) to Figure 23b then,

Apply Kirchhoff's Current Law at Node A, then current I, is the addition of Zener current and load current.

—— or,

——

Zener diode can be used as voltage regulator

A regulator is defined as a circuit that provides constant output voltage when the input of the circuit and load resistor is varied.

Concept: The Zener diode when operated in the breakdown region provides a constant voltage across the terminals of the Zener diode hence can be used as a voltage regulator.

Implementation of the concept: The Zener diode is connected such that it is reverse biased and if the magnitude of the input voltage is greater than the Zener breakdown value, the Zener diode operates in the breakdown region.

Circuit connection: The circuit diagram of the Zener diode voltage regulator is shown in figure 2b. The resistance R_S is used to limit the current through the Zener diode. The input to the circuit is from an unregulated power supply. The meaning of the word unregulated power supply is the voltage of the supply subjected to variation.

Circuit operation: the Zener diode is reverse biased and operates in the breakdown region, hence the output voltage remains constant.

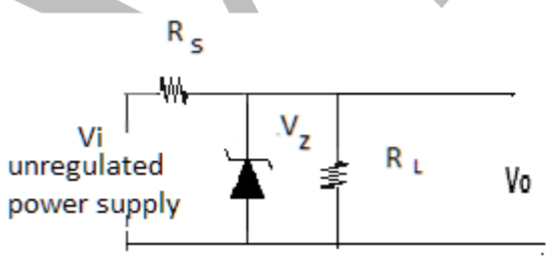


Fig.24a. Zener diode voltage regulator

Design consideration: Design of the circuit means calculating the value of series resistance 'R'. The logic is as follows:

The input voltage V_{in} and the load resistor R_L may change. Due to this variation, the current through the Zener diode will change. The variation of Zener current has the following implications.

If the Zener current becomes less than the minimum value denoted as $I_{Z(min)}$, the Zener diode may not remain in the breakdown region. Then the current will not function like a voltage regulator. Therefore, the current through the Zener diode must be greater than this minimum value. Hence, the value of the resistor ‘R’ must be selected suitably. This condition specifies the maximum value of R denoted as R_{max} and is given by

If the Zener current becomes less than the maximum value, denoted as $I_{Z\ max}$, the Zener diode will damage due to the excessive current. To protect the Zener diode, the current through the Zener diode must be kept less than the maximum value. For this the value of R must be selected. The corresponding resistor value is the minimum value of ‘R’ and is denoted by R_{min} and is given by

The actual value of R must be such that it lies in between the maximum and minimum values calculated above. This can be specified as

$< R <$

Source effect and line regulation

Let can be the change in the output voltage when the input voltage changes by . When the voltage charging the Zener voltage regulator is replaced by the Zener impedance of the circuit is given by the parallel combination of Z_Z parallel with R_L.

$Z = Z_Z \| R_L$

Using voltage division rule

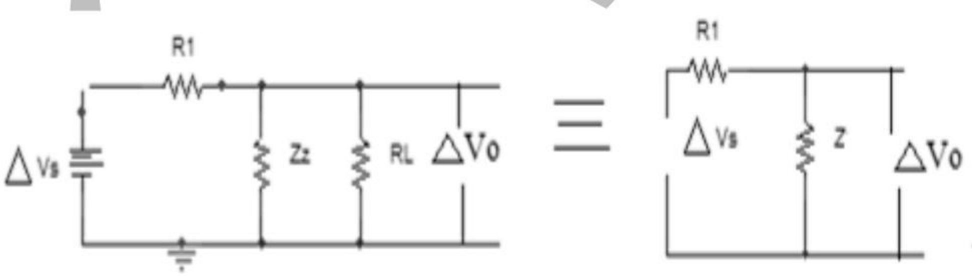


Fig.25. Dynamic equivalent circuit of the Zener voltage regulator

With R_L=0, i.e. No load then

Source effect =ΔV_0 change for 10% change in V_S

Line regulation is given by,

LR=

Output resistance R_0

The output resistance measuring circuit of the Zener diode voltage regulator is shown in figure 26.

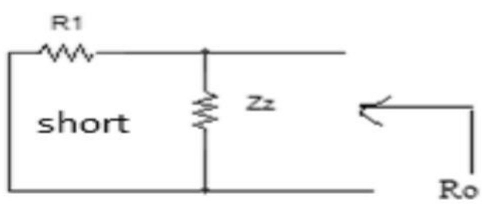


Fig. 26. Equivalent circuit to find the R_0

Consider dynamic equivalent circuit and follow the steps to find the output resistance

- short circuit the input terminal
- Remove R_L

The equivalent resistance measured between the output terminals is the output resistance (R_o). From the output terminal the resistance is parallel combination of R_1 and Z_Z

$R_o=(R_1||Z_Z)=$

Load effect and load regulation

The voltage source representation of Zener regulator can be obtained by replacing Ro in series with the voltage source V_O as shown in figure 2g.

V_o= voltage across R_o+ load voltage

V_o= constant.

When the load current increase by ΔI_L, the voltage across Ro increases by Ro*ΔI_L and the load voltage decreases by same amount

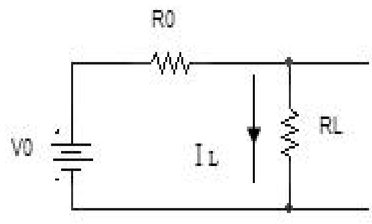


Fig. 27. Voltage source representation of Zener regulator

Therefore the output voltage change is given by $\Delta V_O = R_O * \Delta I_L = [Z_Z \| R_L] * \Delta I_L$

Load regulation=——————

Problems on Voltage Regulators

For a Zener diode regulator shown in figure Q.28(a), Calculate the range of input voltage for which output will remain constant Vo=Vz, Vz=6.1V, Iz_{min}=2.5mA. Iz_{max}=25mA, Rz=0Ω. (04 Marks)

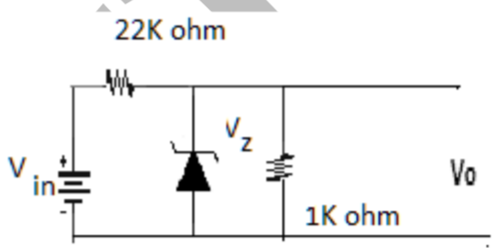


Fig. Q.28(a)

Zener diode regulator is shown in figure 28(a).

Find the range of input voltage

Vo=Vz, Vz=6.1V, Iz_{min}=2.5mA. Iz_{max}=25mA, Rz=0Ω.

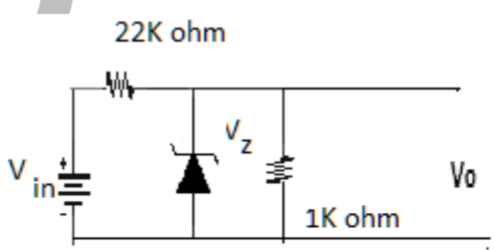


Fig.28b. Zener diode as a voltage regulator

— =——

= 68.6V

=13.2+6.1+5.5

=24.8V

The range is 24.8 V to 68.6 V

Comparison between Zener breakdown and Avalanche breakdown

Zener breakdown	Avalanche breakdown
It is observed in the zener diodes having reverse breakdown voltage less than 5V.	It is observed in the normal diodes having reverse breakdown voltage greater than 5V.
heavily doped PN junction is used.	Lightly doped PN junction is used.
The V-I characteristics with Zener breakdown is very sharp.	The V-I characteristics with the Avalanche breakdown increase gradually. It is not as sharp as that with the Zener breakdown.
Electric Field strength is strong	Electric Field strength is not so strong.
The valence electrons are pulled into conduction due to very intense electric field appearing across the narrow depletion region	The valence electrons are pushed into conduction band due to the energy imparted by colliding accelerated minority carriers.
The depletion region is narrow	widened depletion region is present

TRANSISTORS

Bipolar Junction Transistors: BJT operation, BJT Voltages and Currents, BJT amplification, Common Base, Common Emitter and Common Collector Characteristics, Numerical examples as applicable

Introduction

The term "transistor" derived from the concept of transferring a current from low resistance to high resistance circuit, i.e. transfer of resistance. The term transistor obtained from **"TRANS**fer-res**ISTOR",** means transfer of signal from low resistance region to high resistance region. The transistor is the most important device in electronics. It can be used as an amplifier to increase power, voltage or current. And also it can be used as a switch.

There are two types of transistors

1. Bipolar.
2. Unipolar.

The bipolar or BJT (bipolar junction transistor) uses both electrons and holes as carriers. It is a current controlled device; the output current depends on the input current.
The unipolar or FET (field effect transistor) uses either electrons or holes as carriers. It is a voltage controlled device. A voltage on its gate controls the current flowing through the device.
A transistor consists of three layers and three terminals

- Base,
- Emitter and
- Collector.

The three layers can be either

- n-p-n
- p-n-p

The base layer is lightly doped and is very narrow. This is to reduce the recombination. The emitter is moderately doped and collector is heavily doped and has large cross sectional area. The layers of semiconductor material behave like a two diodes connected back to back. As shown below figure1.

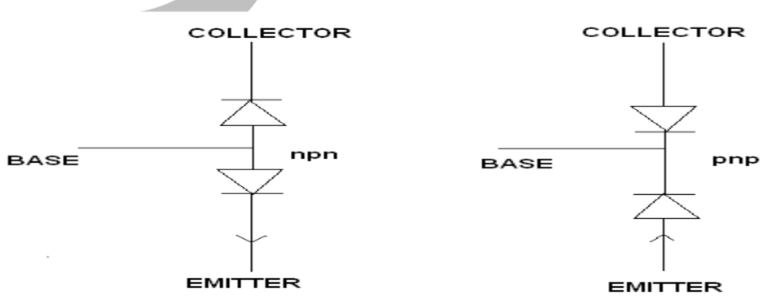


Fig. 1. Two diode Analogy of transistors.

The arrow head at the emitter indicates the conventional transistor bias polarities
The transistor has three regions of operations, namely:

- Cut-off region
- Active region
- Saturation region

In the application, the transistors can be used as: Switch and Amplifier.

- As a switch the transistor must be either in the cut-off region or saturation region.
- In the cut-off region, the switch in the OFF state.
- In the saturation region the switch is in the ON state.

Figure 2 shows the NPN and PNP transistor and its symbol.

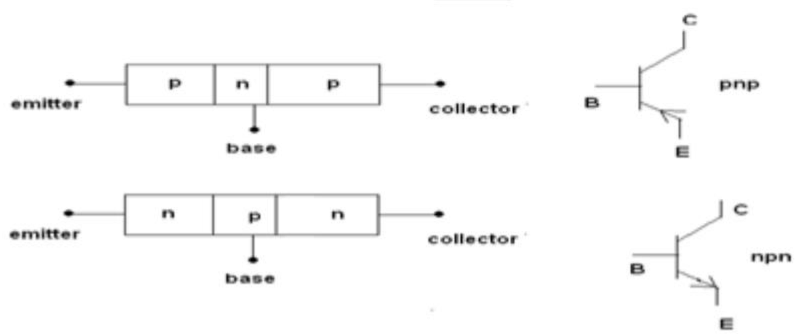


Fig 2. Transistor and its symbol

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In case of an NPN transistor, the emitter current is constituted by the flow of electrons from the emitter into the base region, so that the flow of conventional electric current is from the base to the emitter. The arrow head is put on the emitter lead pointing away from the base as shown in figure 2.
In case of an PNP transistor, the emitter current is constituted by the flow of holes from the emitter into the base region, so that the flow of conventional electric current is from the emitter to base. The arrow head is put on the emitter lead pointing towards the base as shown in figure 2.

As an amplifier the transistor must be configured only in the active region. The status of base to emitter junction and collector to base junction will decide the operating region of the transistor. This is illustrated in the following table1.

Table1. Operating Region and biasing

Operating region	**Base to emitter**	**Collector to base junction junction**
Cut-off	Reverse biased	Reverse biased
Active region	Forward biased	Reverse biased
Saturation region	Forward biased	Forward biased.

Note: The present chapter deals with the use of transistor as an amplifier. Therefore, only active region of operation is discussed.

Unbiased PNP and NPN operation

An biased transistor refers to the situation where no external voltages are applied. Figure 2a and 2b shows an unbiased transistor highlighting the depletion region.
Depletion region is a region where free of charges. The base layer is much narrower compared to the outer layers. The outer layers are more heavily doped than the central layer, with the result that the depletion region penetrate deeply into the lightly doped base.

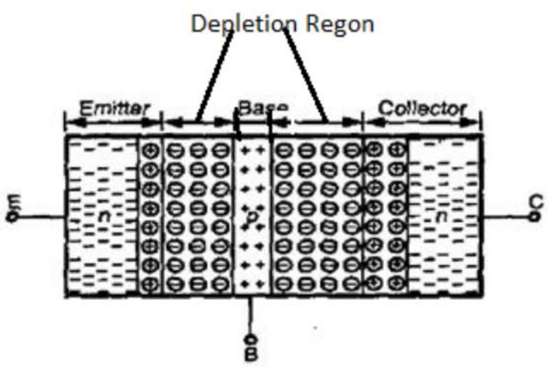

Fig. 2a. Unbiased NPN transistor

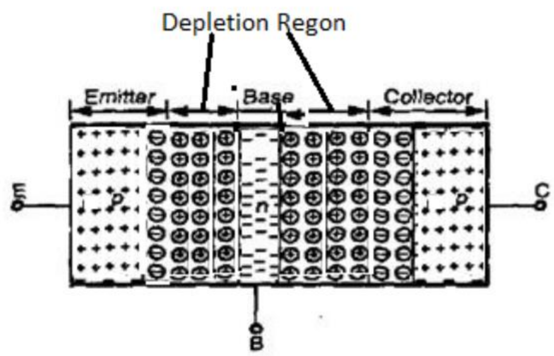

Fig. 2b. Unbiased PNP transistor

Biasing of a Transistor

Biasing is applying external voltage to the device. Two PN junctions of transistors are biased with external voltages, depending upon external bias voltage polarities used. The transistor works in one of the three regions. They are active region, cut-off region and saturation region

Operation of NPN transistor and various currents

To operate the transistor in the active region, the base to emitter (BE) junction is forward biased and collector to base (CB) junction must be reverse biased. Two power supplies are connected for this purpose.

The supply V_{EE} forward biases the base to emitter junction. and The supply V_{CC} reverse biases the collector to base junction. Figure 3 shows NPN transistor working.
At the forward biased base to emitter junction, the barrier potential decreases so its depletion region is narrowed. The reverse biased collector to base junction the barrier potential increases and its depletion region is widened.

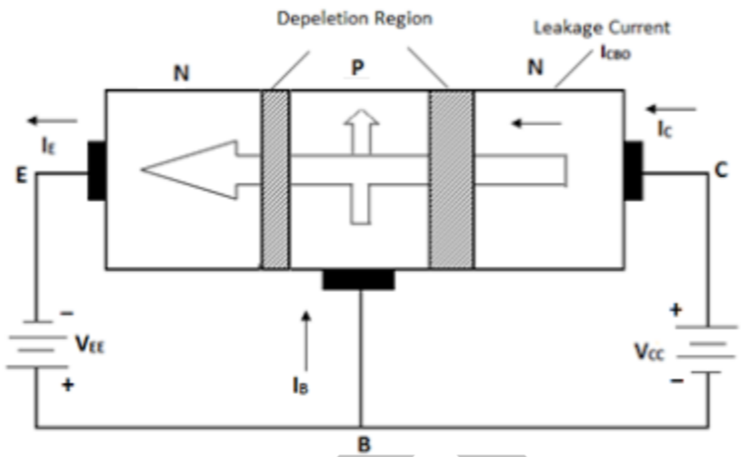

Fig. 3. Working of NPN transistors

The combination of large total potential produced by batteries V_{CC} and V_{EE} sets up electric field. The barrier voltage is negative on P-side and positive on N-side.

As the EB junction is forward biased, the larger number of electrons which are majority charge carriers in the N-region, are replaced by the negative terminal of the bias voltage, and diffuse to the right into the base region. The electron flow towards the base constitutes a emitter current I_E.

Emitter current (I_E):

Across the forward biased junction majority charge carriers can cross the junction. Therefore from the emitter region the holes will cross the junction and reach the base region. The movement of these charge carriers results in flow of current I_E in the emitter.

Base current (I_B):

The electrons crossing into the emitter will undergo recombination with the majority carriers (holes) in the base region. This reduces the number of majority charge carriers in the base layer. To maintain the charge balance, the supply V_{EE} will drive holes into the base region. This constitutes flow of current I_B in the base terminal.

Collector current (I_C):

The electrons crossing the emitter junction into the base layer which do not undergo recombination acquire minority status in the base region, which can cross the reverse biased collector to base junction. This is a component of current in the collector region. This current is αI_E.

The base region contains additional minority charge carriers (electrons) which will also cross the reverse - biased collector to base junction. This constitutes an additional current I_{CBO} in the collector. This is called collector to base reverse saturation current with base open.

Both I_B and I_C flows out of the transistor, while I_E flows into the transistor therefore,

$$I_E = I_B + I_C$$

The total collector current is the sum of collector reverse saturation current I_{CBO} and the fraction of emitter current αI_E.

i.e $$I_C = I_{CBO} + \alpha I_E$$

Note: the flow of current is due to movement of charge carriers across the junction. Both type of charge carriers (hole and electrons) will be crossing the junction. Therefore, the flow of current is due to both types of charge carriers. Hence the transistor is also called **bipolar device**.

Operation of PNP transistor

To operate the transistor in the active region, the base to emitter junction is forward biased and collector to base junction must be reverse biased. Two power supplies are connected for this purpose. The supply V_{EE} forward biases the base to emitter junction.

The supply V_{CC} reverse biases the collector to base junction. At the forward biased base to emitter junction, the barrier potential decreases and at the reverse biased collector to base junction the barrier potential increases. Figure 4 shows the working of PNP transistor.

In forward biased emitter-base junction, the holes which are majority charge carrier in the P-region, are repelled by the positive terminal of the bias voltage V_{EE} and diffuse to the base region. The base is an N-type semiconductor, electrons are the majority carrier. The holes comes from emitter combine with few electrons and constitute a base current. Since the base region is narrow and holes do not remain in the base region long enough for recombination to take place.

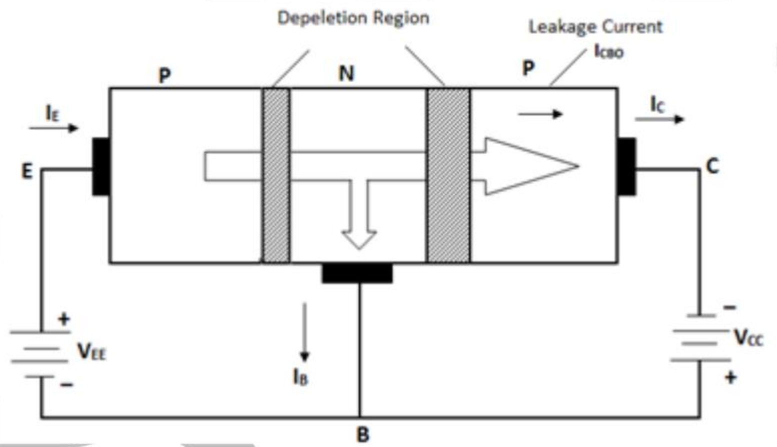

Fig. 4. Working of PNP transistors

Then holes are collected by the collector, as the collector base junction is reverse biased and the negative potential of the bias voltage causes the holes to be readily attracted. this constitute the collector current I_C.

As some recombination of holes and electrons takes place in the base region, electrons from the negative end of the battery V_{EE} go upwards into the base to make up for the electrons lost in recombination.

This electron current mainly constitute the base current I_B.

Thus emitter current I_E is equal to the sum of the base and collector currents. Hence

$$I_E = I_B + I_C$$

The total collector current is the sum of collector current and base current. if I_B is very small.

$$I_E = I_C$$

Transistor voltages

The voltage drops across the terminals are to measured in a circuit. The terminal voltage polarities for the PNP and NPN is shown below as well as conventional arrow head shows current flow direction for both transistors (PNP and NPN).and also the transistor bias polarities.

For example consider the NPN transistor, the base (B) is positive with respect to the emitter terminal (E). Collector is biased more compared to base terminal. This is shown in fig (a). The source voltage is connected to transistor through the resistor. That is input supply voltage V_B is connected to base terminal through resistor R_B. And Vcc is connected to collector terminal through the resistor R_C. The negative terminals of the V_B and Vcc is connected to emitter terminal. It should satisfy condition Vcc > V_B.

Typical transistors base emitter voltage V_{BE} is 0.7 for si and 0.3 for Ge. For collector voltage ranges from 3 to 20 volts

Similarly for PNP transistors also, Figure 5 below shows the terminals polarities and voltages.

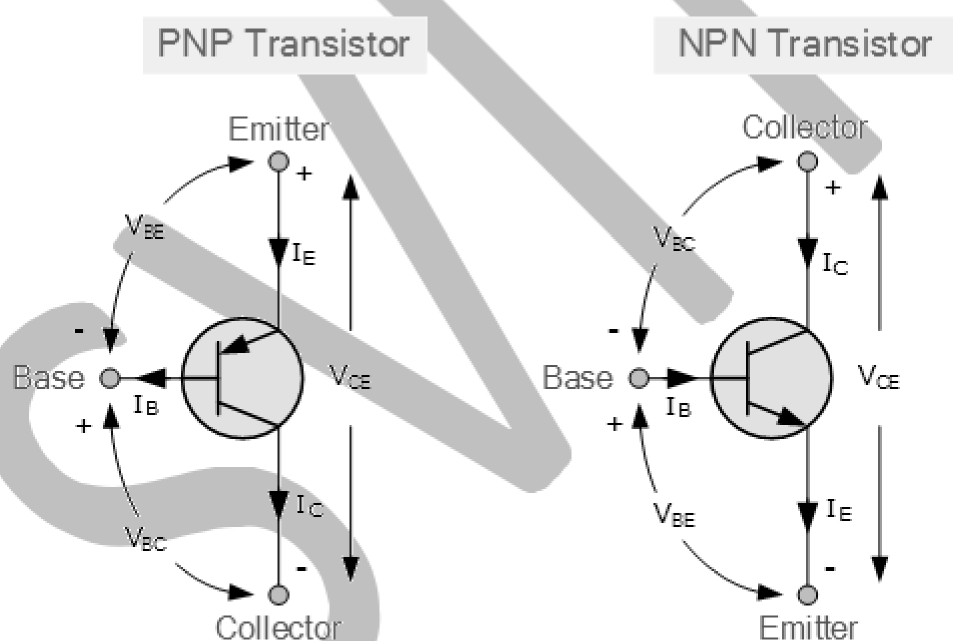

Fig. 5. Transistor terminal polarities and voltage

Transistor currents

Emitter current (I_E):

Across the forward biased junction majority charge carriers can cross the junction. Therefore from the emitter region the holes will cross the junction and reach the base region. The movement of these charge carriers results in flow of current I_E in the emitter.

Base current (I_B):

The holes crossing into the emitter will undergo recombination with the majority carriers (electrons) in the base region. This reduces the number of majority charge carriers in the base layer. To maintain the charge balance, the supply V_{EE} will drive electrons into the base region. This constitutes flow of current I_B in the base terminal.

Collector current (I_C):

The holes crossing the emitter junction into the base layer which do not undergo recombination acquire minority status in the base region, which can cross the reverse biased collector to base junction. This is a component of current in the collector region. This current is αI_E. The base region contains additional minority charge carriers (holes) which will also cross the reverse - biased collector to base junction. This constitutes an additional current I_{CBO} in the collector. This is called collector to base reverse saturation current with base open.
The total collector current is the sum of collector reverse saturation current I_{CBO} and the fraction of emitter current αI_E .**i.e $I_C = I_{CBO} + \alpha I_E$**

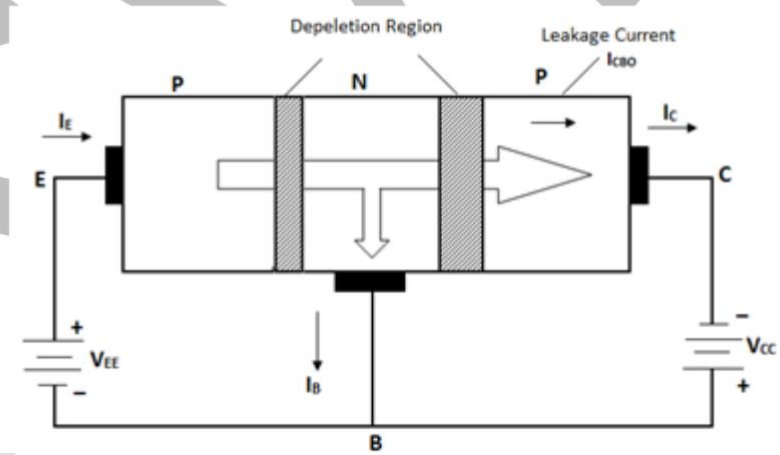

Fig. 6. PNP transistors currents I_C, I_B I_E and

I_{CBO} Derive the relationship between α and β

The current components in a PNP transistor is shown in Figure 6 the current flowing into the emitter is I_E, the emitter current For the PNP transistor I_E can be thought of as a flow of holes from the emitter to the base.

Both I_C and I_B flow out of the transistor, while I_E flows into the transistors hence

$$I_E = I_B + I_C \text{ -------------------------(1)}$$

if I_B is very small

$$I_E \quad I_C$$

The maximum amount of I_E crosses to the collector and only a small part flows out of the base terminal as base current I_B.

The large portion of I_E flows out of the collector as collector current I_C.

emitter to collector dc current gain or the ratio of collector current to emitter current.

For the Transistor common Base configuration, the gain is given by

—

it is also called the common base dc current gain, its value ranges from 0.96 to 0.995.

As the CB junction is reverse biased, a small reverse leakage(saturation) current, I_{CBO} flows across the junction.

Hence collector current can also be written as

$$\mathbf{I_C = I_{CBO} + \alpha I_E}$$

if I_{CBO} is very small and hence can be neglected

$$I_C = \alpha I_E \text{-----------(2)}$$

$$I_C = \alpha(I_B + I_C)$$

(

______

is the base to collector current gain or ratio of collector to base current. typical values includes 25 to 300.

Relationship between is given below.

For the Transistor common emitter configuration, the gain is given by

= (1+ =>

Note: The common collector current gain is =

Consider $I_C=I_E+I_B$

Problems:

1). Calculate the values of I_C, I_E for a BJT with α_{dc}= 0.97 and I_B = 50μA determine β_{dc} Find: I_C, I_E for a Bipolar Junction Transistor

Data given:

α_{dc}= 0.97 and I_B = 50μA determine β

Given α= 0.97 and I_B= 50μA

= $(32.33*50*10^{-6})$ =

1.61mA 1.61mA,

=1.6666mA

2). Find the value of α, and I_E for the given data for a transistor has Ic =2mA and I_B = 100µA.

— =————=20

=2.1mA

3). calculate the α value and β value of a transistor. if I_B = 100µA, and I_C=2mA.

Given **,** I_B = 100µA, and I_C=2mA, — = ——— = 20

—— =——

Bipolar Junction Transistor (BJT) Amplification

The transistor can be used for increasing the magnitude of voltage or current. The transistor used for such application is called an amplifier. For the transistor to be an amplifier, the transistor must be in active region.
The transistor can be used for either voltage or current amplification.

Only in common emitter configuration the transistor can provide both current and voltage amplification.
In common base configuration, current amplification is not possible. Only voltage can be amplified.
Common collector configuration is suitable only for current amplification, whereas the voltage amplification is not possible.

Therefore, based on the requirement of the application suitable configuration must be selected for the amplifier.

The following explanation is for common emitter configuration, since common emitter configuration is most widely used for its ability to provide both voltage and current amplification.

Current Amplification

The base current of the transistor is very small and the collector current is very large. The ratio of collector current to base current is greater than unity. Treating the base current as input and the collector current as the output current, the output current is greater than the input current hence the current is said to be amplified. Current amplification is explained with figure 7.

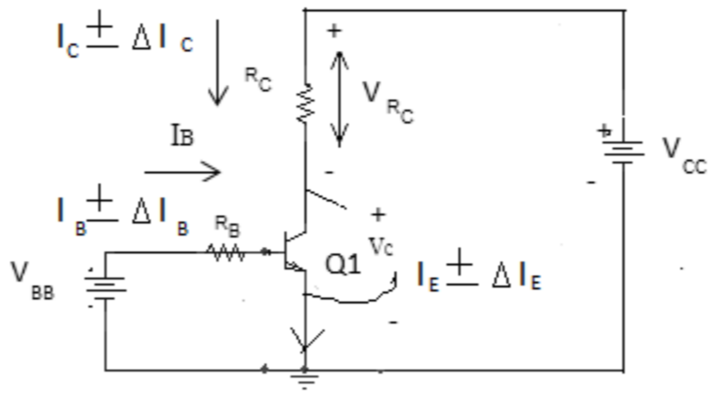

Fig. 7. Common Emitter Configuration for current amplification

The ratio of collector current to base current is the amplification factor, β. At a given operating point Q on the characteristics, the ratio collector current to base current is the current gain β_{dc} of the transistor.

At a given operating point (constant voltage V_{CE}), the ratio of change in collector current to change in base current is called β_{ac}. It is also denoted by h_{fe}.

Note: The changes in current are referred to as ac current.
For identification the ac current can be represented by lower case letters.

$$hfe = \beta ac = \frac{ic}{ib}$$

Voltage Amplification

Consider the transistor circuit shown in figure8 For a given base current I_B, we can obtain the collector current I_C as

I_C= *I_B…………………………………...... (1)

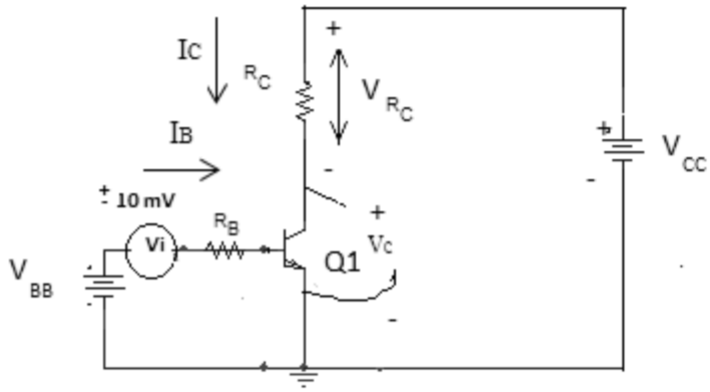

Fig. 8. CE configuration using NPN transistor

Variation in the collector current I_C is given by ΔI_C it occurs due to variation in $\pm V_i$. Apply Kirchhoff's Voltage law to the collector emitter circuit

$V_{CC} = V_C + V_{Rc}$

$V_C = V_{CC} - V_{Rc}$

Where V_{Rc} = Voltage across R_C

$= I_C * R_C$

Therefore $V_C = V_{CC} - I_C * R_C$……………………………………….(2)

For a given change in input voltage ΔV_B, we can calculate the change in the base current ΔI_B from the transistor input characteristics shown in figure. The ΔI_B value intern changes the collector current ΔI_C for given value. The input characteristics of CE configuration is the variation of input current (I_B) for different values of input voltage (V_{BE}) for constant voltage V_{CE}.

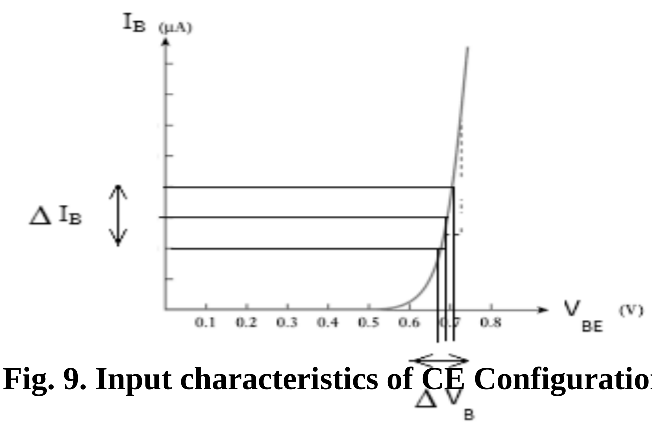

Fig. 9. Input characteristics of CE Configuration

Input characteristics of CE configuration is shown in figure 9. It is a plot of input current (I_B) versus input voltage (V_{BE}). The Change in collector current is given by equation as shown below in equation(3).

$$\Delta I_C = \quad I_B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The transfer or current gain characteristic of CE configuration is shown in figure 10.

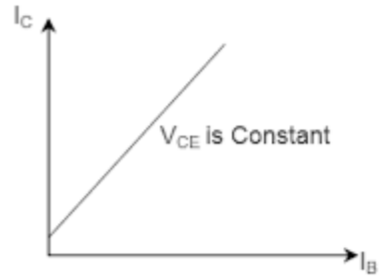

Fig 10. Transfer (or current gain) characteristics of CE configuration And from equation (2), the output voltage is given by

$$V_C = V_{CC} - I_C * R_C$$
$$V_0 = |\Delta V_C| = |\Delta I_C * R_C|$$
$$(\Delta V_C) = (\Delta I_C) * R_C$$

From equation (3), for the small change in I_B there will be large variation in I_C due to the common emitter current gain (i.e.) in turn which increases the output voltage Vc Therefore, voltage gain,

=

Transistor configurations:

The bipolar junction transistor (BJT) has three terminals collector base and emitter. To operate the transistor we need two terminals for input side and output side. Therefore any one of the terminal is made common for both input and output circuits. According to this we have three configurations

- ✓ Common emitter (CE) configuration.
- ✓ Common base (CB) configuration.
- ✓ Common collector (CC) configuration.

Common Emitter configuration

In common emitter configuration of the transistor circuit, the emitter terminal is connected to the ground. Since the emitter is connected to the ground it is called Common emitter configuration.

Here emitter is common to both the input side and the output side of the circuit. The input side refers to the base and emitter terminal, which is forward biased, using supply voltage V_{BB} and V_{CC} supply is connected to the collector and emitter terminal in the reverse biased mode. These two supply voltage are used to apply external supply voltage to the Bipolar Junction Transistor, and to operate that in active mode operation.

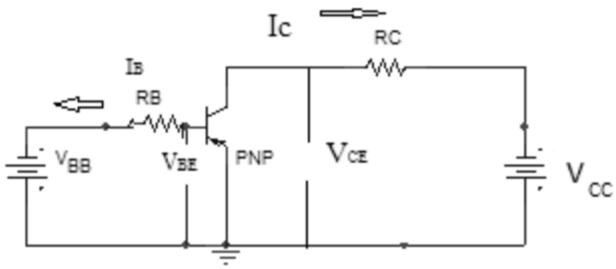

Fig. 11. PNP Transistor in Common emitter configuration

For Common emitter configuration we have two junctions base to emitter junction and collector to base junction. PNP Transistor in Common emitter configuration is shown in figure 11. In above circuit we have R_B, which is connected in series with the voltage source V_{BB} to limit the current through base terminal and the resistance R_C which is in series with the collector terminal is called a load resistance.

We have two transistor currents, input current I_B and output current I_C. And two transistor voltages, input voltage V_{BE} and output voltage V_{CE}.

Input characteristics

The plot of V_{BE} versus I_B constitutes the input characteristics. For plotting the input characteristics, the collector voltage V_{CE} is kept constant.

V_{BE} is the voltage across base to emitter junction and I_B is the current flowing through the base terminal. Since the P-N junction between base to emitter is forward biased, the variation of the base current with respect to base to emitter voltage is similar to that of forward biased P -N junction.

Effect of V_{CE} on the characteristics

For higher values of V_{CE}, the base current decreases, because the base to emitter junction is forward biased, the majority charge carriers cross the emitter junction and reach the base layer. A larger number of these charge carriers are attracted by the potential at the collector terminal and hence cross the collector junction. The remaining charge carriers will travel through the base terminal and this constitutes the base current.

Due to increase in the collector voltage magnitude (V_{CE}), more number of charge carriers will be influenced to cross the collector junction. Hence less number of charge carrier are available to constitute the base current. Thus increase in V_{CE} is associated with decrease in I_B. Therefore as V_{CE} increases the characteristics shift to the right as shown in figure 12.

At higher values of V_{BE} the base current increases exponentially Input characteristics of PNP transistor CE mode is shown in figure 12.

From these characteristics we observe that the resistance is the ratio of change in base-emitter voltage (ΔV_{BE}) to the resulting change in the base current (ΔI_B) at constant collector-emitter voltage V_{CE}.

—— | V_{CE}= constant

Output characteristics

The plot of V_{CE} vs. I_C constitutes the output characteristics. For plotting the output characteristics, the base current I_B is kept constant.

The supply voltage V_{CC} is varied. For different values of V_{CE} the collector current I_C is noted.

The output characteristic is divided into three regions.

- Active region
- Saturation region and
- Cutoff region

Output characteristics of PNP transistor Common Emitter configuration is shown in figure 13.

Active region

In Active region of operation the base to emitter junction is forward biased and collector to base junction is reverse biased. In the active region the collector current is given by

Since the base current (I_B) is kept constant the collector current is also collector voltage (V_{CE}) for a given base current. Since the collector current I_C is directly proportional to the base current the active region is called linear region. But due to Early effect, the collector current slightly increases with increase in the collector voltage (V_{CE}).

Saturation region

Saturation region is defined as the region where both the base to emitter junction and collector to base junctions are forward biased.

If V_{CE} is less than V_{BE}, the transistor operates in the saturation region. V_{BC} becomes negative and the collector to base junction is forward biased. In saturation the collector current increases with the increase in V_{CE} and varies linearly.

Cut-off region

When base current is zero, the collector current is reverse saturation current I_{CBO}. The transistor is then said to be in the cutoff region. During this region of operation both the junctions (base to emitter junction and collector to base junction) are reverse biased.

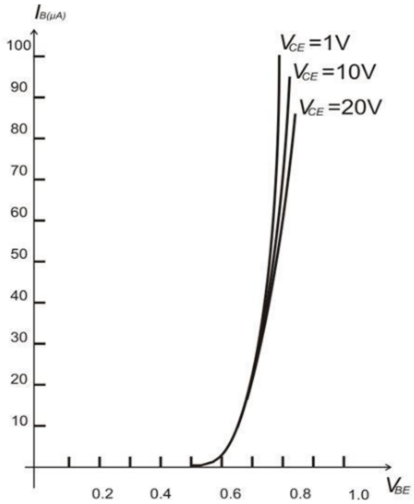

Fig. 12. Input characteristics

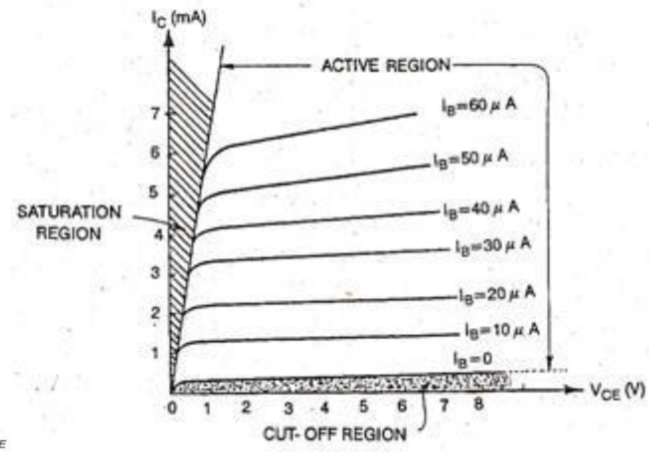

Fig. 13. output characteristics

PNP transistor CE mode

Common Base configuration

The common base configuration is shown in figure 14, for NPN transistor. Here input is applied between emitter and base. The output is taken at the base and collector.

Base is common to input and output circuit hence the name common base configuration. The bias voltages are V_{EE} and V_{CC} and three DC currents I_E, I_C and I_B. The transistor base terminal is common to both the input (EB) terminal and the output (CB) terminal, hence the transistor is said to be common base configuration.

Input characteristics

This is the variation of emitter current I_E with respect to base to emitter voltage V_{EB} when the voltage V_{CB} across the collector and the emitter terminal is kept constant and is shown in figure 15. The input characteristics can be explained as follows.

V_{EB} is the voltage across base to emitter junction and I_E is current flowing through the emitter terminal. Since the p-n junction between base and emitter is forward biased, the variation of emitter current with respect to emitter base voltage is similar to that of forward biased p-n junction. The input characteristics of a transistor in common base configuration is shown in figure.

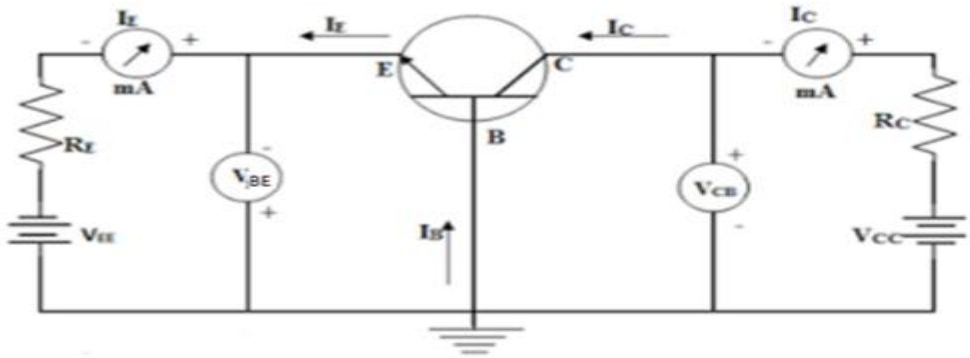

Fig. 14. Common base configuration

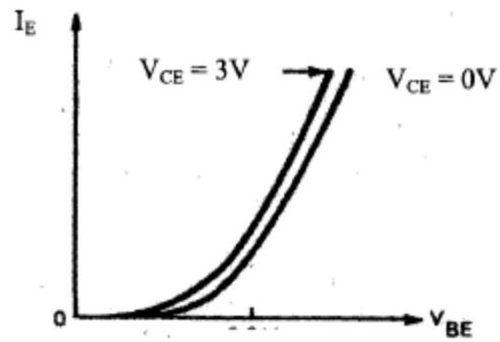

Fig. 15. Input characteristics of Common base configuration

Output characteristics

the variation of collector current with respect to the variation of collector to base voltage for a constant emitter current is called output characteristics. Output characteristics are divided into three regions and are shown in figure 16.

- Active region
- Saturation region and
- Cutoff region

Active region

Active region of operation is the region of operation in which the base to emitter voltage junction is forward biased and collector to base junction is reverse biased. In the active region the collector current is given by

Since α is almost equal to '1' and is negligible; hence we can write

Saturation region

Saturation region is defined as the region where the base to emitter junction (J_E) and collector to base junctions (J_E) both are forward biased.

As V_{CB} becomes positive the collector current I_C sharply decrease. This is the saturation region. In this region the collector current does not depends much on the emitter current

Cut-off region

When emitter current is zero and base to collector voltage is zero, the collector current is reverse saturation current I_{CBO}. The transistor is then said to be in the cutoff region. During this region of operation both the junctions (base to emitter junction and collector to base junction) are reverse biased.

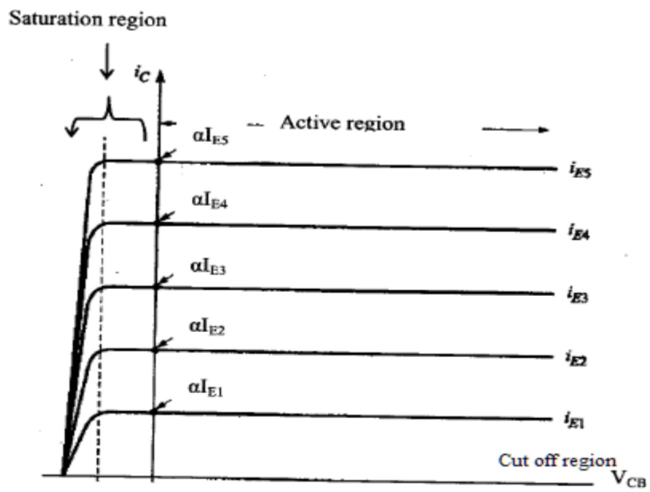

Fig. 16. Output characteristics of Common base configuration

Common Collector Configuration

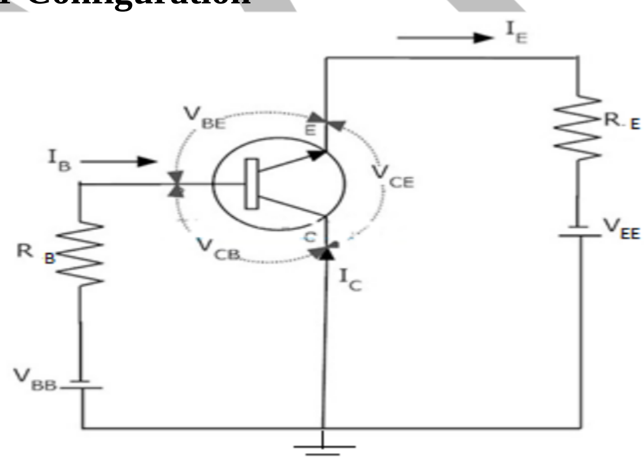

Fig. 17. Common Collector Configuration

Two supply voltages V_{BB} and V_{EE} are connected as follows for biasing the base to emitter junction and collector to base junction.

Input characteristics

- ✓ The plot of V_{CB} vs. I_B constitutes the input characteristics. For plotting the input characteristics, the collector voltage V_{CE} is kept constant.

- ✓ The supply voltage V_{EE} is varied. For different values of V_{EE} the base to collector voltage V_{CB} and base current I_B are noted. For these characteristics, the collector voltage V_{CE} is kept constant.
- ✓ Since base to collector junction is reverse-biased, the characteristics can be understood by considering the base collector voltage V_{CB}.
- ✓ From the KVL equation:

V_{BE} is constant and is approximately equal to 0.7V. The collector voltage V_{CE} is kept constant for input characteristics. Therefore, from the above equation, V_{CB} is a constant. Hence, the input characteristic is a straight line as shown in the figure 18.

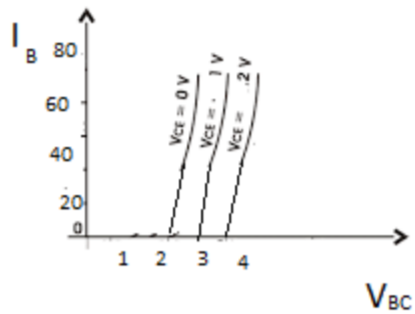

Fig. 18. Input Characteristics of Common Collector Configuration

Output characteristics

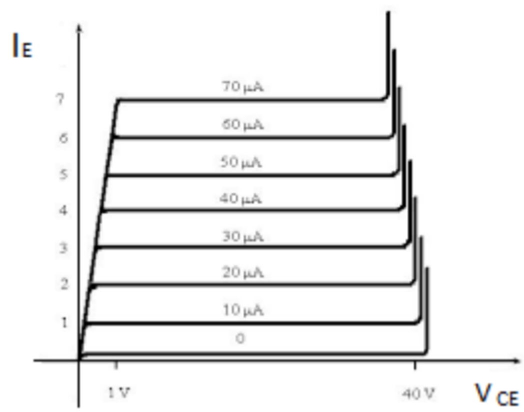

Fig. 19. Output characteristics of Common Collector Configuration

- ✓ The plot of V_{CE} vs. I_E constitutes the output characteristics. For plotting the output characteristics, the emitter current I_E is kept constant and is shown in figure 19.
- ✓ The supply voltage V_{EE} is varied. For different values of V_{CE} the emitter current I_E is noted.
- ✓ From the KVL equation
  - $V_{CB} = V_{CE} - V_{BE}$

- ✓ If V_{CE} is less than V_{BE}, V_{CB} becomes negative and the collector to base junction is forward biased. Therefore, both the junctions are forward biased and the transistor is said to be in saturation condition. In saturation the collector current increases with the increase in V_{CE}.
- ✓ For higher values of V_{CE}, the collector to base voltage V_{CB} becomes positive and the base to collector junction becomes reverse biased and the transistor enters into active region.
- ✓ In the active region the emitter current is constant.
- ✓ The transistor is said to behave like current source.
- ✓ The magnitude of emitter current is a function of base current. For higher values of base current the emitter current in the active region is higher.

Cut-off Region

- ✓ When base current is zero, the collector current is reverse saturation current I_{CBO}. The transistor is then said to be in cutoff region.

The transistor currents

The total collector current is given by

----------------------(1)

Since α is almost equal to '1' and is negligible; hence we can write

-------------------------(2)

Substitute equation (1) in equation (2)

-

=

=

=

= -------(3)

The collector current I_C depends on the base current I_B, the transistor parameter , and curve saturation current

Any small variation in reverse saturation current is multiplied with , hence results in large change in the collector current.

The collector I_C is much larger than the base current. hence the common emitter configuration of a transistor has current amplification.

Early effect

The **Early effect**, named after its discoverer James M. **Early**, is the variation in the width of the base in a bipolar junction transistor (BJT) due to a variation in the applied base-to-collector voltage.

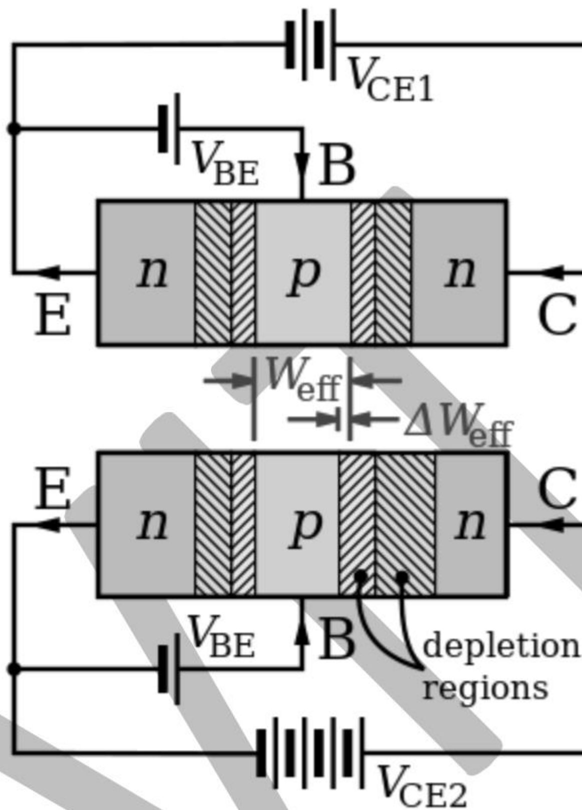

Fig. 20 Early effect

Since the collector to base junction is reverse biased, the depletion layer cists at the collector to base junction. the thickness of the depletion layer depends on the magnitude of the voltage applied at the collector terminal.

A greater reverse bias voltage at the collector increases the collector to base depletion width, decreasing the effective width of the base.

under increased collector- base reverse bias, as shown in figure 20 widening of the depletion region in the base and associated narrowing of the effective base region.

In the adjacent two diagrams, the width of the depletion layer is wider where the collector voltage is higher.

Narrowing of the base width has two consequences:

- There is a lesser chance for recombination within the "smaller" base region.
- The charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases.

Both factors increase the collector or "output" current of the transistor in response to an increase in the collector–base voltage.

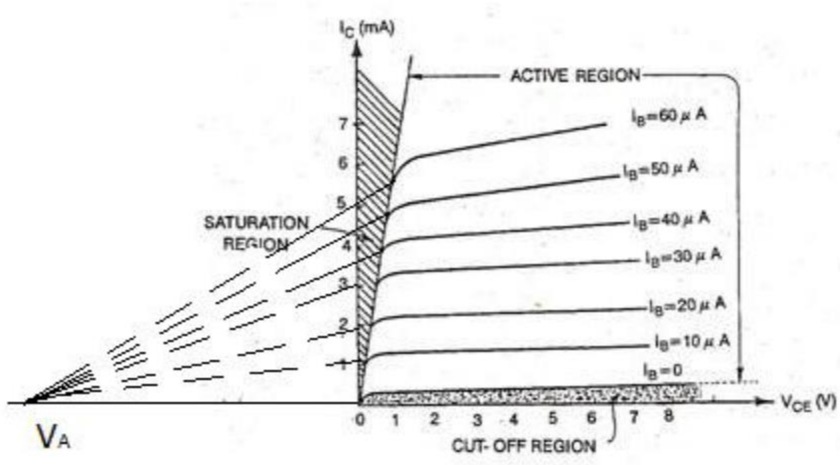

Fig. 21 Early effect and the collector current variation.

Thus in the active region, the collector current doesn't remain constant. Instead collector current increase with increases in the collector voltage this is shown in figure 21. the Early voltage is a negative voltage.

Tangents to the characteristics at large voltages extrapolate backward to intercept the voltage axis at voltage called the Early voltage. Early voltage is defined as the voltage at which the collector current becomes zero.