GANESH INSTITUTE OF ENGINEERING AND TECHNOLOGY (GIET),
Jagannath Prasad, Andharua, BHUBANESWAR

ANALOG ELECTRONICS AND OP-AMP (Th- 02)

(As per the 2019-20 syllabus of the SCTE&VT, Bhubaneswar, Odisha)

Fourth Semester

Electrical Engg.

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SYLLABUS DISTRIBUTION PLAN

S.N.	Name of the Chapter as per the Syllabus	No. of periods in Syllabus	No. of planned periods	Expected marks in final exam
1.	P-N Junction Diode	6	7	10
2.	Special Semiconductor Devices	5	4	5
3.	Rectifier Circuits and Filters	7	8	15
4.	Transistors	7	7	10
5.	Transistor Circuits	7	7	15
6.	Transistor Amplifier and Oscillators	13	13	20
7.	Field Effect Transistors	6	6	10
8.	Operational Amplifiers	9	8	15
	Total	**60**	**60**	**100**

CHAPTER – 1

[P-N JUNCTION DIODE]

LEARNING OBJECTIVE

1 . 1 P-N Junction Diode
1 . 2 Working of Diode
1 . 3 V-I characteristic of PN junction Diode.
1 . 4 DC load line
1 . 5 Important terms such as Ideal Diode, Knee voltage
1 . 6 Junctions break down.
1.6.1 Zener breakdown
1.6.2 Avalanche breakdown
1 . 7 P-N Diode clipping Circuit.
1 . 8 P-N Diode clamping Circuit

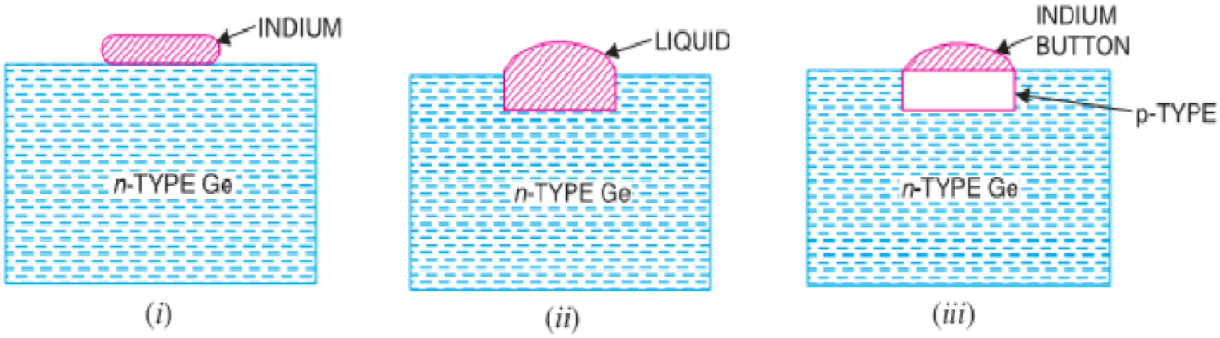
ARTICLE 1.1: P-N JUNCTION DIODE

❖ **DEFINITION:-**

➢ When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is called **p-n Junction**.

❖ **FORMATION OF PN JUNCTION**

➢ It is fabricated by special techniques and one common method of making PN junction is called **Alloying**.



[Figures of different stages of formation of PN junction by Alloying method]

➢ In this method, a small block of indium (trivalent impurity) is placed on an n-type germanium slab as shown in Fig (i). The system is then heated to a temperature of about 500ºC. The indium and some of the germanium melt to form a small puddle of molten germanium-indium mixture as shown in Fig (ii). The temperature is then lowered and puddle begins to solidify.

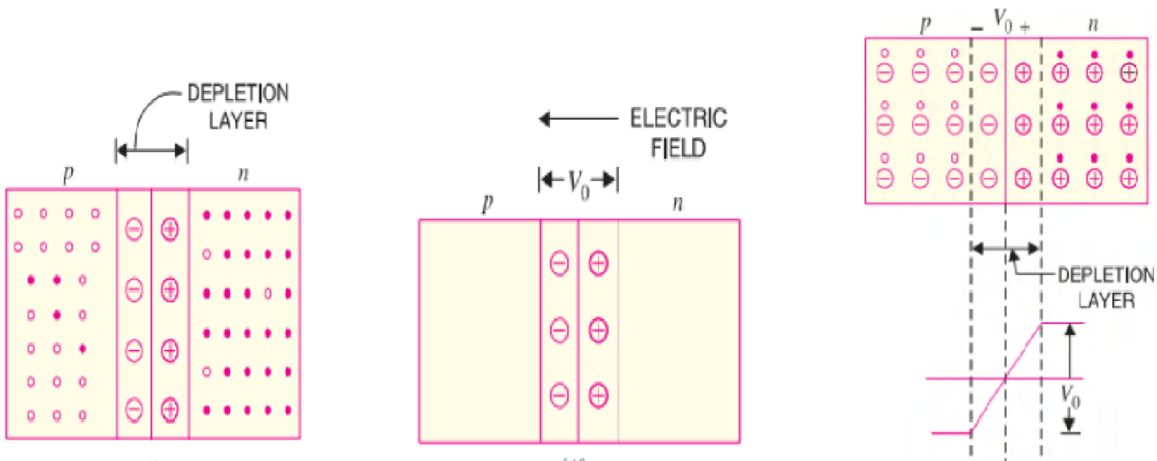
➢ Under proper conditions, the atoms of indium impurity will be suitably adjusted in the germanium slab to form a single crystal.

ARTICLE 1.2: WORKING OF DIODE

- Consider two types of materials: -
  1) P-Type-P-type semiconductor having –ve acceptor ions, +ve charged holes and a few electrons;
  2) N-Type -N-type semiconductor having +ve donor ions, –ve free electrons, and a few holes.

- P-type has high concentration of holes & N-type has high concentration of electrons. The tendency for the free electron to diffuse over p-side and holes to n-side process is called **Diffusion**

- When a free electron move across the junction from n-type to p-type, positive donor ions are removed by the force of electrons. Hence positive charge is built on the n-side of the junction. Similarly negative charge establish on p-side of the junction.
- When sufficient no of donor and accepter ions gathered at the junction, further diffusion is prevented.
- +ve charge on n-side repel holes to cross from p-side to n-side, and –ve charge on p-side repel free electrons to cross from n-type to p-type.
- Thus a barrier is set up against further movement of charge carriers i.e. hole or electrons.
- This barrier is called as **Potential Barrier/ Junction Barrier (V_0)** and is of the order 0.1 to 0.3 volt. This prevents the respective majority carriers for crossing the barrier region. This region is known as **Depletion Layer/region.**
- The term depletion is due to the fact that near the junction, the region is depleted (i.e. emptied) of charge carries (free electrons and holes) due to diffusion across the junction. It may be noted that depletion layer is formed very quickly and is very thin compared to the n region and the p-region.
- Once pn junction is formed and depletion layer created, the diffusion of free electrons further stops.
- The positive and negative charges set up an electric field as shown in fig below.



(i) (ii)

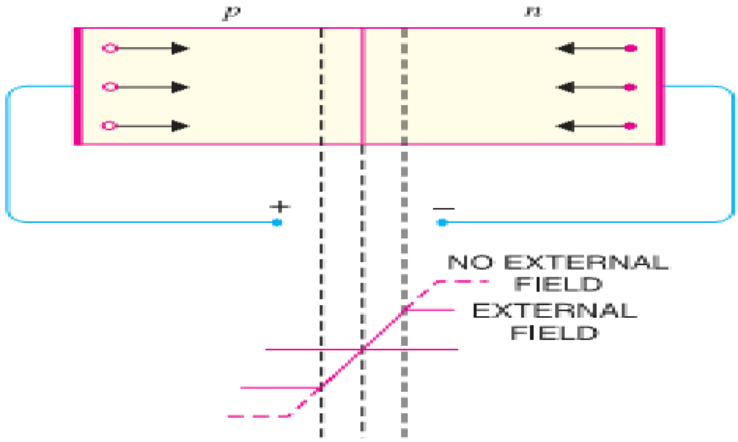
- The electric field is a barrier to the free electrons in the n-region.
- There exists a potential difference across the depletion layer and is called barrier potential

(V_0). The barrier potential of a p-n junction depends upon several factors including the type of semiconductor material, the amount of doping and temperature.

- The typical barrier potential is approximately: - For Si V_0 = 0.7 V, For Ge, V_0 = 0.3V.

❖ PN JUNCTION UNDER FORWARD BIASING

- ***When external D.C. voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow, it is called Forward Biasing***.



- To apply forward bias, connect positive terminal of the battery to p-type and negative terminal to n-type as shown in fig above.
- The applied forward potential establishes an electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction.
- As potential barrier voltage is very small (0.1 to 0.3 V), therefore, a small forward voltage is sufficient to completely eliminate the barrier.
- Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero.

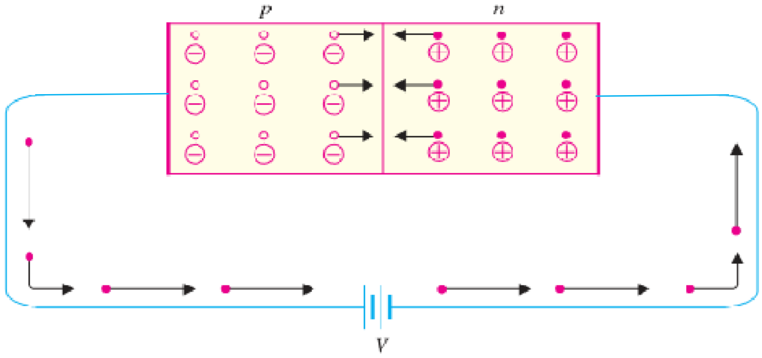
(i) The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated altogether.

(ii) The junction offers low resistance (forward resistance, R_f) to current flow.

(iii) The magnitude of current depends upon the applied forward voltage.

❖ CURRENT FLOW IN A FORWARD BIASED PN JUNCTION:-

- It is concluded that in n-type region, current is carried by free electrons whereas in p-type region, it is carried by holes. However, in the external connecting wires, the current is carried by free electrons.

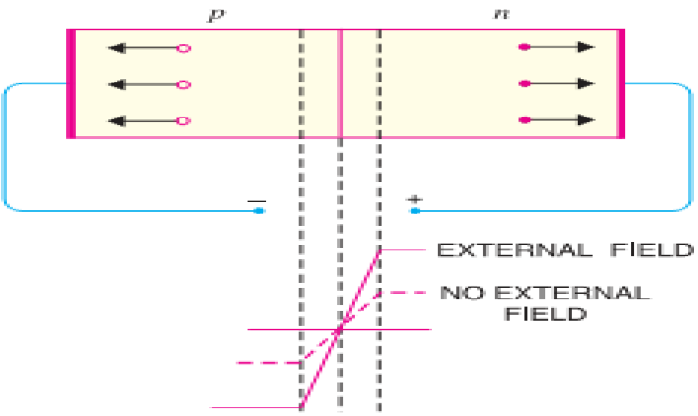


❖ PN JUNCTION UNDER REVERSE BIASING

- ***When the external D.C. voltage applied to the junction is in such a direction that***

potential barrier is increased, it is called Reverse Biasing.

To apply reverse bias, connect negative terminal of the battery to p-type and positive terminal to n-type.



- With reverse bias to PN junction, the following points are worth noting:
  (i) The potential barrier is increased.
  (ii) The junction offers very high resistance (Reverse Resistance R_r) to current flow.
  (iii) No current flows in the circuit due to the establishment of high resistance path.

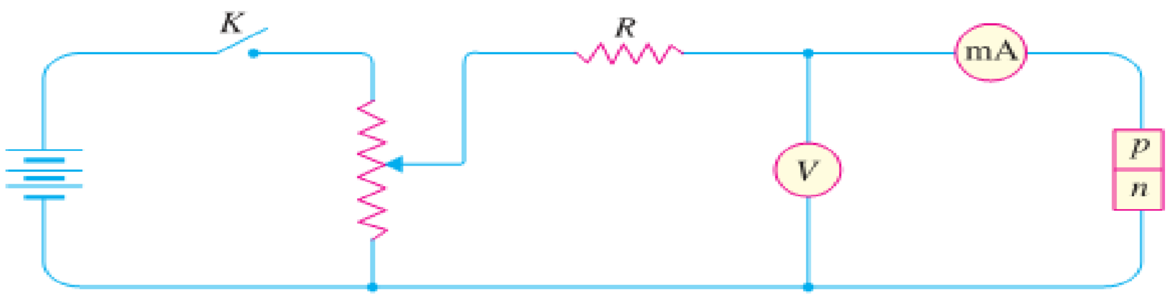
ARTICLE 1.3: VOLT-AMPERE CHARACTERISTICS OF PN JUNCTION

- Volt-ampere or V-I characteristic of a pn junction (also called a crystal or semiconductor diode) is the curve between voltage across the junction and the circuit current.
- Usually, voltage is taken along x-axis and current along y-axis. Fig. shows the circuit arrangement for determining the V-I characteristics of a pn junction.
- The characteristics can be studied under three heads namely:
  1) Zero external voltage
  2) Forward Bias
  3) Reverse Bias.

❖ ZERO EXTERNAL VOLTAGE: -

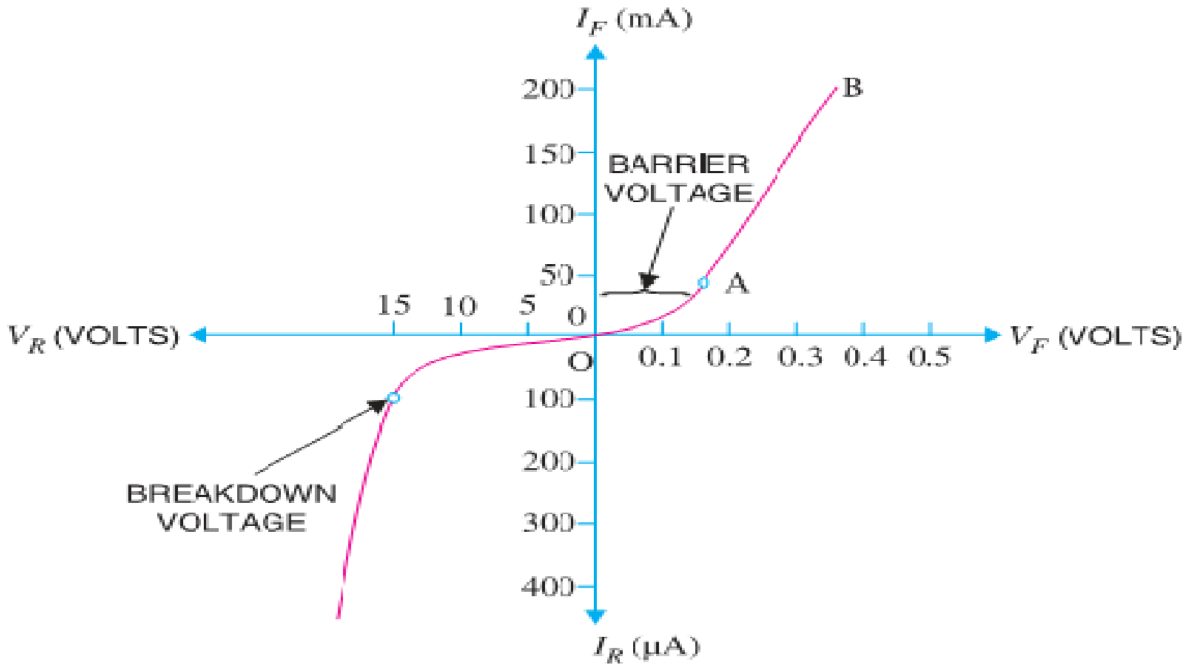
- When the external voltage is zero, i.e. circuit is open at K; the potential barrier at the junction does not permit current flow.

Therefore, the circuit current is zero as indicated by point O in Fig.



(II) FORWARD BIAS: -

- In this case p-type connected to positive terminal and n-type connected to negative terminal, the potential barrier is reduced.
- At some forward voltage (0.7 V for Si and 0.3 V for Ge), the potential barrier is altogether eliminated and current starts flowing in the circuit.
- From now onwards, the current increases with the increase in forward voltage.
- Thus, a rising curve OB is obtained with forward bias as shown in Fig. From the forward characteristic, it is seen that at first (region OA), the current increases very slowly and the curve is non-linear.
- It is because the external applied voltage is used up in overcoming the potential barrier.
- However, once the external voltage exceeds the potential barrier voltage, the pn junction behaves like an ordinary conductor.
- Therefore, the current rises very sharply with increase in external voltage (region AB on the curve). Here the curve is almost linear.



(III) REVERSE BIAS:-

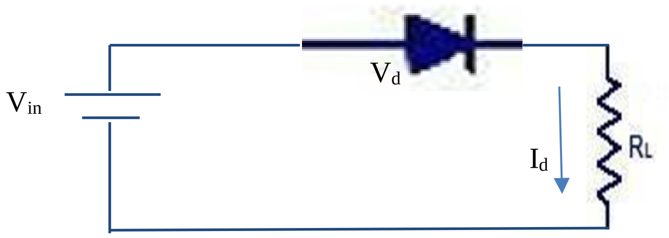
- In this case, p-type connected to negative terminal and n-type connected to positive terminal, potential barrier at the junction is increased.
- Therefore, the junction resistance becomes very high and practically no current flows through the circuit.
- However, in practice, a very small current (of the order of μA) flows in the circuit with reverse bias as shown in the reverse characteristic.
- This is called Reverse Saturation Current (I_s) and it is due to minority carriers.
- These undesirable free electrons in p-type and holes in n-type are called minority carriers. Therefore, a small current flows in the reverse direction
- If reverse voltage is increased continuously, the kinetic energy of electrons may become high enough to knock out electrons from the semiconductor atoms.
- At this stage breakdown of the junction occurs, characterized by a sudden rise of reverse current and a sudden fall of the resistance of barrier region. This may destroy the junction permanently.
- **Note:** -The forward current through a p-n junction is due to the majority carriers produced

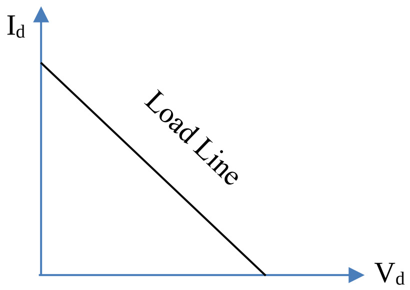
by the impurity.

- However, reverse current is due to the minority carriers produced due to breaking of some covalent bonds at room temperature.

ARTICLE 1.4: DC LOAD LINE

- The line obtained by joining the maximum values of I_d and V_d in the output characteristics of a diode circuit is known as the DC Load Line. In this case V_d is drawn on X-axis and I_d is drawn along Y-axis





Applying KVL law, we know that Vin = $V_d + I_d * R_l$

Hence, $I_d * R_l = - V_d + Vin$

Hence, $I_d = - (V_d) * (-1/ R_l) + Vin / R_l$ (Y = mX + C)

ARTICLE 1.5
IMPORTANT TERMS i.e. IDEAL DIODE AND KNEE VOLTAGE

(i) **IDEAL DIODE: -** In case of ideal diode, the junction acts as a short circuit. Hence, the forward resistance is 0 and reverse resistance is infinite. Similarly barrier voltage (Vb) is negligible / 0.

(ii) **BREAKDOWN VOLTAGE**: **-** It is the minimum reverse voltage at which pn junction breaks down with sudden rise in reverse current.

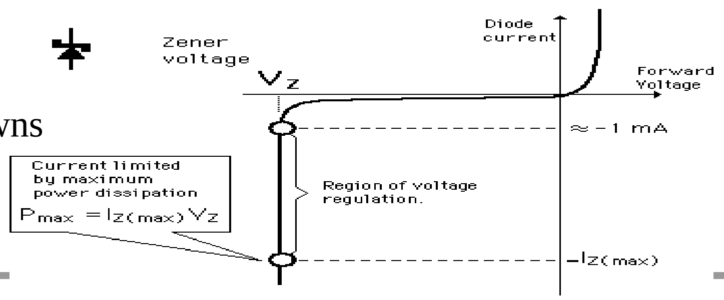
(iii) **KNEE VOLTAGE**: **-** It is the forward voltage at which the current through the junction starts to increase rapidly.

(iv) **PEAK INVERSE VOLTAGE (PIV)**:**-** It is the maximum reverse voltage that can be applied to the pn junction without damage to the junction. If the reverse voltage across the junction exceeds its PIV, the junction may be destroyed due to excessive heat.

ARTICLE 1.6
JUNCTION BREAKDOWN

- There are two types of junction breakdowns

1. Zener breakdown
2. Avalanche breakdown



1. **ZENER BREAKDOWN:-**

- A properly doped crystal diode which has a sharp breakdown voltage is known as a **Zener Diode**.

- The breakdown voltage is sometimes called Zener Voltage as it was invented by American scientist C. Zener and the sudden increase in current is known as Zener Current. The breakdown or Zener voltage depends upon the amount of doping. If the **diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage**.
- On the other hand, a lightly doped diode has a higher breakdown voltage. Fig. shows the symbol of a Zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into z-shape.

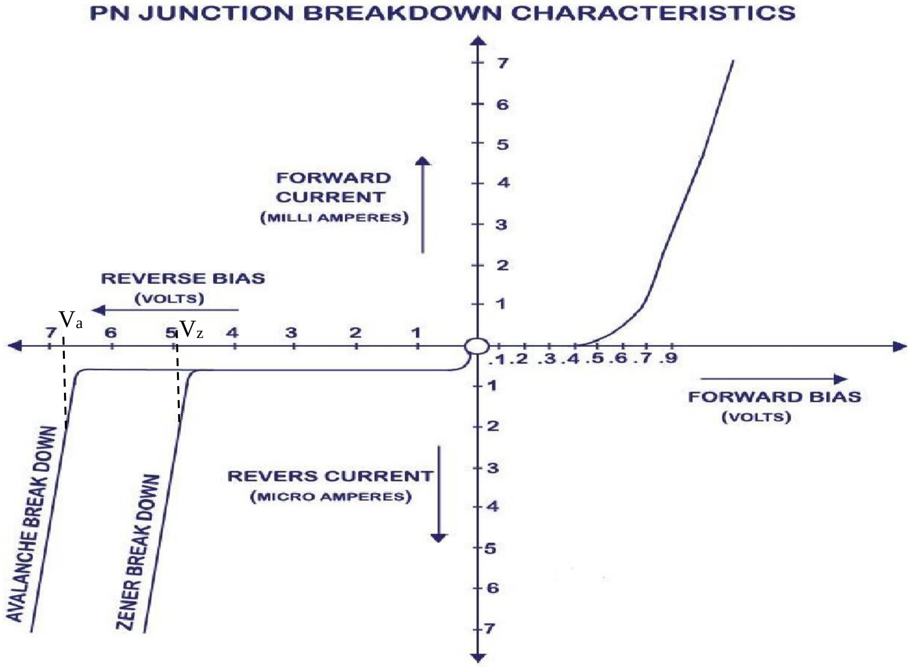
WORKING/OPERATION OF ZENER BREAKDOWN:-

- When the reverse voltage across the pn junction diode increases, the electric field across the diode junction increases.
- This results in a force of attraction on the negatively charged electrons at junction.
- This force frees electrons from its covalent bond and moves those free electrons to conduction band. When the electric field increases (with applied voltage), more and more electrons are freed from its covalent bonds.
- This results in drifting of electrons across the junction and electron hole recombination occurs. So a net current is developed and it increases rapidly with increase in electric field. Zener breakdown phenomena occurs in a pn junction diode with heavy doping & thin junction.
- Zener breakdown does not result in damage of diode since current is only due to drifting of electrons, there is a limit to the increase in current as well.

2. **AVALANCHE BREAKDOWN:-**

- Avalanche breakdown occurs in a p-n junction diode which is moderately doped and has a thick junction.
- Avalanche breakdown usually occurs when we apply a high reverse voltage across the diode (obviously higher than the zener breakdown voltage, say V_z).
- By increasing the applied reverse voltage, the electric field across junction will keep increasing. If applied reverse voltage is V_a and the depletion layer width is d, then the generated electric field can be calculated as $E_a = - V_a/d$.
- This generated electric field exerts a force on the electrons at junction and it frees them from covalent bonds. These free electrons will gain acceleration and it will start moving across the junction with high velocity.
- This results in collision with other neighboring atoms. These collisions in high velocity will generate further free electrons. These electrons will start drifting and electron-hole

pair recombination occurs across the junction. This results in net current which rapidly increases.

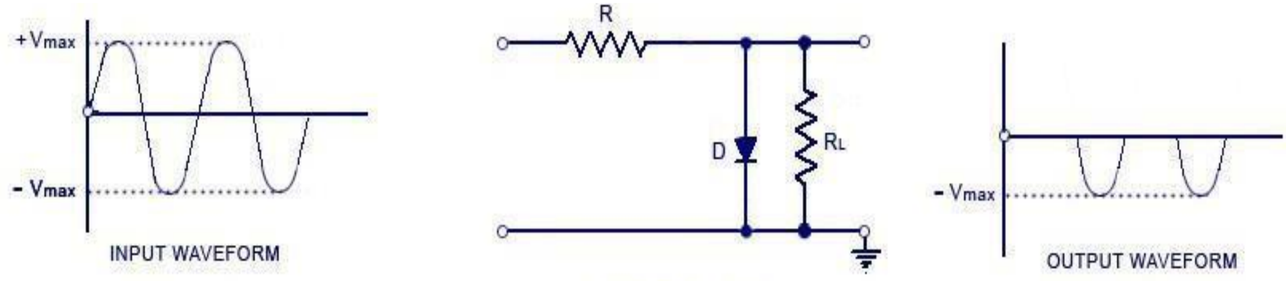


- From the above fig we can see that avalanche breakdown occurs at a voltage (V_a) which is higher than zener breakdown voltage (V_z).
- It is because avalanche phenomena occurs in a diode which is moderately doped and junction width (say d) is high where as zener break down occurs in a diode with heavy doping and thin junction (here d is small).
- In avalanche breakdown, the depletion layer width is higher and hence much more reverse voltage has to be applied to develop the same electric field strength

ARTICLE 1.7

P-N DIODE CLIPPING CIRCUITS

- The circuit with which the waveform is shaped by removing (or clipping) a portion of the applied wave is known as a clipping circuit.
- These clippers can remove signal voltages above or below a specified level.
- The important diode clippers are:-
    1. Positive clipper and negative clipper
    2. Biased positive clipper and biased negative clipper
    3. Combination clipper.
- **POSITIVE CLIPPER**
- A positive clipper is that which removes the positive half-cycles of the input voltage.
- The positive clipper is of two types
    1. Positive series clipper
    2. Positive shunt clipper
- The below Fig. shows the typical circuit of a positive shunt clipper using a diode.



Positive Shunt Clipper

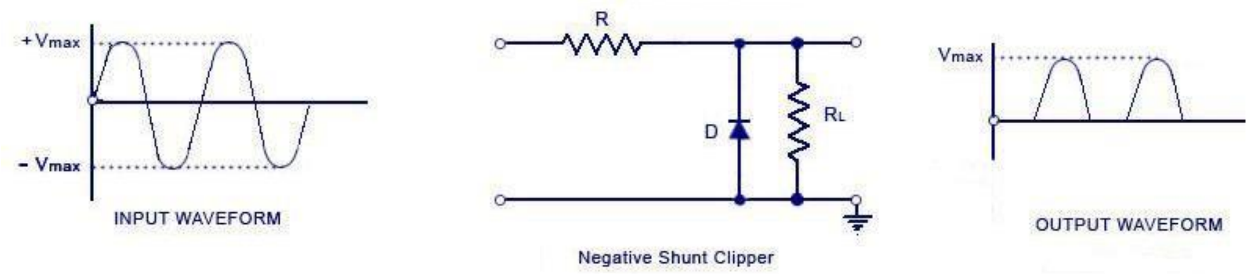
- Here the diode is kept in parallel with the load.
- During the positive half cycle, the diode 'D' is forward biased and the diode acts as a closed switch. This causes the diode to conduct heavily.
- Thus output voltage during the positive half cycles is zero. (Vo = 0)
- During the negative half cycles of the input signal voltage, the diode D is reverse biased and behaves as an open switch. Consequently the entire input voltage appears across the diode or across the load resistance R_L if R is much smaller than R_L (Vo = Vin)
- Actually the circuit behaves as a voltage divider with an output voltage of $-[R_L / R + R_L] V_{max} \cong -V_{max}$ (Taking or assuming when $R_L >> R$).

➢ NEGATIVE CLIPPER

➢ A negative clipper is that which removes the positive half-cycles of the input voltage. The negative clipper is of two types

1. Negative series clipper
2. Negative shunt clipper

➢ The below Fig. shows the typical circuit of a negative shunt clipper using a diode.



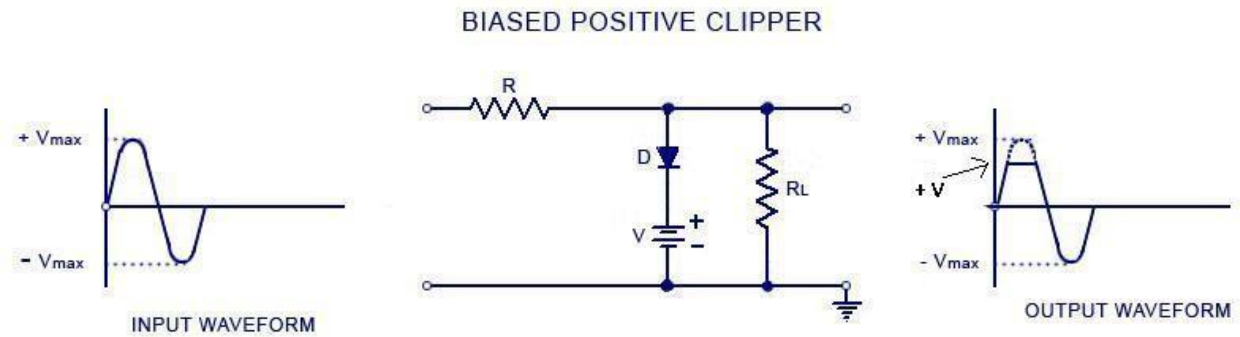
➢ During the negative half cycle, the diode 'D' is forward biased and the diode acts as a closed switch. This causes the diode to conduct heavily.

➢ Thus output voltage during the negative half cycles is zero. (Vo = 0)

➢ During the positive half cycles of the input signal voltage, the diode D is reverse biased and behaves as an open switch. Consequently the entire input voltage appears across the diode or across the load resistance R_L if R is much smaller than R_L (Vo = Vin)

➢ BIASED POSITIVE CLIPPER

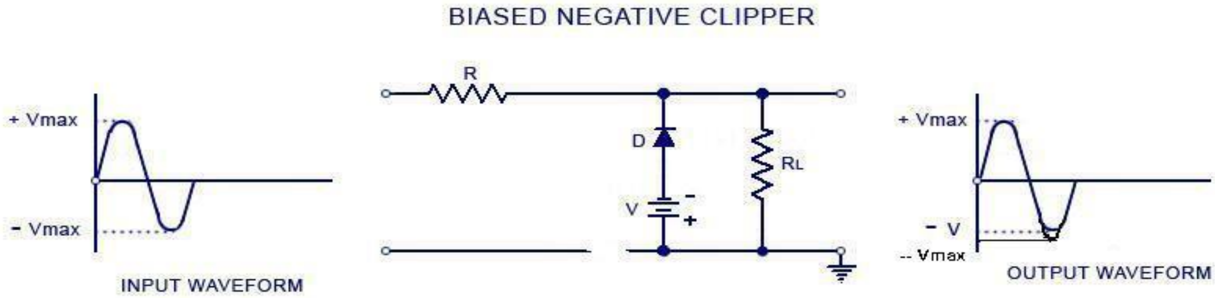
➢ When a small portion of the positive half cycle is to be removed, it is called a biased positive clipper. The circuit diagram and waveform is shown in the figure below.



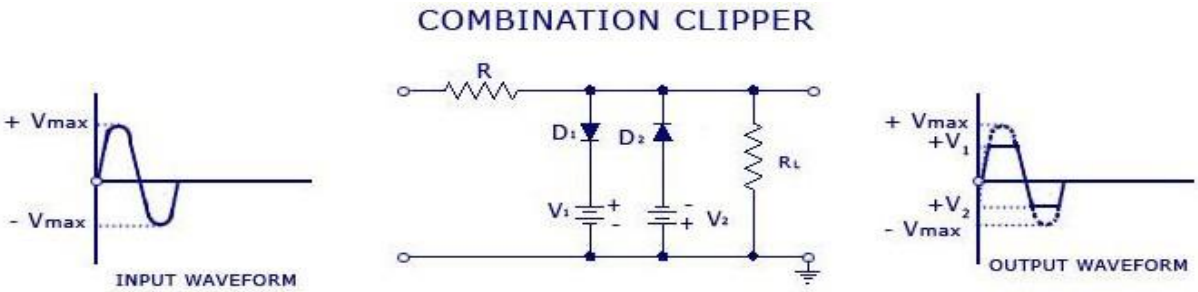
➢ During negative half cycle, the diode 'D' is reverse-biased. This causes it to act as an open-switch. Thus the entire negative half cycle appears across the load, as illustrated by output waveform. (Vo = Vin)

➢ During positive half cycle, when the input signal voltage is positive but does not exceed battery the voltage 'V', the diode 'D' remains reverse-biased and most of the input voltage appears across the output. (Vo = V)

- When during the positive half cycle of input signal, the signal voltage becomes more than the battery voltage V, the diode D is forward biased and so conducts heavily. The output voltage is equal to '+ V' and stays at '+ V' as long as the magnitude of the input signal voltage is greater than the magnitude of the battery voltage, 'V'.
- Thus a biased positive clipper removes input voltage when the input signal voltage becomes greater than the battery voltage.
- **BIASED NEGATIVE CLIPPER**
- When a small portion of the negative half cycle is to be removed, it is called a biased negative clipper. The circuit diagram and waveform is shown in the figure below.



- During positive half cycle, when the input signal voltage is positive, the diode 'D' is reverse-biased. This causes it to act as an open-switch. Thus the entire positive half cycle appears across the load, as illustrated by output waveform.
- During negative half cycle, when the input signal voltage is negative but does not exceed battery the voltage 'V', the diode 'D' remains reverse-biased and most of the input voltage appears across the output.
- When during the negative half cycle of input signal, the signal voltage becomes more than the battery voltage V, the diode D is forward biased and so conducts heavily. The output voltage is equal to '-V' and stays at '-V' as long as the magnitude of the input signal voltage is greater than the magnitude of the battery voltage, 'V'.
- Thus a biased negative clipper removes input voltage when the input signal voltage becomes greater than the battery voltage.
- **COMBINATION CLIPPER:-**
- Combination clipper is employed when a portion of both positive and negative of each half cycle of the input voltage is to be clipped (or removed) using a biased positive and negative clipper together. The circuit for such a clipper is given in the figure below.



- For positive input voltage signal when input voltage exceeds battery voltage $+V_1$ diode D_1 conducts heavily while diode D_2 is reversed biased and so voltage $+V_1$ appears across the output. This output voltage $+V_1$ stays as long as input signal voltage exceeds $+V_1$.
- On the other hand for the negative input voltage signal, the diode D_1 remains reverse biased and diode D_2 conducts heavily only when input voltage exceeds battery voltage V_2 in magnitude.
- Thus during the negative half cycle the output stays at $-V_2$ so long as the input signal voltage is greater than $-V_2$.
- **APPLICATIONS OF CLIPPER:-**

(i) **CHANGING THE SHAPE OF WAVEFORM: -** Clippers can alter the shape of a waveform. For example, a clipper can be used to convert a sine wave into a rectangular wave, square wave etc. They can limit either the negative or positive alternation or both alternations of an a.c. voltage.

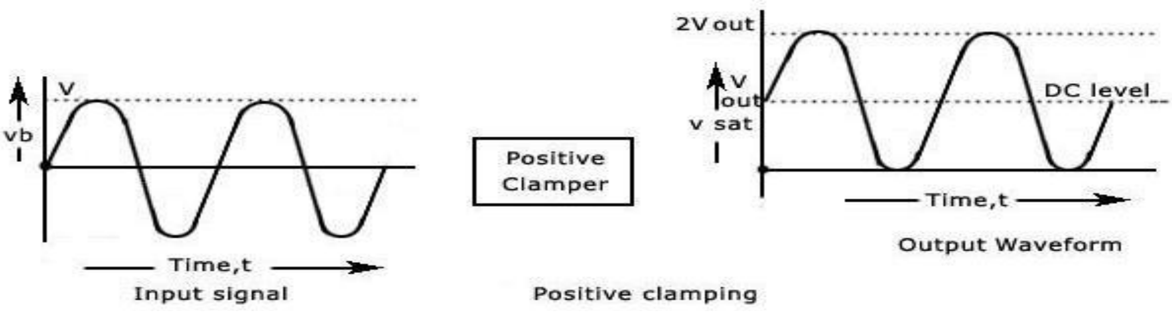
(ii) **CIRCUIT TRANSIENT PROTECTION:-** Transients can cause considerable damage to many types of circuits e.g., a digital circuit. In that case, a clipper diode can be used to prevent the transient form reaching that circuit.

(iii) Clippers find extensive use in radar, digital and other electronic systems.

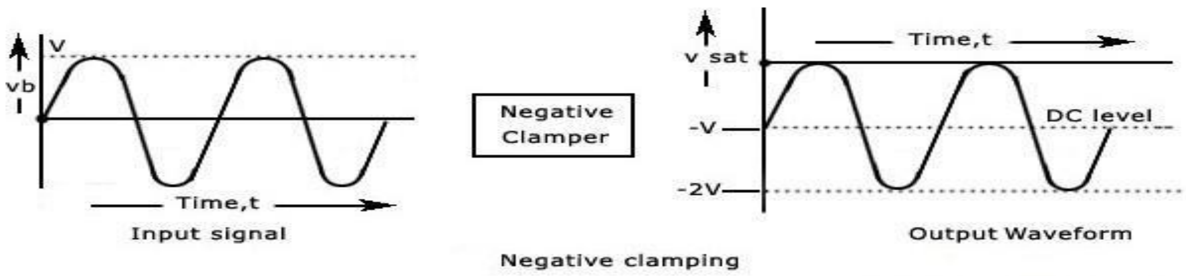
ARTICLE 1.8

P-N DIODE CLAMPING CIRCUITS

- A clamping circuit is used to place either the positive or negative peak of a signal at a desired level. The dc component is simply added or subtracted to/from the input signal.
- The clamper is also referred to as an IC restorer and ac signal level shifter.
- The clamper is of two types :-
  1. Positive clamper
  2. Negative clamper
- The circuit will be called a positive clamper, when the signal is pushed upward side by the circuit and the negative peak of the signal coincides with the zero level.



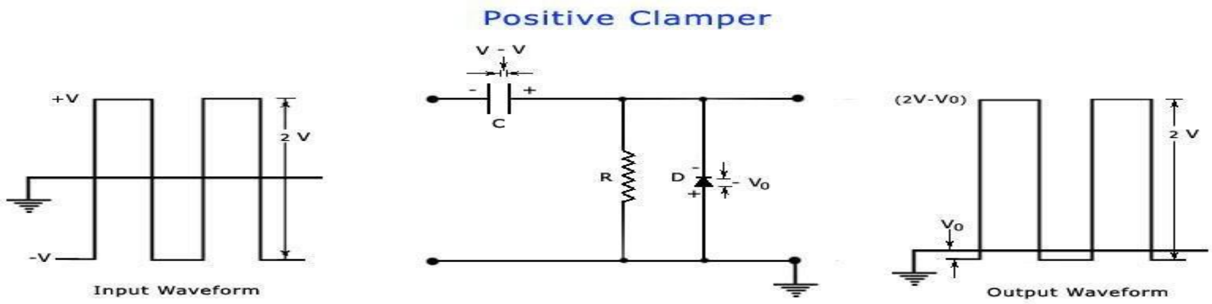
- The circuit will be called a negative clamper, when the signal is pushed downward by the circuit and the positive peak of the input signal coincides with the zero level.



1. In this circuit, a diode, a capacitor and a resistor are required.
2. The shape of the waveform will be the same, but its level is shifted either upward or downward,
3. There will be a change in the peak and average values of the waveform. In the figure shown above, the input waveform has a peak value of V_{max} and average value over a complete cycle is zero. The clamped output varies from 2 V_{max} and 0 (or 0 and $-2V_{max}$). Thus the peak value of the clamped output is $2V_{max}$ and average value is V_{max}.
4. The values of the resistor R and capacitor C affect the waveform.
5. The values for the resistor R and capacitor C should be determined from the time constant equation of the circuit, t = RC. The values must be large enough to make sure that the voltage across capacitor C does not change significantly during the time interval the diode is non-conducting. In a good clamper circuit, the circuit time constant t = RC should be at least ten times the time period of the input signal voltage.

❖ **POSITIVE CLAMPER:-**

➢ The circuit that shifts the original signal in a vertical upward direction.



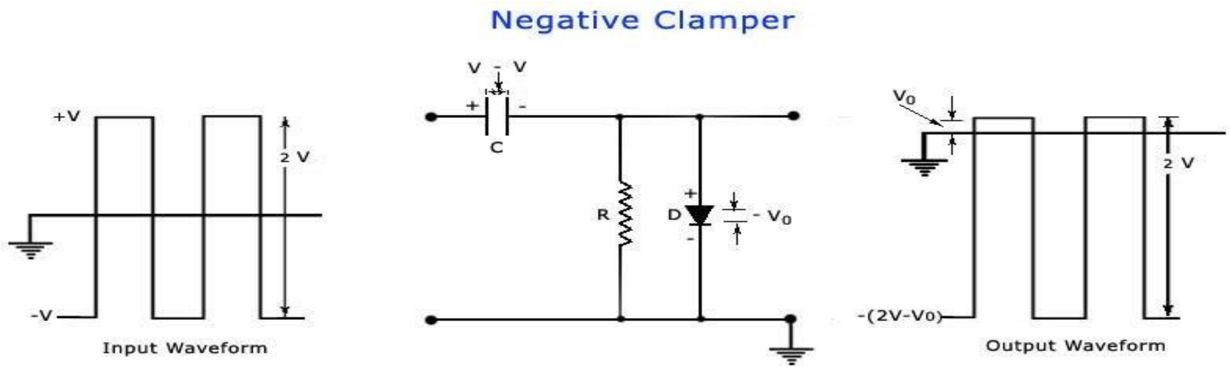
➢ During the negative half cycle of the input signal, the diode D will be forward biased and the capacitor C is charged with the polarity shown.

➢ The output voltage will be equal to 0 volt for an ideal diode, and capacitor is charged to input voltage (Vc = Vin).

- During the positive half cycle, the diode becomes reverse-biased and acts as an open- circuit. Thus, there will be no effect on the capacitor voltage.
- The resistance R, being of very high value, cannot discharge C a lot during the positive portion of the input waveform.
- Thus during positive input, the output voltage will be the sum of the input voltage and capacitor voltage ($V_o = V_{in} + V_c = V_{in} + V_{in} = 2\ V_{in}$
- The value of the peak-to-peak output will be the difference of the negative and positive peak voltage levels is equal to $V_o = 2\ V_{in} – 0 = 2\ V_{in}$

❖ NEGATIVE CLAMPER:-

- The circuit that shifts the original signal in a vertical downward direction.
- During the positive half cycle of input signal, the diode D will be forward biased and the capacitor C is charged with the polarity shown.
- The output voltage will be equal to 0 volt and capacitor is charged to $V_c = V_{in}$
- During the negative half cycle, the diode becomes reverse-biased and acts as an open- circuit. Thus, there will be no effect on the capacitor voltage.



- The resistance R, being of very high value, cannot discharge C a lot during the negative portion of the input waveform.
- Thus during negative input, the output voltage will be the sum of the input voltage and capacitor voltage. $V_o = -V_c – V_{in} = -2\ V_{in}$
- The value of the peak-to-peak output will be the difference of the negative and positive peak voltage levels is equal to $V_0 = -2\ V_{in}$

❖ APPLICATIONS OF CLAMPER:-

➢ Clamping circuits are often used in television receivers as dc restorers in the TV receiver They also find applications in storage counters, analog frequency meter, capacitance meter, divider and stair-case waveform generator.

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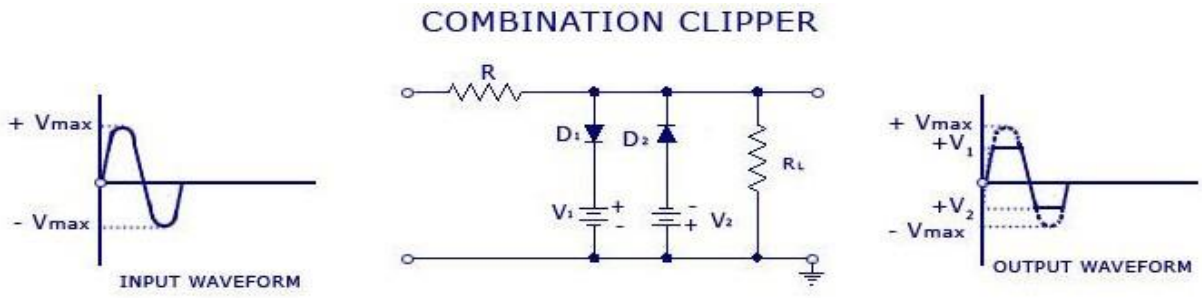
Practice Questions

Probable short questions with answers

1. What is P-N junction diode ?
2. What is knee voltage (W2010, 2014, 2018, 2019)
   Ans: *The voltage at whice the diode starts conducting is called knee voltage*
3. What do you mean by ideal diode (W2017)
   Ans: *An ideal diode conducts when forward biased and remains off when reverse biased. It is a theoretical concept of a practical diode*
4. What is clamper circuit
5. What is clipper circuit
6. Write any two (2) difference between avalanche and zener breakdown (W2011, 2014, 2015, 2018)
   Ans: *Avalanche breakdown is a phenomenon that that can occur in both insulating and semi-conducting materials*
   Zener breakdown occurs in heavily doped PN junction
7. Draw the circuit diagram of combinational clipper (W2018)
   Ans:



Probable long question

1. Write down short notes on
   a) Avalanche breakdown
   b) Zener breakdown
2. Explain the working principle of P-N junction diode
3. State and explain V-I characteristics of P-N junction diode
4. Explain the P-N diode clipping and clamping circuit with diagram (W2016, 2017)
5. Briefly explain the PN junction in forward bias mode with neat diagram (W2015,2018,2019)

CHAPTER - 2

------------------ [SPECIAL SEMICONDUCTOR DEVICES] ---------------------

LEARNING OBJECTIVE

2 . 1 Thermistors, Sensors & barretters
2 . 2 Zener Diode
2 . 3 Tunnel Diode
2 . 4 PIN Diode

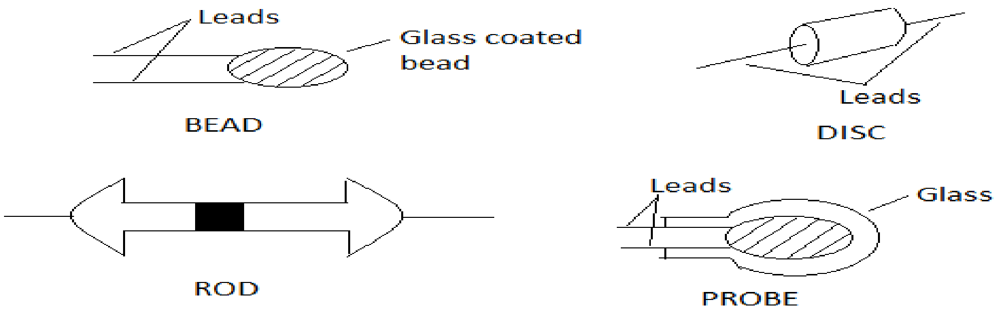
ARTICLE 2.1:
THERMISTOR, SENSOR AND BARRATERS

❖ THERMISTOR

- Thermistor is the contraction of the term Thermal Resistor.
- It is generally composed of semiconductor materials. Most thermistors have a negative coefficient of temperature that is their resistance decreases with the increases of temperature.
- This high sensitivity to temperature changes makes thermistors extremely useful for precision temperature measurement, control and compensation.
- The temperature measurement of thermistor ranges from -60 0C to 150 0C and the resistance of thermistor ranges from 0.5Ω to 0.75MΩ. It exhibits highly non-linear characteristics of resistance versus temperature.

❖ CONSTRUCTION

- These thermistors are composed of sintered mixture of metallic oxides such as Manganese, Nickel, Cobalt, Copper, Iron and Uranium.
- These may be in the form of beads or rods or discs or probes.



[Different Types Of Thermistors]

❖ APPLICATIONS

- It is used for measurement and control of temperature and for temperature compensation.
- It is used for measurement of power at high frequency. It is also used for thermal conductivity.
- Thermistor is used for measurement of level, flow and pressure of liquid, composition of

gases and vaccum measurement. It is used for providing time delay.

❖ BARRETERS

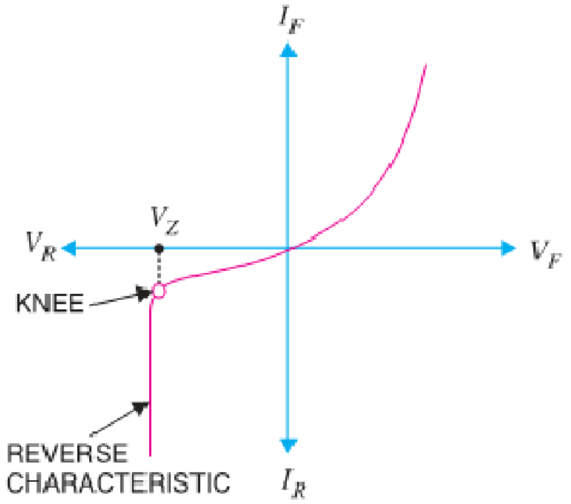
- Barreters are the short length wires with fine diameters with operating range around 1,500C.

❖ SENSORS

- A **sensor** is a device that detects events or changes in quantities and provides a corresponding output, generally as an electrical or optical signal; for example, a thermocouple converts temperature to an output voltage.
- Sensors are used in everyday objects such as touch-sensitive elevator buttons and lamps which dim or brighten by touching the base, besides innumerable applications of which most people are never aware.
- A sensor's sensitivity indicates how much the sensor's output changes when the input quantity being measured changes.
- For instance, if the mercury in a thermometer moves 1 cm when the temperature changes by 1° C, the sensitivity is 1 cm/°C .

ARTICLE 2.2:
ZENER DIODE

- A properly doped crystal diode which has a sharp breakdown voltage is known as a **Zener Diode**.
- It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called **Breakdown Voltage** is reached where the reverse current increases sharply to a high value.
- The breakdown region is the knee of the reverse characteristic as shown in Fig.



- The breakdown voltage is sometimes called **Zener Voltage** and the sudden increase in current is known as **Zener Current**.
- In this case, the diode is heavily doped, depletion layer is very thin and consequently the

breakdown of the junction occurs at a lower reverse voltage.

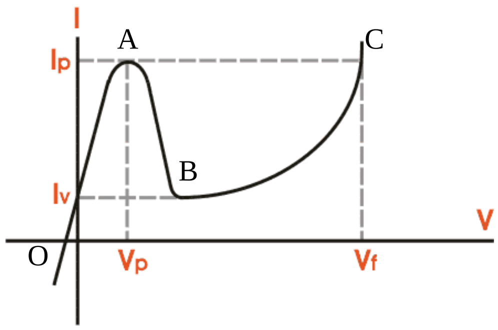
The following points may be noted about the Zener diode:

1. A Zener diode is like an ordinary diode except that it is properly doped to have a sharp breakdown voltage.
2. A Zener diode is always reverse connected i.e. it is always reverse biased.
3. A Zener diode has sharp breakdown voltage, called Zener voltage V_Z.
4. When forward biased, its characteristics are just those of ordinary diode.
5. The Zener diode is not immediately burnt just because it has entered the breakdown region.

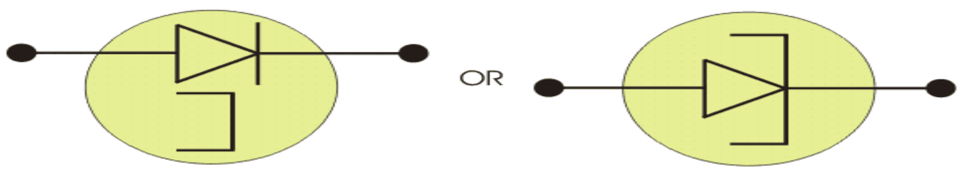
- As long as the external circuit connected to the diode limits the diode current to less than burn out value, the diode will not burn out.
- Zener diode operated in this region will have a relatively constant voltage across it, regardless of the value of current through the device. This permits the Zener diode to be used as a **Voltage Regulator.**

ARTICLE 2.3:
TUNNEL DIODE

- In this case, the junction is very thin. P and N type materials are heavily doped
- Under normal forward bias operation, as voltage begins to increase (from O to A), electrons at first tunnel through the very narrow p–n junction barrier because filled electron states in the conduction band on the n-side become aligned with empty valence band hole states on the p-side of the p-n junction.
- As voltage increases further (A to B) these states become more misaligned and the current drops – this is called *negative resistance* because current decreases with increasing voltage.
- As voltage increases yet further (B to C), the diode begins to operate as a normal diode, where electrons travel by conduction across the p–n junction, and no longer by tunneling through the p–n junction barrier.
- The most important operating region for a tunnel diode is the negative resistance region.
- When used in the reverse direction, tunnel diodes are called **back diodes** (or **backward diodes**).
- Under reverse bias, filled states on the p-side become increasingly aligned with empty states on the n-side and electrons now tunnel through the pn junction barrier in reverse direction.
- In the tunnel diode, the dopant concentrations in the p and n layers are increased to the point where the **reverse breakdown voltage** becomes **zero** and the diode conducts in the reverse direction.
- In the current voltage characteristics of **tunnel diode**, we can find a negative slope region (A - B) when forward bias is applied.

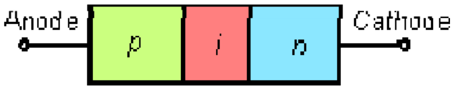


- The doping is very high so at absolute zero temperature the Fermi levels lies within the bias of the semiconductors. When no bias is applied any current flows through the junction.



ARTICLE 2.4:
PIN DIODE

- The PIN diode consists of P-type, N-type material and an intrinsic layer in between them.
- The intrinsic layer of the PIN diode is a layer without doping, and as a result this increases the size of the depletion region - the region between the P and N layers where there are no majority carriers. This change in the structure gives the PIN diode its unique properties.



Basic PIN diode structure

- The PIN diode operates in exactly the same way as a normal diode.
- The only real difference is that the depletion region, that normally exists between the P and N regions in an unbiased or reverse biased diode is larger.
- The region between the P and N regions contains no charge carriers as any holes or electrons combine As the depletion region has no charge carriers it acts as an insulator.
- Within a PIN diode the depletion region exists, but if the diode is forward biased, the carriers enter the depletion region (including the intrinsic region) and as the two carrier types meet, current starts to flow.
- When the diode is forward biased, the carrier concentration, i.e. holes and electrons is very much higher than the intrinsic level carrier concentration.
- Due to this high level injection level, the electric field extends deeply (almost the entire length) into the region.

❖ PIN DIODE USES AND ADVANTAGES

1. **HIGH VOLTAGE RECTIFIER:** The PIN diode can be used as a high voltage rectifier. The intrinsic region provides a greater separation between the PN and N regions, allowing higher reverse voltages to be tolerated.
2. **RF SWITCH:** The PIN diode makes an ideal RF switch. The intrinsic layer between the P and N regions increases the distance between them. This also decreases the capacitance between them, thereby increasing he level of isolation when the diode is reverse biased.
3. **PHOTODETECTOR:** As the conversion of light into current takes place within the depletion region of a photdiode, increasing the depletion region by adding the intrinsic layer improves the performance by increasing he volume in which light conversion occurs.

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PRACTICE QUESTIONS

Probable short questions with answers

1. What is thermistor (W2014, 2018)
   Ans: *The word thermistor is an acronym for thermal register. It is a temperature sensitive register and can be used to detect very small changes in temperature*
2. What is Sensor?

3. Write down application of Pin diode.

Ans: Pin diode is used as:

- ***HIGH VOLTAGE RECTIFIER:*** *The PIN diode can be used as a high voltage rectifier. The intrinsic region provides a greater separation between the PN and N regions, allowing higher reverse voltages to be tolerated.*

- ***RF SWITCH:*** *The PIN diode makes an ideal RF switch. The intrinsic layer between the P and N regions increases the distance between them. This also decreases the capacitance between them, thereby increasing he level of isolation when the diode is reverse biased.*
- ***PHOTODETECTOR:*** *As the conversion of light into current takes place within the depletion region of a photdiode, increasing the depletion region by adding the intrinsic layer improves the performance by increasing he volume in which light conversion occurs.*

4. What is the application of zener diode? (W2019)

Ans: *Zener diode is used as a*

- *voltage regulator*
- *fixed reference voltage in transistor biasing circuit*
- *peak clippers and/or limiter in wave shaping circuit*

Probable long questions

Write a short note on:

(i) Tunnel diode (W2018)

(ii) Zener diode

CHAPTER - 3

[RECTIFIERS CIRCUITS AND FILTERS]

LEARNING OBJECTIVE

3.1 Classification of rectifiers
3.2 Analysis of half wave, full wave centre tapped and Bridge rectifiers and calculate:
3.2.1 DC output current and voltage
3.2.2 RMS output current and voltage
3.2.3 Rectifier efficiency
3.2.4 Ripple factor
3.2.5 Regulation
3.2.6 Transformer utilization factor
3.2.7 Peak inverse voltage
3.3 Filters:
3.3.1 Shunt capacitor filter
3.3.2 Choke input filter
3.3.3 π filter

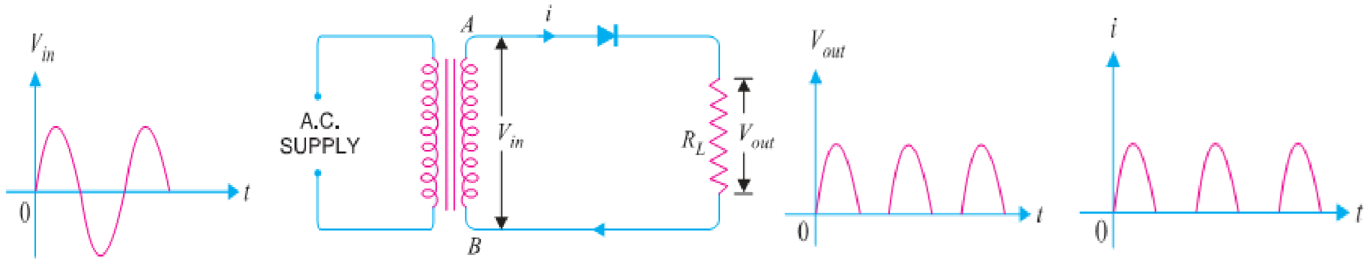
ARTICLE 3.1:
RECTIFIERS AND ITS CLASSIFICATIONS

❖ **INTRODUCTION: -**

- Rectifier is a circuit which uses one or more diodes to convert AC voltages (signal) to pulsating DC voltages (signals)
- For reasons associated with economics of generation and transmission, the electric power available is usually an A.C. Supply. The supply voltage varies sinusoidal and has a frequency of 50 Hz. It is used for lighting, heating and electric motors.
- But there are many applications (e.g. electronic circuits) where D.C. supply is needed. When such a D.C. Supply is required, the mains A.C. Supply is rectified by using *Crystal Diodes*.
- The following two rectifier circuits can be used: -
  - (i) Half-wave rectifier
  - (ii) Full-wave rectifier
    - a) Center tapped full-wave rectifier
    - b) Bridge type full-wave rectifier

ARTICLE 3.2:
ANALYSIS OF HALF-WAVE AND FULL-WAVE RECTIFIER

- **HALF-WAVE RECTIFIER:-**
- In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input A.C. Supply.
- The negative half-cycles of A.C. Supply is suppressed i.e. during negative half-cycles, no current is conducted and hence no voltage appears across the load.
  Therefore, current always flows in one direction through the load though after every half-cycle



(Input Wave form) (Half wave Rectifier Circuit) (Output voltage wave) (Output Current)

Circuit Details: -

- The above Fig shows the circuit where a single crystal diode acts as a half-wave rectifier.
- The A.C. Supply to be rectified is applied in series with the diode and load resistance R_L. Generally, A.C. Supply is given through a transformer.
- The *use of transformer* permits two advantages.
  - ✓ Firstly, it allows us to step up or step down the A.C. input voltage as the situation demands.
  - ✓ Secondly, the transformer isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

OPERATION:-

- The A.C. voltage across the secondary winding AB changes polarities after every half-cycle.
- During the positive half-cycle of input A.C. voltage, end A becomes positive w.r.t. end B. This makes the diode forward biased and hence it conducts current.
- During the negative half-cycle, end A is negative w.r.t. end B. Under this condition, the diode is reverse biased and it conducts no current.
- Therefore, current flows through the diode during positive half-cycles of input A.C. voltage only; it is blocked during the negative half-cycles. In this way, current flows through load R_L always in the same direction. Hence D.C. output is obtained across R_L.
- It may be noted that output across the load is *pulsating D.C*. These pulsations in the output are further smoothened with the help of filter circuits discussed later.

Disadvantages : -

(i) The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. Therefore, an elaborate filtering is required to produce steady direct current.

(ii) The A.C. supply delivers power only half the time. Therefore, the output is low.

❖ FULL-WAVE RECTIFIER

In full-wave rectification, current flows through the load in the same direction for both half-cycles of input A.C. voltage. This can be achieved with two diodes working alternately.

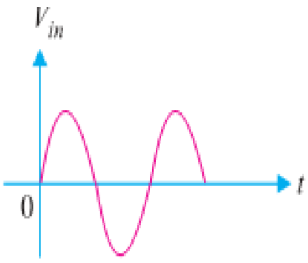
❖ CENTRE-TAP FULL-WAVE RECTIFIER:-

Circuit Details: -

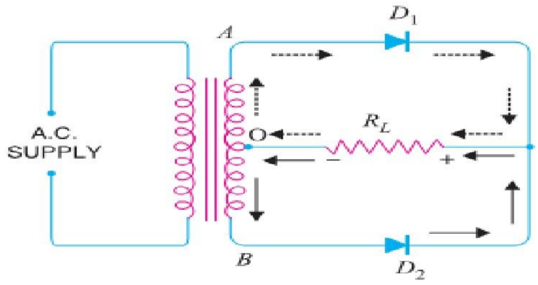
- The circuit employs two diodes D_1 and D_2 as shown in Fig below. A centre tapped secondary winding AB is used with two diodes connected so that each uses one half-cycle of input A.C. voltage.

Circuit Operation: -

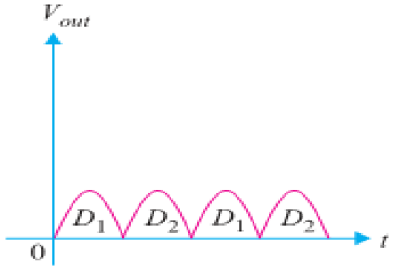
- During the positive half-cycle of secondary voltage, the end A of the secondary winding becomes positive and end B negative. This makes the diode D_1 forward biased and diode D_2 reverse biased.
- Therefore, diode D_1 conducts while diode D_2 does not. The conventional current flow is through diode D_1, load resistor R_L and the upper half of secondary winding as shown by the dotted arrows.
- During the negative half-cycle, end A of the secondary winding becomes negative and end B positive.
- Therefore, diode D_2 conducts while diode D_1 does not. The conventional current flow is through diode D_2, load R_L & lower half winding shown by solid arrows.
- It may be seen that current in the load R_L is in the same direction for both half-cycles of input A.C. voltage. Therefore, D.C. is obtained across the load R_L.



(Input Wave form)



(Centre-Tap Full-Wave Rectifier Circuit)



(Output wave form)

- **Advantages:-**

  (i) The D.C. output voltage and load current values are twice than that of a half wave rectifier.
  (ii) The ripple factor is much less (0.482) than that of half rectifier (1.21).
  (iii) The efficiency is twice (81.2%) than that of half wave rectifier (40.6%).

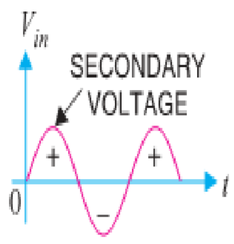
- **Disadvantages:-**

  (i) It is difficult to locate the centre tap on the secondary winding.
  (ii) The D.C. output is small as each diode utilizes only one-half of the transformer secondary voltage.
  (iii) The diodes used must have high peak inverse voltage.

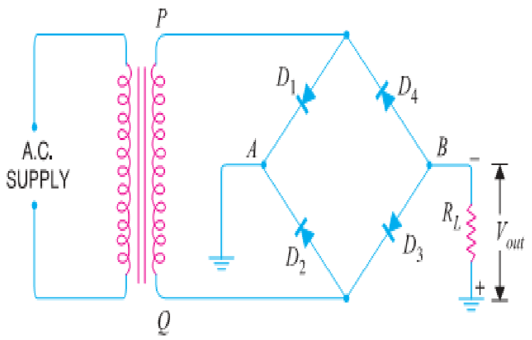
❖ FULL-WAVE BRIDGE RECTIFIER: -

Circuit Details: -

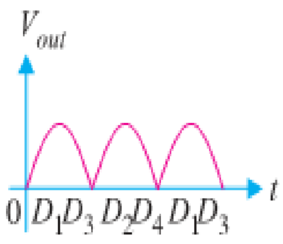
- The need for a centre tapped power transformer is eliminated in the bridge rectifier.
- It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in Fig below.
- The A.C. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer.
- Between other two ends of the bridge, the load resistance R_L is connected.



(Input Wave Form)



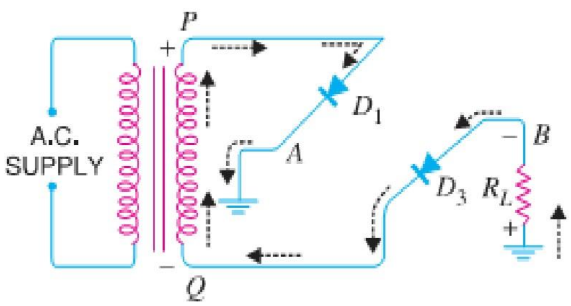
(Full-Wave Bridge Rectifier Circuit)



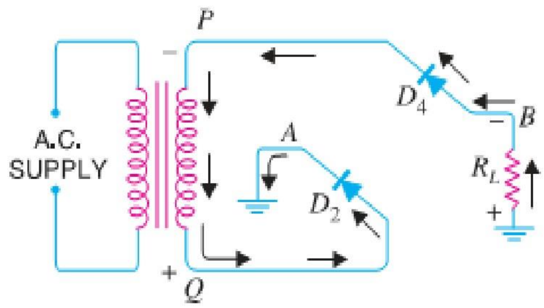
(Output wave form)

CIRCUIT OPERATION :-

- During the positive half-cycle of secondary voltage, the end P of the secondary winding becomes positive and end Q negative.
- This makes diodes D_1 and D_3 forward biased while diodes D2 and D4 are reverse biased.
- Therefore, only diodes D_1 and D_3 conduct. These two diodes will be in series through the load R_L as shown in Fig. below. The conventional current flow is shown by dotted arrows. It may be seen that current flows from A to B through the load R_L.
- During the negative half-cycle of secondary voltage, end P becomes negative and end Q positive. This makes diodes D_2 and D_4 forward biased whereas diodes D_1 and D_3 are reverse biased.
- Therefore, only diodes D_2 and D_4 conduct. These two diodes will be in series through the load R_L as shown in Fig. below. The current flow is shown by the solid arrows.
- It may be seen that again current flows from A to B through the load i.e. in the same direction as for the positive half-cycle. Hence, D.C. output is obtained across load R_L.



(Full-Wave Bridge Rectifier Circuit in +ve Half Cycle)



(Full-Wave Bridge Rectifier Circuit -ve Half Cycle)

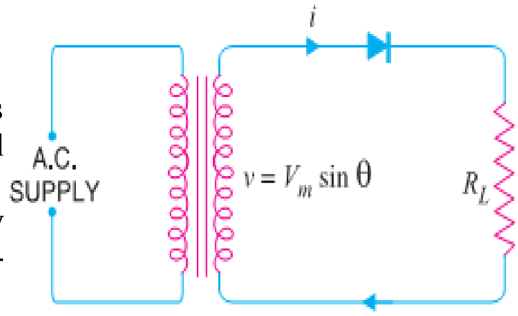
- **Advantages: -**

  (i) The need for centre-tapped transformer is eliminated.
  (ii) The output is twice that of the centre-tap circuit for the same secondary voltage.
  (iii) The PIV is one-half that of the centre-tap circuit (for same D.C. output).

- **Disadvantages: -**

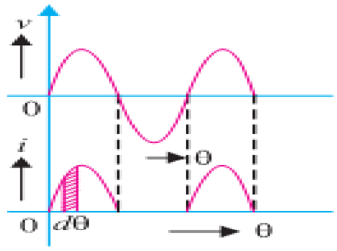
  (i) It requires four diodes. (ii) Internal resistances high.

ARTICLE 3.2.1:
OUTPUT DC CURRENT AND VOLTAGE



- Consider a half-wave rectifier shown in Fig.
- Let v = $V_m \sin\theta$ be the alternating voltage that appears across the secondary winding. Let r_f and R_L be the diode resistance and load resistance respectively.
- The diode conducts during positive half-cycles of a.c. supply while no current conduction takes place during negative half-cycles.

- The output current is pulsating direct current. Therefore, in order to find D.C. power, average current has to be found out.



$$\text{Average Value} = \frac{\text{Area Under The Curve Over a cycle}}{Base} = \int_0^{\pi} \frac{i\, d\theta}{2\pi}$$

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i\, d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{rf + R_L} d\theta = \frac{Vm}{2\pi(rf + R_L)}\int_0^{\pi} \sin\theta\, d\theta$$

$$= \frac{V_m \sin\theta}{rf + R_L}[-\cos\theta]_0^{\pi} = \frac{Vm}{2\pi(rf + R_L)} \times [(-\cos\pi) - (-\cos 0)]$$

$$= \frac{Vm}{2\pi(rf + R_L)} \times 2 = \frac{Vm}{(rf + R_L)} \times \frac{1}{\pi} = \frac{I_m}{\pi}\left[\because I_m = \frac{V_m}{(rf + R_L)}\right]$$

$$\text{D.C. Power, } \mathbf{P_{dc}} = I_{dc}^2 \times R_L = \left(\frac{I_m}{\pi}\right)^2 \times R_L$$

dc

ARTICLE 3.2.2:

R.M.S. OUTPUT CURRENT AND VOLTAGE

NOTE: - $I_{rms} = [\frac{1}{2\pi}\int_0^{2\pi} i^2\, d\square]^{½} = [\frac{1}{2\pi}\int_0^{\pi} I_m^2 sin^2\theta\, d\square + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0\, d\square]^{½} = [\frac{I_m^2}{2\pi}\int_0^{\pi}\frac{1-cos2\theta}{2}\, d\square]^{½}$

$= [\frac{I_m^2}{4\pi}[\square - \frac{sin2\square}{2}]_0^{\pi}]^{½} = [\frac{I_m^2}{4\pi}[\pi - 0 - \frac{sin2\pi}{2} + sin0]]^{½} = [\frac{I_m^2}{4\pi} \times \pi]^{½} = [\frac{I_m^2}{4}]^{½} = \frac{I_m}{2} \rightarrow \mathbf{I_{rms} = \frac{I_m}{2}}$

Similarly, $\mathbf{V_{rms} = V_m/2}$ for Half Wave and For Full Wave Rectifier $\mathbf{I_{rms} = I_m/\sqrt{2}}$ and $\mathbf{V_{rms} = V_m/\sqrt{2}}$

ARTICLE 3.2.3:

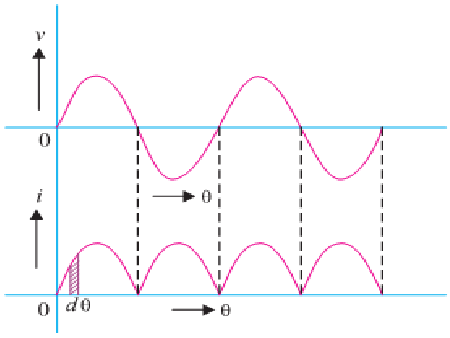
RECTIFIER EFFICIENCY

The ratio of d.c. power output to the applied input a.c. power is known as rectifier efficiency i.e

$$\text{Rectifier efficiency, } \eta = \frac{\text{d.c. power output}}{\text{Input a.c. power}}$$

$$\text{D.C. Power, } \mathbf{P_{dc} = I_{dc}^2 \times R_L = (\frac{I_m}{\pi})^2 \times R_L}$$

$$\mathbf{P_{ac} = (\frac{I_m}{2})^2 \times (r_f + R_L)}$$



- Half-wave rectification efficiency is

- The A.C. power input is given by : $P_{ac} = I_{rms}^2(r_f + R_L)$ For a half-wave rectified wave, $\mathbf{I_{rms} = I_m/2}$

  ∴ $\mathbf{P_{ac} = (\frac{I_m}{2})^2 \times (r_f + R_L)}$

  ∴ Rectifier efficiency $= \frac{\text{d.c.output power}}{\text{a.c.input power}} = (\frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2\,(r_f + R_L)}) = \frac{0.406R_L}{r_f + R_L} = \frac{\mathbf{0.406R_L}}{\mathbf{1+\frac{r_f}{R_L}}}$

  The efficiency will be maximum if r_f is negligible as compared to R_L.

  ∴ **Max. Rectifier Efficiency for HALF WAVE Rectifier = 40.6%**

- It shows that in half-wave rectification, maximum of 40.6% of a. c. power is converted into d. c. power.

- Full-wave rectification efficiency is

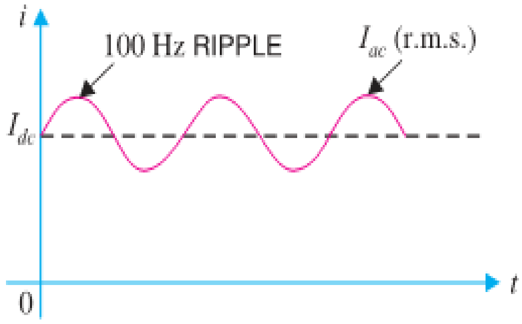
$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m/\pi)^2 R_L}{(\frac{I_m}{\sqrt{2}})^2(r_f + R_L)} = \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812\, R_L}{r_f + R_L} = \frac{\mathbf{0.8\ 12}}{\mathbf{1+\frac{r_f}{R_L}}}$$

The efficiency will be maximum if r_f is negligible as compared to R_L. ∴ Maximum efficiency = 81.2%

- This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

ARTICLE 3.2.4:
RIPPLE FACTOR: -

- The output of a rectifier consists of a d.c. component and an a.c. component (also known as ripple).
- The a.c. component is undesirable and accounts for the pulsations in the rectifier output.
- The effectiveness of a rectifier depends upon the magnitude of a.c. component in the output; the smaller this component, the more effective is the rectifier.
- Ripple mean unwanted ac signal present in the rectified output.
- The ratio of R.M.S. value of A.C. component to the D.C. component in the rectifier output is known as *ripple factor* i.e.



$$\text{Ripple factor} = \frac{\text{r.m.s. value of a.c component}}{\text{value of d.c. component}} = \frac{I_{ac}}{I_{dc}}$$

- **Mathematical Analysis**.

- The output current of a rectifier contains d.c. as well as a.c. component.
- By definition, the effective (i.e. r.m.s.) value of total load current is given by :

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2} \quad \text{Or} \quad I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

- Dividing throughout by I_{dc}, we get,

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2} \quad \text{(But } I_{ac}/I_{dc} \text{ is the ripple factor.)}$$

$$\therefore \text{Ripple factor} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

(i) **For half-wave rectification: -**

In half-wave rectification, $I_{rms} = I_m/2$; $I_{dc} = I_m/\pi$

$$\therefore \text{Ripple factor} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1} = 1.21$$

- It is clear that a.c. component exceeds the d.c. component in the output of a half-wave rectifier.
- This results in greater pulsations in the output.
- Therefore, half-wave rectifier is ineffective for conversion of a.c. into d.c.

(i) **For full-wave rectification**: -

In full-wave rectification, $I_{rms} = \frac{I_m}{\sqrt{2}}$; $I_{dc} = \frac{2I_m}{\pi}$

$$\therefore \text{Ripple factor} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2I_m/\pi}\right)^2 - 1} = 0.48 \quad \text{i.e.} \quad \frac{\text{effective a.c.component}}{\text{d.c.component}} = 0.48$$

- This shows that in the output of a full-wave rectifier, the d.c. component is more than the a.c. component. Consequently, the pulsations in the output will be less than in half-wave rectifier.
- For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

ARTICLE 3.2.5:
REGULATION

Regulation is the measure of how well a power transformer can maintain constant secondary voltage given a constant primary voltage and wide variance in load current. The lower the percentage, the more stable the secondary voltage and the better the regulation

ARTICLE 3.2.6:
TRANSFORMER UTILIZED FACTOR

- It may be defined as the ratio of d.c. power delivered to the load and the a.c. rating of the transformer secondary.

Thus, **$TUF = P_{dc} / P_{ac}$**

- For half wave rectifier, TUF = **0.287**; Center taped rectifier, TUF = **0.693**; Bridge rectifier, TUF **= 0.812**.
- The TUF is very useful in determining the rating of a transformer to be used with rectifier circuit.

ARTICLE 3.2.7:
PEAK INVERSE FACTOR (PIF)

- The maximum value of reverse voltage occurs at the peak of the input cycle, which is equal to V_m.
- This maximum reverse voltage is called peak inverse voltage (PIV). Thus the PIV of diode : -

  a) For Half Wave = $V_{m.,}$ **b)** For Center Tapped =$2V_m$ and **c)** For Bridge Rectifier = V_m **.**

Average Value of Voltage & Current for HALF WAVE Rectifiers: -

- If V_m= Maximum value of the a.c. input voltage, then the average or d.c. value of the output voltage and current is given by

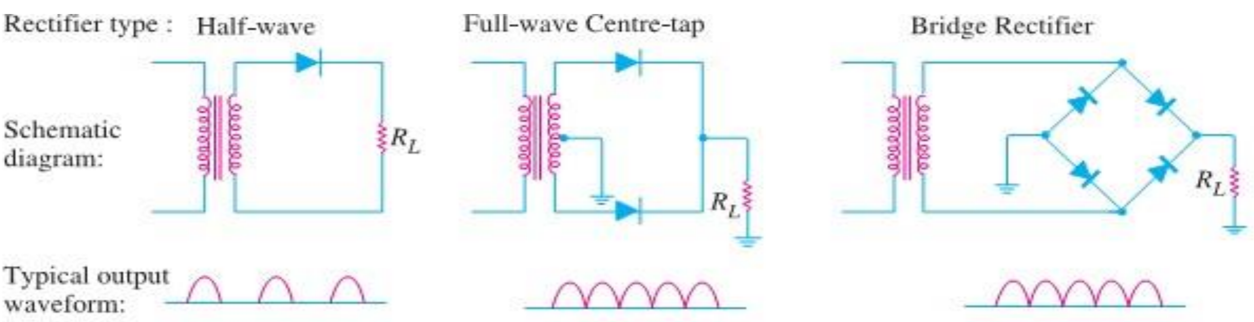
$V_{dc} = V_m/\pi = 0.318\ V_m$ and **$I_{dc} = I_m/\pi = 0.318\ I_m$**

Average Value of Voltage & Current for FULL WAVE Rectifiers: -

- If V_m= Maximum value of the a.c. input voltage, then the average or d.c. value of the output voltage and current is given by

$V_{dc} = 2V_m/\pi = 0.636\ V_m$ and **$I_{dc} = 2I_m/\pi = 0.636\ I_m$**

- **COMPARISON OF RECTIFIERS:**



S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	no	yes	no
3	Max. efficiency	40.6%	81.2%	81.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	f_{in}	$2 f_{in}$	$2 f_{in}$
6	Peak inverse voltage	V_m	$2 V_m$	V_m

ARTICLE 3.3

FILTER CIRCUIT

- The output of a rectifier has pulsating character i.e. it contains A.C. and D.C. components.
- The A.C. component is undesirable and must be kept away from the load.
- A **filter circuit** is a device which removes the A.C. component of rectifier output but allows the D.C. component to reach the load.
- A filter circuit is generally a combination of inductors (L) and capacitors (C).
- The filtering action of L and C depends upon the basic electrical principles.
- A capacitor offers infinite reactance to d.c.
- We Know that $X_C = 1/2\pi fC$. But for D.C., f = 0.

  ∴ $X_C = 1/2\pi fC = 1/\ 2\pi \times 0 \times C = \infty$ (Means Capacitor shows *infinite reactance* to DC)

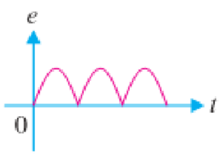
  ♣ ***Hence, a Capacitor does not allow d.c. to pass through it.***

- We know $X_L = 2\pi fL$. For d.c., f = 0

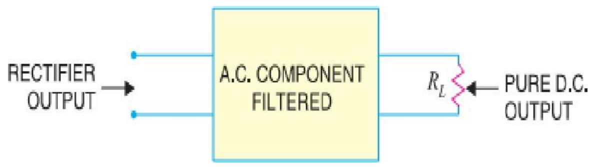
  ∴ $X_L = 2\pi \times 0 \times L = 0$ (Means Inductor shows *zero reactance* to DC)

  ♣ ***Hence Inductor passes d.c. quite readily.***

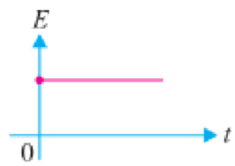
- *A Capacitor passes A.C. but does not pass D.C. at all. On the other hand, an Inductor opposes A.C. but allows D.C. to pass through it.*
- It then becomes clear that suitable network of L and C can effectively remove the A.C. component, allowing the D.C. component to reach the load.



(Pulsating D.C)



(Filter Circuit)



(Pure D.C)

- **Types Of Filter Circuits:-**
- There are different types of filter circuits according to their construction. The most commonly used filter circuits are : -

  ♣ *Inductive Filter or Series Inductor*,

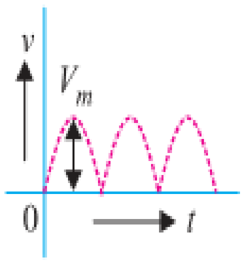
  ♣ *Capacitor Filter or Shunt Capacitor*,

  ♣ *Choke Input Filter or LC Filter* and

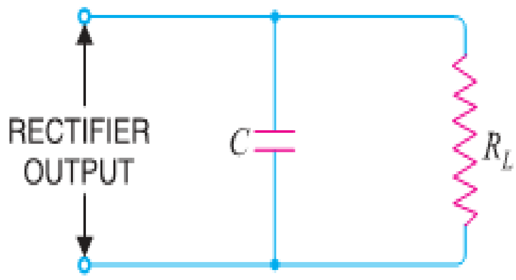
  ♣ *Capacitor Input Filter* or *π-Filter*.

ARTICLE 3.3.1

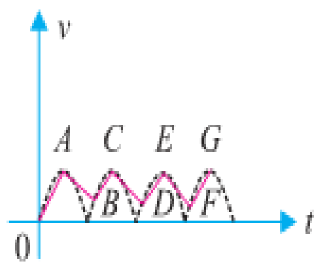
CAPACITOR FILTER OR SHUNT CAPACITOR:-



(Rectified output Pulsating d.c)



(Capacitor Filter Circuit)



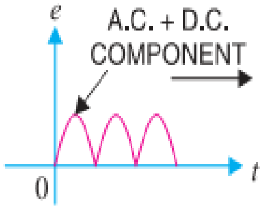
(Output of Capacitor Filter)

- Fig. (ii) Shows a typical capacitor filter circuit. It consists of a capacitor C placed across the rectifier output in parallel with load R_L.
- The pulsating direct voltage of the rectifier is applied across the capacitor. As the rectifier voltage increases, it charges the capacitor and also supplies current to the load.

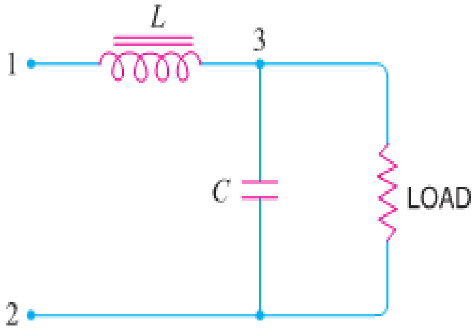
- At the end of quarter cycle [Point A in Fig. (iii)], the capacitor is charged to the peak value V_m of the rectifier voltage.
- Now, the rectifier voltage starts to decrease. As this occurs, the capacitor discharges through the load and voltage across it decreases as shown by the line AB in Fig. (iii).
- The voltage across load will decrease only slightly because immediately the next voltage peak comes and recharges the capacitor.
- This process is repeated again and again and the output voltage waveform becomes ABCDEFG. It may be seen that very little ripple is left in the output.
- The capacitor filter circuit is extremely popular because of its low cost, small size, little weight and good characteristics.

ARTICLE 3.3.2

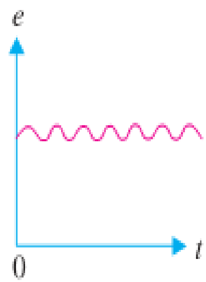
Choke Input Filter Or LC Filter:-



(Rectified output Pulsating d.c)



(Choke Input Filter Circuit)

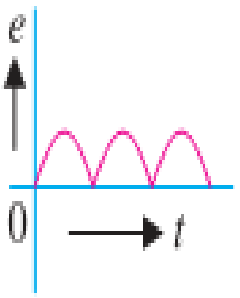


(Output of Choke Input Filter)

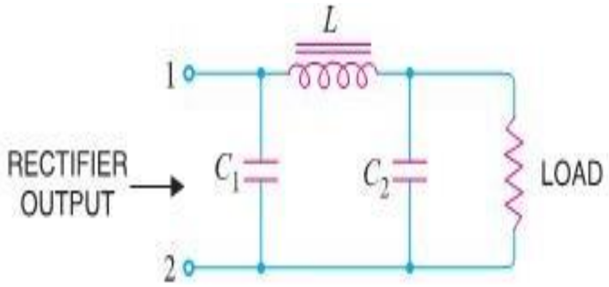
- Fig. shows a typical choke input filter circuit. It consists of a choke L connected in series with the rectifier output and a filter capacitor C across the load.
- The pulsating output of the rectifier is applied across terminals 1 and 2 of the filter circuit.
- The result is that most of the a.c. component appears across the choke while whole of d.c. component passes through the choke on its way to load. This results in the reduced pulsations at terminal 3.
- At terminal 3, the rectifier output contains d.c. component and the remaining part of a.c. component which has managed to pass through the choke.
- Now, the low reactance of filter capacitor bypasses the a.c. component but prevents the d.c. component to flow through it. Therefore, only d.c. component reaches the load.
- In this way, the filter circuit has filtered out the a.c. component from the rectifier output, allowing d.c. component to reach the load.

ARTICLE 3.3.3

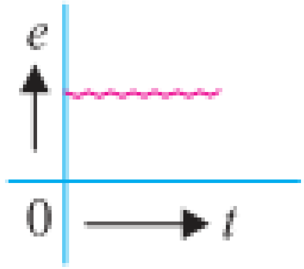
Capacitor Input Filter or π-Filter:-



(Rectified output Pulsating d.c)



(Capacitor Input or π- Filter Circuit)



(Output of π-Filter)

- Fig. shows a typical capacitor input filter or π-filter. It consists of a filter capacitor C_1 connected across the rectifier output, a choke Lin series and another filter capacitor C_2 connected across the load.
- The filtering action of the three components viz C_1 , L and C_2 of this filter is described below:

(a) The **filter capacitor C_1** offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor C_1 bypasses an appreciable amount of a.c. component while the d.c. component continues its journey to the choke L.

(b) The **choke L** offers high reactance to the a.c. component but it offers almost zero reactance to the d.c. component. Therefore, it allows the d.c. component to flow through it, while the un bypassed a.c. component is blocked.

(c) The **filter capacitor C_2** bypasses the a.c. component which the choke has failed to block. Therefore, only d.c. component appears across the load and that is what we desire

--- ALL THE BEST --- --- ॐ --- --- ALL THE BEST ---

PRACTICE QUESTIONS:

Probable short questions with answers

1. What is rectifier?
2. What is Peak Inverse Voltage (W2019)
   Ans: *It is the maximum reverse voltage that a diode can withstand without destroying the junction*
3. Name the different types of rectifiers.
4. Define ripple and ripple factor (W2009,2010,2011,2018,2019)
   Ans: *The amount of AC component present in the rectifier output is called ripple.*
   The ratio of r.m.s. value of AC component to the DC component of the rectifier output is called the ripple factor.

$$\text{Ripple factor} = \frac{\text{r.m.s. value of a.c component}}{\text{value of d.c. component}} = \frac{I_{ac}}{I_{dc}}$$

   For HWR its value is 1.21 and for FWR it is 0.48

5. Write down the necessity of ripple factor (S2019)
   Ans: *Ripple factor is important in defining the effectiveness of the rectifier output*
   The smaller the ripple factor the more effective the rectifier
   The more the ripple factor means more fluctuating ac component present in the rectifier output
6. What is TUF (W2014,2017)
   Ans: *It is defined as the ratio of d.c. power delivered to the load and the a.c. rating of the transformer secondary*

$TUF = P_{dc} / P_{ac}$

For half wave rectifier, TUF = 0.287; Center taped rectifier, TUF = 0.693; Bridge rectifier, TUF = 0.812. The TUF is very useful in determining the rating of a transformer to be used with rectifier circuit.

7. Write down the disadvantages of center-tapped FW rectifier.

Probable long questions

1. Write short notes on (W2018)
   a) Choke input filter
   b) Pipe filter
2. With neat circuit diagram, explain full-wave bridge rectifier and derive its rectifier efficiency (W2007,2008,2014, 2015, 2016, 2017, 2018, 2019)
3. Find out the efficiency of half-wave rectifier (W2014, 2017, 2018, 2019)
4. Find out the efficiency of full-wave rectifier
5. Derive the expression for efficiency of center-tap full-wave rectifier with a neat diagram (S2019)

CHAPTER - 4

[TRANSISTORS]

LEARNING OBJECTIVE

4.1 Principle of Bipolar junction transistor
4.2 Different modes of operation of transistor
4.3 Current components in a transistor
4.4 Transistor as an amplifier
4.5 Transistor circuit configuration & its characteristics
4.5.1 CB Configuration
4.5.2 CE Configuration
4.5.3 CC Configuration

ARTICLE 4.1:
PRINCIPLE OF BIPOLAR JUNCTION TRANSISTOR

- **INTRODUCTION:-**

➢ When a third doped element is added to a crystal diode in such a way that two PN junctions are formed, the resulting device is known as a **Transistor**.

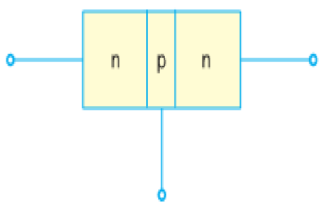
➢ This is a new type of electronics device which can able to amplify a weak signal in a fashion comparable and often superior to that realized by vacuum tubes.

➢ A transistor consists of two PN junctions formed by sandwiching either p-type or n-type semiconductor between a pair of opposite types. Hence Transistor is classified into two types, namely: -

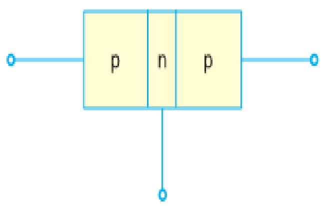
  - **(i)** n-p-n transistor **(ii)** p-n-p transistor

➢ An n-p-n transistor is composed of two n-type semiconductors separated by a thin section of p-type.

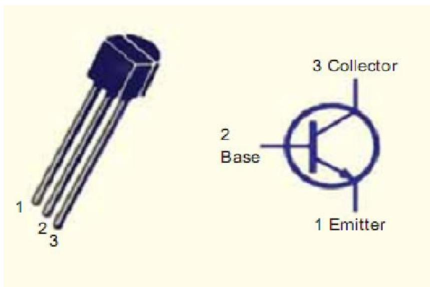
➢ However, a p-n-p transistor is formed by two p-sections separated by a thin section of n-type as shown in Figure below.



(i)



(ii)



- **NAMING: -**

➢ A transistor has *two pn junctions*. As discussed later, one junction is forward biased and the other is reverse biased.

➢ The *forward biased junction* has a low resistance path whereas a *reverse biased junction* has a high resistance path.

➢ The weak signal is introduced in the low resistance circuit and output is taken from the high resistance circuit. Therefore, a transistor transfers a signal from a low resistance to high resistance.

➢ .

- **NAMING THE TRANSISTOR TERMINALS:-**

✍ A transistor (PNP or NPN) has three sections of doped semiconductors.

✍ The section on one side is the **emitter** and the section on the opposite side is the **collector**.

✍ The middle section is called the **base** and forms two junctions between the emitter and collector.

✚ **(i) Emitter: -**

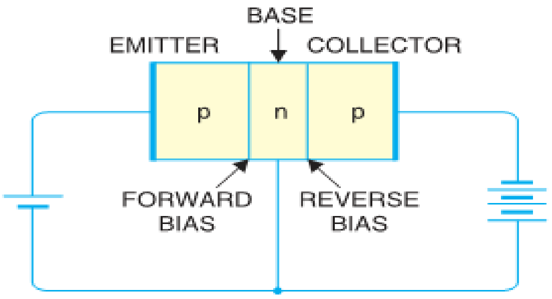
- The section on one side that *supplies charge carriers* (electrons or holes) is called the emitter.
- The emitter is always forward biased w.r.t. base so that it can supply a large number of majority carriers.
- The emitter (p-type) of PNP transistor is forward biased and supplies hole charges to its junction with the base. Similarly the emitter (n-type) of NPN transistor has a forward bias and supplies free electrons to its junction with the base.

(ii) Collector: -

- The section on the other side that *collects the charges* is called the collector. The collector is always reverse biased. Its function is to remove charges from its junction with the base.
- The collector (p-type) of PNP transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly the collector (n-type) of NPN transistor has reverse bias & receives electrons.

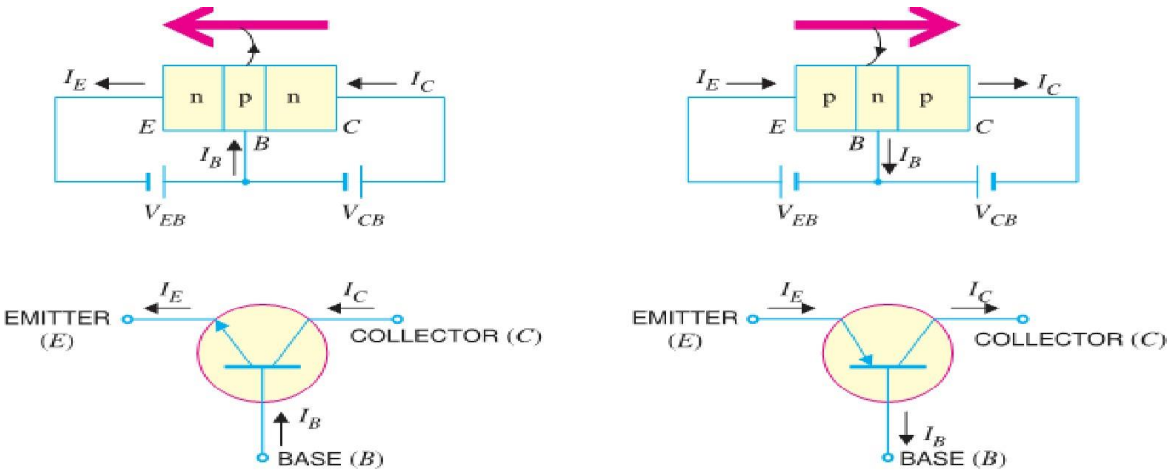
(iii)Base: -

- The middle section which forms two PN-junctions between emitter & collector is called base.
- The base-emitter junction is forward biased, allowing low resistance for the emitter circuit.
- The base-collector junction is reverse biased and provides high resistance in the collector circuit.



(i) (ii)

- **TRANSISTOR SYMBOL:-**



(i) (ii)

ARTICLE 4.2:
MODES OF OPERATIONS OF TRANSISTORS

A transistor has two junctions (emitter-base and collector-base junction), and each of these two junctions may be forward biased or reverse biased. Accordingly, there are four possible ways of biasing:

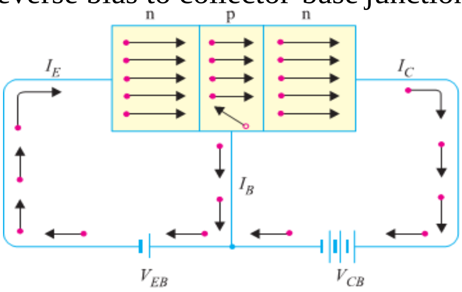
Conditions	Emitter-Base (EB) Junction	Collector- Base (CB) Junction	Region of operation
Forward – Reverse (FR)	Forward Biased	Reverse Biased	Active
Forward – Forward (FF)	Forward Biased	Forward Biased	Saturation
Reverse – Reverse (RR)	Reverse Biased	Reverse Biased	Cut-off
Reverse – Forward (RF)	Reverse Biased	Forward Biased	Inverted

Generally, transistor is operated in active region for amplifier purpose; however, in switching circuits, cut-off and saturation biases are being used.

ARTICLE 4.3:
CURRENT COMPONENTS IN A TRANSISTOR

- **<u>WORKING OF NPN TRANSISTOR (NPN): -</u>**

➢ The NPN transistor with forward bias to emitter- base junction & reverse bias to collector-base junction.



➢ The forward bias causes the electrons in the n-type emitter to flow towards the base.

➢ This constitutes the emitter current **I_E**. As these electrons flow through the p-type base, they tend to combine with holes.

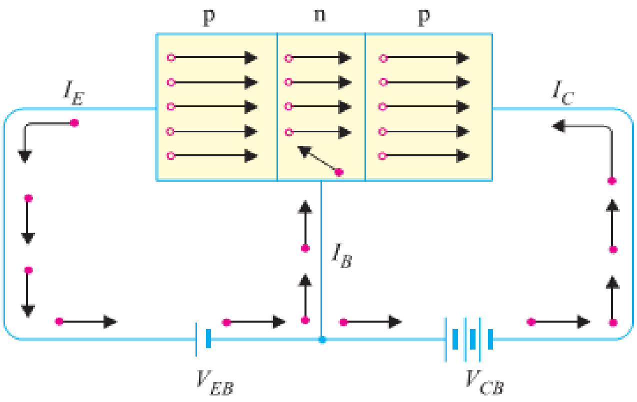
➢ As the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base current **I_B**.

➢ The remainders (more than 95%) cross over into the collector region to constitute collector current **I_C**.

➢ In this way, almost the entire emitter current flows in the collector circuit.

➢ It is clear that emitter current is the sum of collector and base currents i.e. $\mathbf{I_E = I_B + I_C}$

- **<u>WORKING OF PNP TRANSISTOR (PNP): -</u>**



➢ Fig. shows the basic connection of a PNP transistor.

➢ The forward bias causes the holes in the p-type emitter to flow towards the base.

➢ This constitutes the emitter current I_E.

➢ As these holes cross into n-type base, they tend to combine with the electrons.

➢ As the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector current I_C.

➢ In this way, almost the entire emitter current flows in the collector circuit.

➢ It may be noted that current conduction within PNP transistor is by holes. However, in the external connecting wires, the current is still by electrons

ARTICLE 4.4:
TRANSISTOR AS AN AMPLIFIER

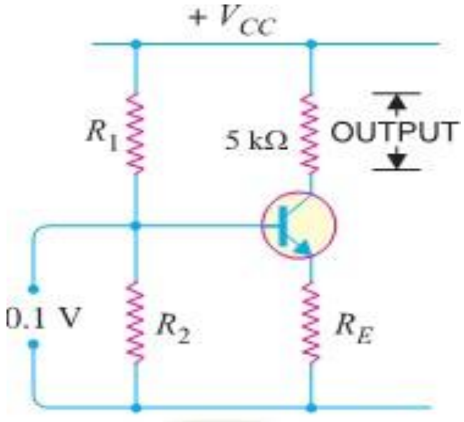
- **AMPLIFIER:-**

➢ The device which increases the strength of a weak signal is known as *Amplifier*. This can achieve by use of Transistor. It may be classified according to the number of stage of amplification, Such as:-

✓ **Single Stage Transistor Amplifier: -** When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as *Single Stage Transistor Amplifier*.

✓ **Multi stage Transistor Amplifier:-**When a transistor circuit containing more than one stage of amplification is known as *Multi stage Transistor Amplifier*.

➢ **SINGLE STAGE TRANSISTOR AMPLIFIER:-**



➢ A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components.

➢ When a weak A.C. signal is given to the base of transistor, a small base current starts flowing.

➢ Due to transistor action, a much larger (β times the base current) current flows through the collector load R_C.

➢ As the value of R_C is quite high (usually 4-10 kΩ), therefore, a large voltage appears across R_C.

➢ Thus, a weak signal applied in the base circuit appears in amplified form in the collector circuit.

It is in this way that a transistor acts as an amplifier.

ARTICLE 4.5:
TRANSISTOR CIRCUIT CONFIGURATION AND ITS CHARACTERISTICS

➢ There are three leads in a transistor such as emitter, base and collector terminals.

➢ However, when a transistor is to be connected in a circuit, we require **four terminals**; two for the input and two for the output.

➢ This difficulty is overcome by making one terminal of it in common to both input and output terminals.

➢ The input is fed between this common terminal and one of the other two terminals.

➢ The output is obtained between the common terminal and the remaining terminal.

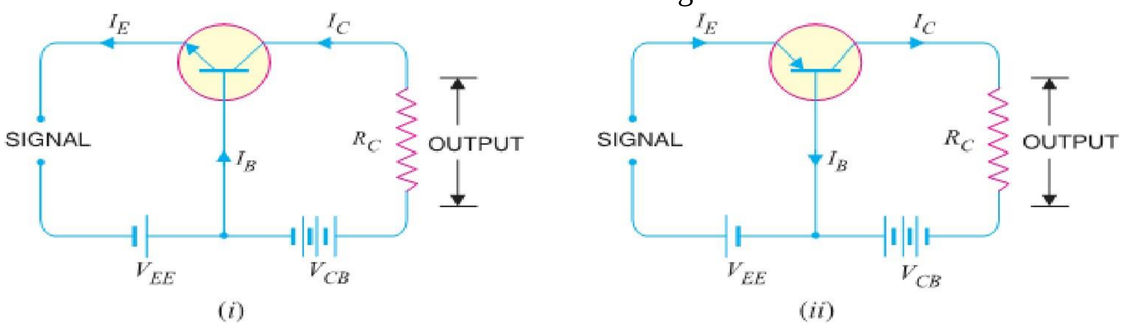
➢ So a transistor can be connected in a circuit in the following ways:-

(i) Common Base connection (**ii**) Common Emitter connection (**iii**) Common Collector connection

ARTICLE 4.5.1:
COMMON BASE CONFIGURATION

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base.

Here, base of the transistor is common to both input and output circuits and hence the name **C**ommon **B**ase connection. A Common Base NPN and PNP in figure below.

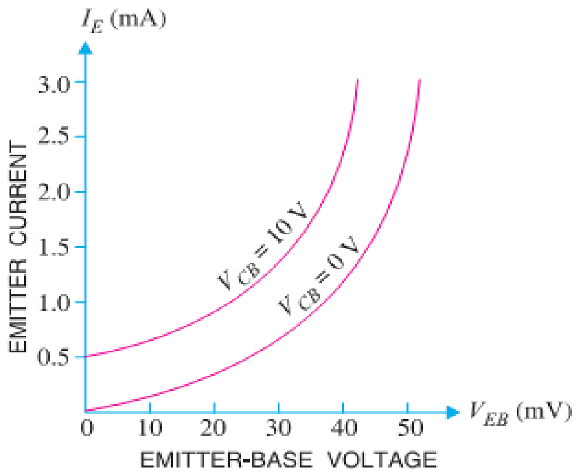


- **TRANSISTOR CHARACTERISTICS:-**

1) Characteristics of Common Base Connection

- The complete electrical behavior of a transistor can be described by stating the interrelation of the various currents and voltages.
- These relationships can be conveniently displayed graphically and the curves thus obtained are known as the characteristics of transistor.
- The most important characteristics of common base connection are **input characteristics** and **output characteristics**.

A) Input Characteristics:-



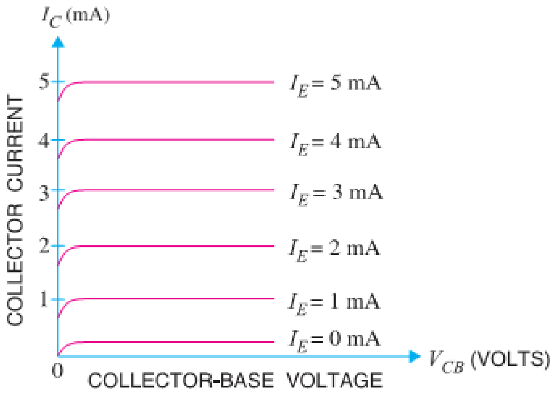
- It is the curve between emitter current $\mathbf{I_E}$ & emitter-base voltage $\mathbf{V_{BE}}$ at constant collector-base voltage $\mathbf{V_{CB}}$.
- The emitter current is generally taken along y-axis and emitter-base voltage along x-axis. Fig. Shows the input characteristics of a typical transistor in CB arrangement.
- The following points may be noted from these characteristics :
  - ♣ The emitter current I_E increases rapidly with small increase in emitter-base voltage V_{EB}. It means that input resistance is very small.
  - ♣ The emitter current is almost independent of collector-base voltage V_{CB}. This leads to the conclusion that emitter current (and hence collector current) is almost independent of collector voltage.
- **Input Resistance: -** It is the ratio of change in emitter-base voltage (ΔV_{EB}) to the resulting change in emitter current (ΔI_E) at constant collector-base voltage (V_{CB}) i.e.

$$\text{Input resistance, } r_i = \frac{\Delta V_{BE}}{\Delta I_E} \quad \text{at constant } V_{CB}$$

- In fact, input resistance is the opposition offered to the signal current. As a very small V_{EB} is sufficient to produce a large flow of emitter current I_E, thus, input resistance is quite small, of the order of a few ohms.

B) Output Characteristics:-

- It is the curve between collector current $\mathbf{I_C}$ & collector-base voltage $\mathbf{V_{BC}}$ at constant emitter current $\mathbf{I_E}$.
- Generally, collector current is taken along y-axis and collector-base voltage along x-axis.
- The fig. shows the input and output characteristics of a typical transistor in CB arrangement.
- The following points may be noted from characteristics :



  - ♣ The collector current I_C varies with V_{CB} only at very low voltages (< 1V). The transistor is never operated in this region.
  - ♣ When the value of V_{CB} is raised above 1 − 2 V, the collector current becomes constant as indicated by straight horizontal curves. It means that now I_C is independent of V_{CB} and depends upon I_E only. This is consistent with the theory that the emitter current flows almost entirely to the collector terminal. The transistor is always operated in this region.
  - ♣ A very large change in collector-base voltage produces only a tiny change in collector current. This means that output resistance is very high.

Output Resistance: - It is the ratio of change in collector-base voltage (ΔV_{CB}) to the resulting change in collector current (ΔI_C) at constant emitter current i.e.

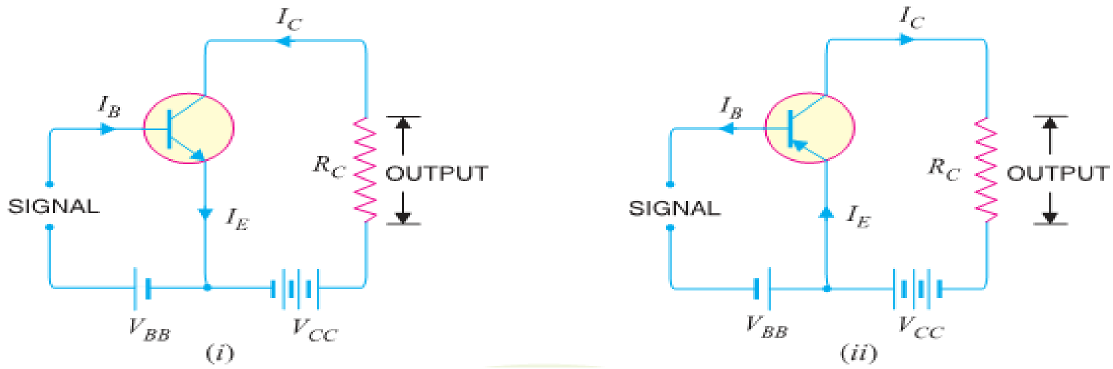
$$\text{Output resistance, } r_o = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_E$$

- The output resistance of CB circuit is very high, of the order of several tens of kilo-ohms.

(i) Common Emitter Connection

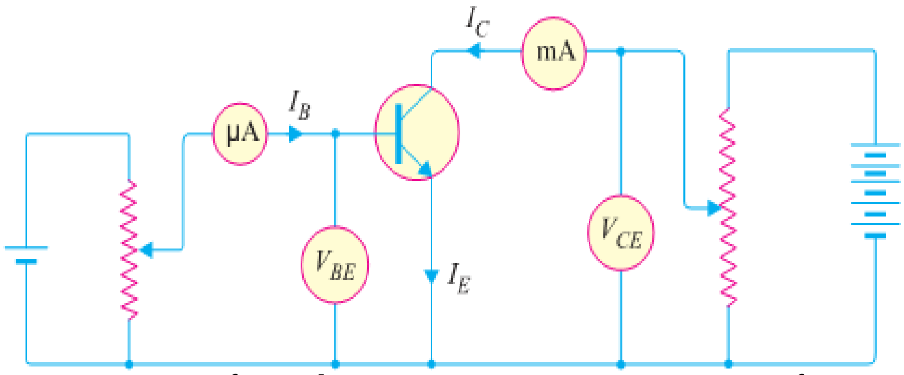
In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter.

Here, emitter of the transistor is common to both input and output circuits and hence the name **C**ommon **E**mitter connection. A Common Emitter NPN and PNP transistor circuit is shown in figure below.



2) Characteristics of Common Emitter Connection:-

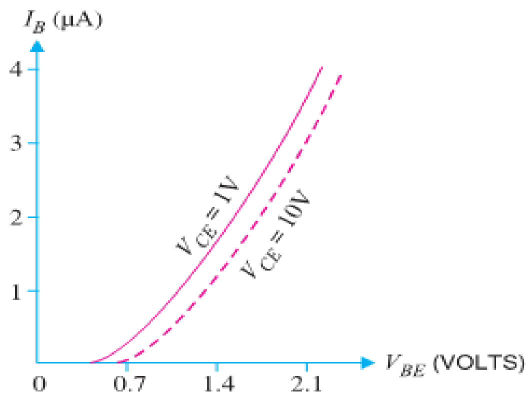
- The important characteristics of this circuit arrangement are the input characteristic and output characteristic.



(Circuit Arrangement for studying Common Emitter Connection of Transistor)

A) Input Characteristics:-

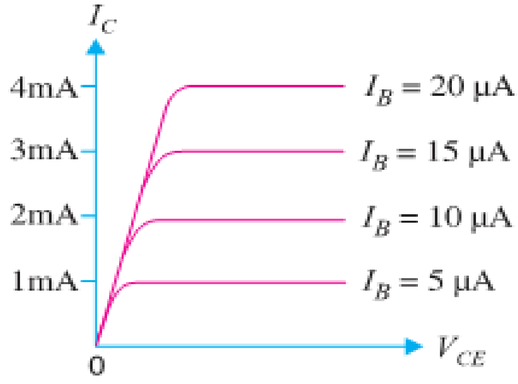
- It is the curve between base current IB & base-emitter voltage VBE at constant collector-emitter volt V_{CE}. The input characteristics of a CE connection can be determined by the circuit shown in Fig. Keeping V_{CE} constant (Let 10 V), note the base current I_B for various values of V_{BE}.
- Then plot the readings obtained on the graph, taking I_B along y-axis and V_{BE} along x-axis. This gives the input characteristic at V_{CE} = 10V as shown in Fig.
- The following points may be noted from the characteristics :
  - ♣ The characteristic resembles that of a forward biased diode curve. This is expected since the base-emitter section of transistor is a diode and it is forward biased.
  - ♣ As compared to CB arrangement, I_B increases less rapidly with V_{BE}. Therefore, input resistance of a CE circuit is higher than that of CB circuit.



- **Input Resistance: -** It is the ratio of change in base-emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant V_{CE}. The value of input resistance for CE circuit is of the order of a few hundred ohms

B) Output Characteristics: -

- It is the curve between collector current $\mathbf{I_C}$ and collector-emitter voltage $\mathbf{V_{CE}}$ at constant base current $\mathbf{I_B}$.
- The output characteristics of CE circuit can be drawn with the help of above circuit arrangement in Fig.
- Keeping the base current I_B fixed at some value say, 5 µA, note the collector current I_C for various values of V_{CE}.
- Then plot the readings on a graph, taking I_C along y-axis and V_{CE} along x-axis.
- This gives the output characteristic at I_B = 5 µA as shown in Fig. The test can be repeated for I_B= 10 µA to obtain the new output characteristic as shown in Fig.
- Following similar procedure, a family of output characteristics can be drawn as shown in Fig.



- The following points may be noted from the characteristics:

  - ♣ (i) The collector current I_C varies with V_{CE} for V_{CE} between 0 and 1V only. After this, I_C becomes almost constant & independent of V_{CE}.
  - ♣ This value of V_{CE} upto which I_C changes with V_{CE} is called the knee voltage (V_{knee}). The transistors are always operated in the region above knee voltage.
  - ♣ (ii) Above knee voltage, I_C is almost constant. However, a small increase in I_C with increasing V_{CE} is caused by the collector depletion layer getting wider and capturing a few more majority carriers before electron-hole combinations occur in the base area.
  - ♣ (iii) For any value of V_{CE} above knee voltage, the collector current I_C is approximately equal to $\beta \times I_B$
- **Output Resistance: -** It is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant I_B i.e.

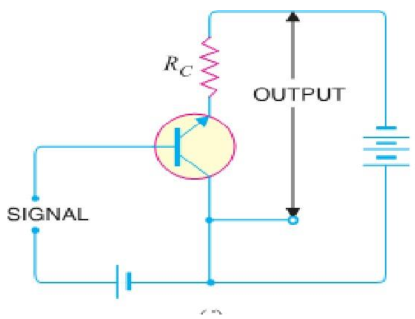
$$\text{Output resistance, } r_o = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B$$

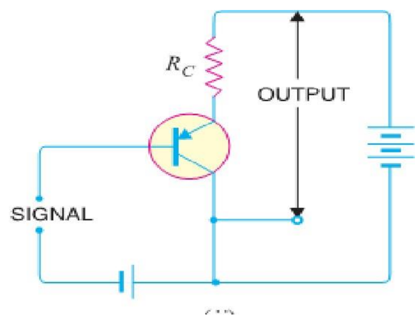
- It may be noted that whereas the output characteristics of CB circuit are horizontal, they have noticeable slope for the CE circuit.
- Therefore, output resistance of CE circuit is less than that CB circuit. Its value is of the order of 50 kΩ.

(i) Common Collector Connection

In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector.

Here, collector of the transistor is common to both input and output circuits and hence the name **C**ommon **C**ollector connection. A Common Collector NPN and PNP in figure below.





3) Characteristics of Common Collector Connection:-

- In a Common Collector circuit connection the load resistor connected from emitter to ground, so the collector tied to ground even though the transistor is connected in a manner similar to the CE connection.
- Hence there is no need for a set of common-collector characteristic to choose the parameters of the circuit. The output characteristic of the CC configuration is same as CE configuration.
- For CC Connection the output characteristic are plot of **I_E versus V_{CE}** for a constant value of **I_B**.
- There is an almost unnoticeable change in the vertical scale of I_C of the CE connection if I_C is replaced by I_E for CC connection.
- The input circuit of CC connection, the CE characteristic is sufficient to obtain the required information.
- Hence Common Collector circuit connection is known as **Emitter Follower**.

- **COMPARISON OF TRANSISTOR CONNECTIONS:-**

S. No.	Characteristic	Common base	Common emitter	Common collector
1.	Input resistance	Low (about 100 Ω)	Low (about 750 Ω)	Very high (about 750 kΩ)
2.	Output resistance	Very high (about 450 kΩ)	High (about 45 kΩ)	Low (about 50 Ω)
3.	Voltage gain	about 150	about 500	less than 1
4.	Applications	For high frequency applications	For audio frequency applications	For impedance matching
5.	Current gain	No (less than 1)	High (β)	Appreciable

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PRACTICE QUESTIONS:

Probable short questions with answers

1. What is an emitter follower (W2018, S2019)
   Ans: *Common collector circuit is also called emitter follower. Here collector terminal is at ground (a.c. 0). In this case, the output voltage (taken at emitter terminal) is same as input voltage applied to base terminal. Hence output follows input voltage and hence called as emitter follower*
2. Explain transistor as an amplifier.
3. Show current directions in an N-P-N transistors diagram
4. Why transistor is called BJT?
5. Write down the application of common collector transistor

Probable long questions

1. Explain the working principle of N-P-N transistor; Brief on input and output characteristics of common base configuration
2. Describe the transistor connection over CB, CE and CC configuration (W2015, 2017, 2018)
3. Explain the input and output characteristics of common emitter configuration transistor

CHAPTER – 5

[TRANSISTOR CIRCUITS]

LEARNING OBJECTIVE

ARTICLE 5.1: TRANSISTOR BIASING

- **The proper flow of zero signal collector current and the maintenance of proper collector-emitter voltage during the passage of signal is known as *Transistor Biasing*.**
- To achieve faithful amplification the following basic conditions must be satisfied:-

  (i) Proper zero signal collector current
  (ii) Minimum proper base-emitter voltage (V_{BE}) at any instant
  (iii) Minimum proper collector-emitter voltage (V_{CE}) at any instant

- The fulfillment of these will ensure that transistor works over the active region of the output characteristics.
- The basic purpose of transistor biasing is to keep the base-emitter junction properly forward biased and collector-base junction properly reverse biased during the application of signal.
- ✓ **NEED OF TRANSISTOR BIASING:-**

  (i) It should ensure proper zero signal collector current.
  (ii) It should ensure that V_{CE} does not fall below 0.5 V for Ge transistors and 1 V for Si transistors.
  (iii) It should ensure the stabilization of operating point.

ARTICLE 5.2: STABILIZATION

- The process of making operating point independent of temperature changes or variations in transistor parameters is known as *Stabilization*.
- ❖ **NEED FOR STABILIZATION:-** Stabilization of the operating point is necessary due to the following reasons :
  - ♣ (i) Temperature dependence of IC
    We know, $I_c = \beta I_b + (1+\beta) I_{co}$
    - Reverse saturation current Ico doubles for every 10^o C rising temperature.
    - B increases with rising temperature
    - Base emitter voltage V_b decreases by 2.5 mV per ^oC
  - ♣ (ii) Individual variations
    - The value of β and V_{be} are not exactly the same for any 2 transistors even though same type
  - ♣ (iii) Thermal runaway

- The self-destruction of an unsterilized transistor is known as ***Thermal Runaway***.

ARTICLE 5.3: STABILITY FACTOR

- The rate of change of collector current I_C w.r.t. the collector leakage current I_{CO} [= I_{CEO}] at constant β and I_B is called stability factor i.e.

$$\text{Stability factor, } S = \frac{dI_C}{dI_{CO}} \text{ at constant } I_B \text{ and } \beta$$

General Expression for Stability Factor S

We know, $I_c = \beta I_b + (1+\beta) I_{co}$

Differentiating above equation with respect to Ic considering β to be constant, we have

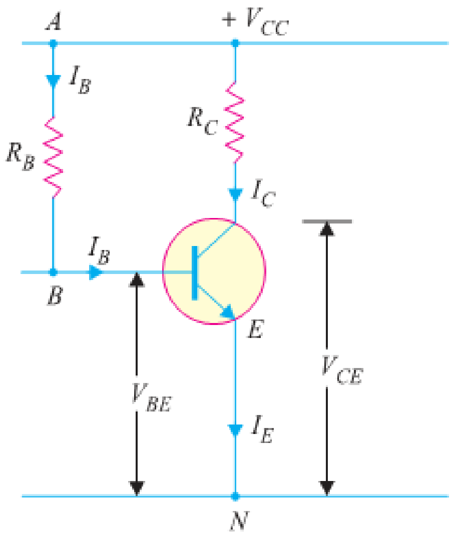
$$1 = \beta \frac{d I_B}{d I_C} + (1+\beta) \frac{d I_{CO}}{d I_C} = \beta \frac{d I_B}{d I_C} + \frac{1+\beta}{S}$$

$$\text{So stability factor, } S = \frac{1+\beta}{1-\beta \frac{d I_B}{d I_C}}$$

ARTICLE 5.4: METHODS OF TRANSISTOR BIASING

- In the transistor amplifier circuits drawn so far biasing was done with the aid of a battery V_{BB} which was separate from the battery V_{CC} used in the output circuit. However, for simplicity and economy, it is desirable that transistor circuit should have a single source of supply the one in the output circuit (i.e. V_{CC}).
- The following are the most commonly used methods of obtaining transistor biasing from one source of supply:
  - **(i)** Base resistor method
  - **(ii)** Biasing with collector-feedback resistor
  - **(iii)** Voltage-divider bias
- In all these methods, the same basic principle is employed i.e. required value of base current (and hence I_C) is obtained from V_{CC} in the zero signal conditions.
- The value of collector load R_C is selected keeping in view that V_{CE} should not fall below 0.5 V for germanium transistors and 1V for silicon transistors.

ARTICLE 5.4.1: BASE RESISTOR METHOD



- In this method, a high resistance R_B (several hundred kΩ) is connected between the base and +ve end of supply for npn transistor and between base and negative end of supply for pnp transistor.
- Here, the required zero signal base current is *provided by* V_{CC} and it flows through R_B. It is because now base is positive w.r.t. emitter i.e. base-emitter junction is forward biased.
- The required value of zero signal base current I_B (and hence $I_C = \beta I_B$) can be made to flow by selecting the proper value of base resistor R_B.
- **Circuit analysis:-**

  It is required to find the value of R_B so that required collector current flows in the zero signal conditions.

  Let I_C be the required zero signal collector current.

  $\therefore I_B = I_C / \beta$

  Considering the closed circuit ABENA and applying Kirchhoff's voltage law, we get,

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

  $I_B R_B = V_{CC} - V_{BE}$

  $I_B = (V_{CC} - V_{BE}) / R_B = V_{CC} / R_B$ (Since V_{BE} is very small)

- It may be noted that V_{CC} is a fixed known quantity and I_B is chosen at some suitable value. Hence, R_B can always be found directly, and for this reason, this method is sometimes called **fixed-bias method**.

So stability factor, $S = \dfrac{1+\beta}{1-\beta \dfrac{d I_B}{d I_C}}$

This implies $S = (1+\beta)$, since $dI_B/ dI_c = 0$; Hence base bias circuit is unstable.

- **Advantages :**
  (i) This biasing circuit is very simple as only one resistance R_B is required.
  (ii) Biasing conditions can easily be set and the calculations are simple.
- **Disadvantages :**
  (i) This method provides poor stabilization.
  (ii) The stability factor is very high.

ARTICLE 5.4.2: COLLECTOR TO BASE BIAS (BIASING WITH FEEDBACK CIRCUIT)

- In this method, one end of R_B is connected to the base and the other end to the collector. Here, the required zero signal base current is determined not by V_{CC} but by the *collector-base voltage* V_{CB}. It is clear that V_{CB} forward biases the base-emitter junction and hence base current I_B flows through R_B. This causes the zero signal collector current to flow in the circuit.
- **Circuit Analysis:-**
  The required value of R_B needed to give the zero signal current I_C can be determined as follows.

From the above circuit diagram, $V_{CC} = I_C R_C + I_B R_B + V_{BE}$

$$R_B = \frac{V_{CC} - V_{BE} - I_C R_C}{I_B} = \frac{V_{CC} - V_{BE} - \beta I_B R_C}{I_B} \quad (\because I_C = \beta I_B)$$

Alternately, $V_{CE} = V_{BE} + V_{CB}$ or $V_{CB} = V_{CE} - V_{BE}$

$$\therefore \quad R_B = \frac{V_{CB}}{I_B} = \frac{V_{CE} - V_{BE}}{I_B}; \quad \text{where} \quad I_B = \frac{I_C}{\beta}$$

- **Advantages :-**
  (i) It is a simple method as it requires only one resistance R_B.
  (ii) This circuit provides some stabilization of the operating point than fixed bias method.
- **Disadvantages:-**
  (i) The circuit does not provide good stabilization.
  (ii) This circuit provides a negative feedback which reduces the gain of the amplifier.
  (iii)This will reduce the base current and hence collector current.

ARTICLE 5.4.3: VOLTAGE DIVIDER BIAS METHOD (SELF BIAS)

- This is the most widely used method of providing biasing and stabilization to a transistor. In this method, two resistances R_1 and R_2 are connected across the supply voltage V_{CC} and *provide biasing*. The emitter resistance R_E *provides stabilization*. The name ''voltage divider'' comes from the voltage divider formed by R_1 and R_2. The voltage drop across R_2 forward biases the base- emitter junction. This causes the base current and hence collector current flows in the zero signal conditions.
- **Circuit analysis:-**
- Suppose that the current flowing through resistance R_1 is I_1. As base current I_B is very small, therefore, it can be assumed with reasonable accuracy that current flowing through R_2 is also I_1.

(i) Collector current I_C :-

$$I_1 = \frac{V_{CC}}{R_1 + R_2}$$

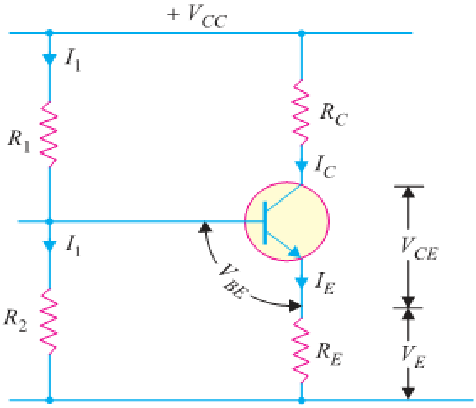
∴ Voltage across resistance R_2 is

$$V_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2$$

Applying Kirchhoff's voltage law to the base circuit

$V_2 = V_{BE} + V_E = V_{BE} + I_E R_E$

$$I_E = \frac{V_2 - V_{BE}}{R_E} \; ; \quad I_C = \frac{V_2 - V_{BE}}{R_E} \; ; \quad \text{Since } I_E \simeq I_C$$



(Voltage Divider Bias Circuit)

- Thus I_C in this circuit is almost independent of transistor parameters and hence good stabilization is ensured. Due to this reason the potential divider bias has become universal method for providing transistor biasing.

(ii) Collector-emitter voltage (V_{CE}): -

Applying Kirchhoff's voltage law to the collector side,

$V_{CC} = I_C R_C + V_{CE} + I_E R_E = I_C R_C + V_{CE} + I_C R_E$ (As $I_C \simeq I_E$)

So, $V_{CC} = I_C (R_C + R_E) + V_{CE}$ => $V_{CE} = V_{CC} - I_C (R_C + R_E)$

- **Advantages : -**
- In this circuit, excellent stabilization is provided by R_E. Consider the Following Equation,

  $V_2 = V_{BE} + I_C R_E$
- Suppose the collector current I_C increases due to rise in temperature. This will cause the voltage drop across emitter resistance R_E to increase.

Stability factor S.

The circuit to the left of the base terminal is replaced by its thevenin's equivalent circuit, as shown below.

Open circuit voltage across base and ground terminals (V_{th})

... and ground terminals,

$$V_{Th} = V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

Resistance seen into the base and ground terminals with V_{CC} short-circuited,

$$R_{Th} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

Applying Kirchhoff's voltage law around the closed base circuit yields

$$V_{Th} = I_B R_{Th} + V_{BE} + I_E R_E$$
$$= I_B R_{Th} + V_{BE} + (I_B + I_C) R_E$$

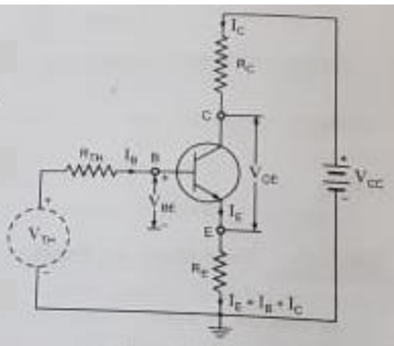
Differentiating above Eq. (13.19) w.r.t. I_C (considering V_{BE} to be independent of I_C) we have

$$0 = R_E + (R_{Th} + R_E)\frac{dI_B}{dI_C}$$

or $$\frac{dI_B}{dI_C} = \frac{-R_E}{R_{Th} + R_E}$$

stability factor S is given as

$$S = \frac{1+\beta}{1-\beta\dfrac{dI_B}{dI_C}}$$



(b) Simplified Equivalent Circuit

Substituting the value of $\frac{dI_B}{dI_C}$

$$\text{Stability factor, } S = \frac{1+\beta}{1+\beta\dfrac{R_E}{R_{Th}+R_E}} = (1+\beta)\frac{1+R_{Th}/R_E}{1+\beta+\dfrac{R_{Th}}{R_E}}$$

PRACTICE QUESTIONS:

Probable short questions with answers

1. What is transistor biasing (W2008, 2016, 2018)
   Ans:
   The proper flow of zero signal collector current and the maintenance of proper collector-emitter voltage during the passage of signal is known as Transistor Biasing.
   To achieve faithful amplification the following basic conditions must be satisfied:-
   - *Proper zero signal collector current*
   - *Minimum proper base-emitter voltage (V_{BE}) at any instant*
   - *Minimum proper collector-emitter voltage (V_{CE}) at any instant*

   The fulfillment of these will ensure that transistor works over the active region of the output characteristics.

2. What do you mean by stabilization and what are the factors required for the same (W2011, 2015, 2017, 2018, 2019)
   Ans: *The rate of change of collector current IC w.r.t. the collector leakage current ICO [= ICEO] at constant β and IB is called stability factor i.e.*

$$\text{Stability factor, } S = \frac{dI_C}{dI_{CO}} \text{ at constant } I_B \text{ and } \beta$$

   General Expression for Stability Factor S
   We know, Ic = βIb + (1+β) Ico
   Differentiating above equation with respect to Ic considering β to be constant, we have

$$1 = \beta \frac{d\,I_B}{d\,I_C} + (1+\beta)\frac{d\,I_{CO}}{d\,I_C} = \beta \frac{d\,I_B}{d\,I_C} + \frac{1+\beta}{S}$$

$$\text{So stability factor, } S = \frac{1+\beta}{1-\beta \frac{d\,I_B}{d\,I_C}}$$

3. Write down different methods of biasing?
4. Which type of biasing is better and why?
5. Define alpha and beta (W2019)
   Ans: *Alpha is defined as the ratio of change in collector current to change in emitter current at common base configuration.*
   Alpha = Ic / Ie

   Beta is defined as the ratio of change in collector current to change in base current at common emitter configuration
   $\beta = Ic / I_B$

6. What is Q-point and why it is essential (W2019)
   Ans: *Operating point of a transistor is also called Q-point and/or biased point. It is the DC voltage or current at a specified terminal of a transistor with no input signal applied. At this point transistor provides faithful amplification.*

Probable short questions with answers

1. Define alpha, beta and gamma if a circuit in various modes and explain the relationship among them (W2008, 2011, 2015, 2019)
2. Describe the different methods for transistor biasing. Derive expression for emitter follower biasing and

determine the equation. (W2015)

3. Explain feedback biasing.
4. Explain voltage divider biasing in detail with neat CKT diagram (W2015, 2016, 2017, 2019)
5. Define stability factor and explain the base registor method of transistor biasing (W2014)

CHAPTER - 6

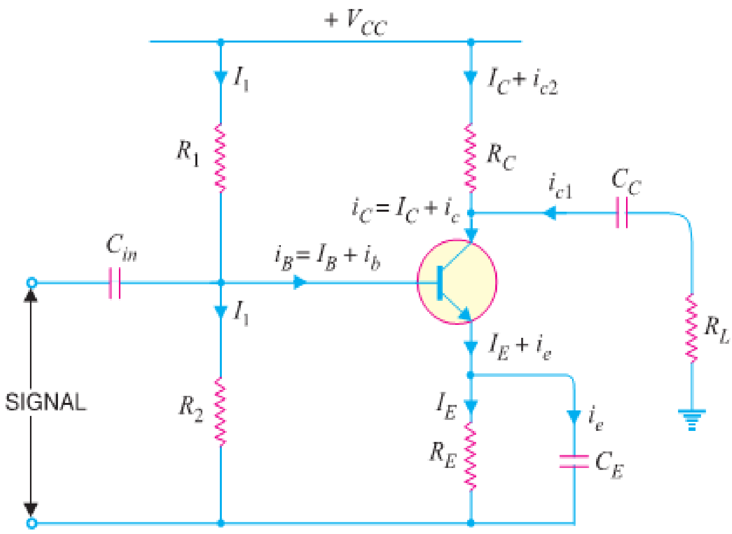
---------------------- [TRANSISTOR AMPLIFIERS & OSCILLATORS --------------------

LEARNING OBJECTIVE

6.1 Practical circuit of transistor amplifier
6.2 DC load line and DC equivalent circuit
6.3 AC load line and AC equivalent circuit
6.4 Calculation of gain
6.5 Phase reversal
6.6 H-parameters of transistors
6.7 Simplified H-parameters of transistors
6.8 Generalised approximate model
6.9 Analysis of CB, CE, CC amplifier using generalised approximate model
6.10 Multi stage transistor amplifier
6.10.1 R.C. coupled amplifier
6.10.2 Transformer coupled amplifier
6.11 Feed back in amplifier
6.11.1 General theory of feed back
6.11.2 Negative feedback circuit
6.11.3 Advantage of negative feed back
6.12 Power amplifier and its classification
6.12.1 Difference between voltage amplifier and power amplifier
6.12.2 Transformer coupled class A power amplifier
6.12.3 Class A push – pull amplifier
6.12.4 Class B push – pull amplifier
6.13 Oscillators
6.13.1 Types of oscillators
6.13.2 Essentials of transistor oscillator
6.13.3 Principle of operation of tuned collector, Hartley, colpitt, phase shift, wein- bridge oscillator (no mathematical derivations)

ARTICLE 6.1: PRACTICAL CIRCUIT TRANSISTOR AMPLIFIER

- In practice, voltage divider biasing circuit is used as an amplifier. DC signal is applied for biasing purpose only
- An input ac signal is applied for amplification
- For this, a capacitor (Cin) is placed between input signal and base of the transistor; similarly, capacitor (Co / Cc) is placed between collector and load, known as coupling capacitor
- Further, a bypass capacitor (Ce) is placed between emitter to ground.
- Accordingly, the circuit with indicative circuit diagram is shown in the adjacent figure



DETAILS OF CURRENTS

- **(i) Base Current: -** When no signal is applied in the base circuit, D.C. base current I_B flows due to biasing circuit.
- When A.C. signal is applied, A.C. base current i_b also flows.
- Therefore, with the application of signal, Total Base Current i_B is given by: $\mathbf{i_B = I_B + i_b}$

- **(ii) Collector Current: -** When no signal is applied, a D.C. collector current I_C flows due to biasing circuit.
- When A.C. signal is applied, A.C. collector current i_c also flows.
- Therefore, the Total Collector Current i_C is given by: - $\mathbf{i_C = I_C + i_c}$

  Where $I_C = \beta\ I_B$ = zero signal collector current and $i_c = \beta\ i_b$ = collector current due to signal.

- **(iii) Emitter Current**:- When no signal is applied, a D.C. emitter current IE flows.
- When A.C. signal is applied, A.C. Emitter Current ie also flows.
- Therefore the Total Emitter Current is : - $i_E = I_E + ie$

- It is useful to keep in mind that: $I_E = I_B + I_C$ and $i_e = i_b + i_c$.
- But base current is usually very small, therefore, as a reasonable approximation, $I_E \approx I_C$ and $i_e \approx i_c$.

❖ LOAD LINE ANALYSIS: -

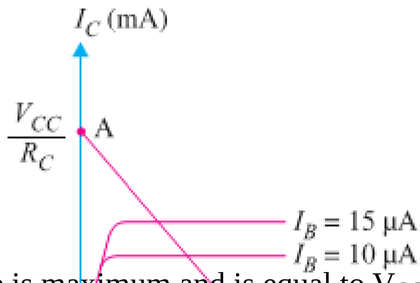
- In the transistor circuit analysis, it is generally required to determine the collector current for various values of collector-emitter voltages.
- One of the methods can be used to plot the output characteristics and determine the collector current at any desired collector-emitter voltage.
- However, a more convenient method, known as **load line method** can be used to solve such problems.
- This method is quite easy and is frequently used in the analysis of transistor applications.
- The line obtained by joining the maximum values of Ic and V_{ce} in the output characteristics of a transistor circuit is known as the DC Load Line

ARTICLE 6.2: D.C. LOAD LINE & DC EQUIVALENT CIRCUIT

- It is the line on the output characteristics of a transistor circuit which gives the values of I_C and V_{CE} corresponding to zero signal or D.C. conditions.
- Consider a common emitter NPN transistor circuit where no signal is applied.
- The value of collector-emitter voltage V_{CE} at any time is given by ; $V_{CE} = V_{CC} - I_C R_C$ Or $I_C R_C = V_{CC} - V_{CE}$

  Or $I_C = V_{CC}/ R_C - V_{CE}/ R_C$

  Or $I_C = (-1/ R_C) V_{CE} + V_{CC}/ R_C$ ($\equiv Y = mX + C$)



- As V_{CC} and R_C are fixed values, and can be represented by a straight line on the output characteristics. This is known as **D.C. Load Line.**

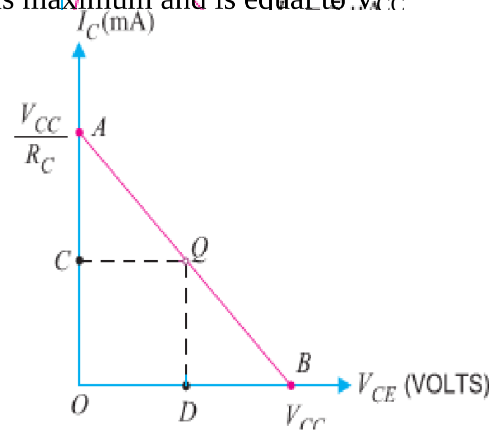
  (i) When the collector current $I_C= 0$, then collector-emitter voltage is maximum and is equal to V_{CC}

  i.e. Max. $V_{CE}= V_{CC} - I_C R_C = V_{CC}$ (As $I_C = 0$)
- This gives the first point B (OB $=V_{CC}$) on the collector-emitter voltage axis as shown in Fig.

  (ii) When collector-emitter voltage $V_{CE} = 0$, the collector current is maximum and is equal to V_{CC}/R_C

  i.e. $V_{CE}= V_{CC} - I_C R_C$ or $0 = V_{CC} - I_C R_C$

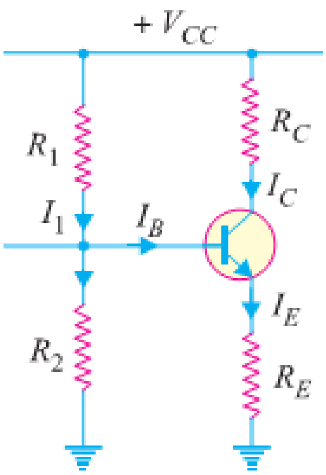
  ∴ Max. $I_C= V_{CC}/R_C$
- This gives the second point A (OA $=V_{CC}/R_C$) on the collector current axis as shown in Fig.
- By joining these two points, **D.C. Load Line** AB is constructed.



❖ **D. C. Equivalent Circuit: -** In order to draw the equivalent D.C. circuit, the following two steps are applied to the transistor circuit:-

(a) Reduce all A.C. sources to zero.

(b) Open all the capacitors.



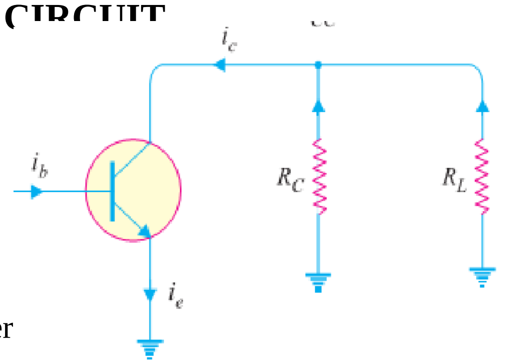
- Referring D.C. Equivalent Circuit

  D.C. Load $R_{DC}= R_C+ R_E$ & $V_{CC} = V_{CE}+ I_C (R_C+ R_E)$
- The maximum value of V_{CE} will occur when there is no collector current i.e. $I_C= 0$.

  ∴ **Maximum $V_{CE}= V_{CC}$**
- The maximum collector current will flow when $V_{CE}= 0$.

  ∴ **Maximum $I_C=V_{CC}/ (R_C+R_E)$**

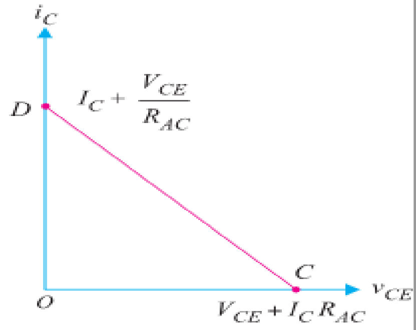
ARTICLE 6.3: A.C. LOAD LINE & AC EQUIVALENT CIRCUIT



This is the line on the output characteristics of a transistor circuit which gives the values of i_C and v_{CE} when signal is applied.

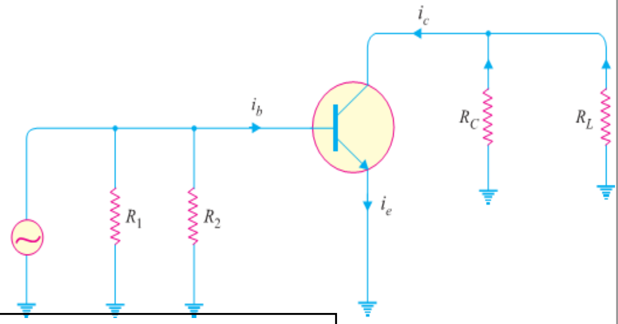
1. One maximum collector-emitter voltage point **($V_{CE\ MAX}$)** and
2. Other is maximum collector current point. **($I_{C\ MAX}$)**

- Under the application of A.C. signal, these values are Maximum collector-emitter voltage, $\mathbf{V_{CE\ MAX} = V_{CE} + I_C R_{AC}}$.
- This locates the point C of the A.C. load line on the collector-emitter voltage axis.
- Maximum collector current, $\mathbf{I_{C\ MAX} = I_C + V_{CE}/R_{AC}}$
- This locates the point D of A.C. load line on the collector-current axis.
- By joining points C and D, the **A.C. Load Line** CD is constructed.



A.C. Equivalent Circuit: - In order to draw A.C. equivalent circuit, the following two steps are applied to the transistor circuit:

(a) Reduce all D.C. sources to zero (i.e. V_{CC}= 0).
(b) Short all the capacitors.



- Referring A.C. Equivalent circuit A.C. load equal to $R_C \parallel R_L$ i.e.

A.C. load, $\mathbf{R_{AC} = (R_C R_L / (R_C + R_L)}$

- Maximum positive swing of A.C. collector-emitter voltage = $I_C \times R_{AC}$

∴ Total maximum **collector-emitter voltage,** $\mathbf{V_{CE\ MAX} = V_{CE} + I_C R_{AC}}$

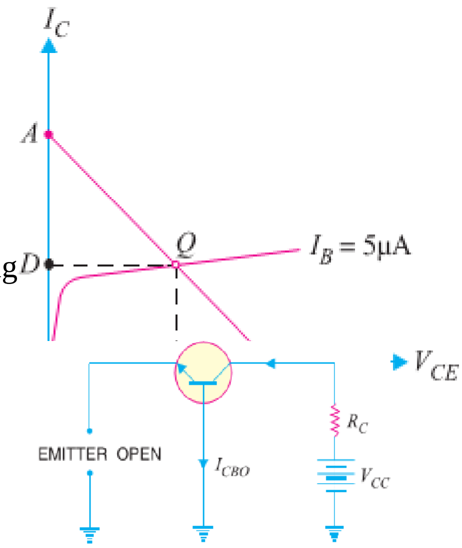
- Maximum positive swing of A.C. collector current = V_{CE}/R_{AC}

∴ Total maximum **collector current,** $\mathbf{I_{C\ MAX} = I_C + V_{CE}/R_{AC}}$

❖ OPERATING POINT: -

- The zero signal values of I_C and V_{CE} are known as the **Operating point**.
- It is called operating point because the variations of I_C and V_{CE} takes place about this point when signal is applied.
- It is also called quiescent (silent) point or **Q-Point** because it is the point on I_C –V_{CE} characteristic when the transistor is silent i.e. in the absence of the signal.
- The point Q where the load line and the characteristic intersect is the only point which satisfies both these conditions. Therefore, the point Q describes the actual state of affairs in the circuit in the zero sig operating point.

  It follows, therefore, that the zero signal values of I_C and V_{CE}(i.e. operating point) are determined by the point where d.c. load line intersects at proper base current curve.



ARTICLE 6.4: CALCULATION OF GAIN

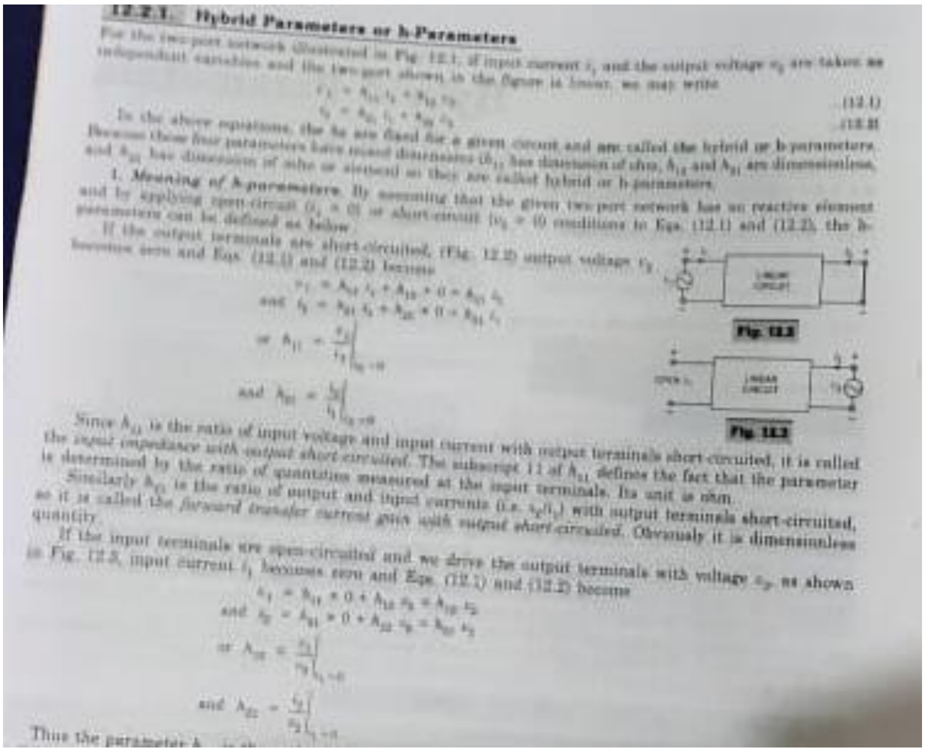
Current Gain = Output current / Input current = Ic / I_b = β I_b / I_b = β

Voltage gain = Output voltage / input voltage = - (Ic * Rc) / I_b * R_b = - β Rc/ R_b

ARTICLE 6.5: PHASE REVERSAL

In case of common emitter configuration, the output current becomes 180^o phase shift of input current. Similarly voltage also. So, in case of transistor, there is a phase shift of 180^0 between input and output signal. But in case of CC there is no phase shift.

ARTICLE 6.6: H-PARAMETER OF TRANSISTORS



12.2.1. Hybrid Parameters or h-Parameters

For the two-port network illustrated in Fig. 12.1, if input current i_1 and the output voltage v_2 are taken as independent variables and the two-port shown in the figure is linear, we may write

$$v_1 = h_{11} i_1 + h_{12} v_2 \quad (12.1)$$
$$i_2 = h_{21} i_1 + h_{22} v_2 \quad (12.2)$$

In the above equations, the hs are fixed for a given circuit and are called the hybrid or h-parameters. Because these four parameters have mixed dimensions (h_{11} has dimension of ohm, h_{12} and h_{21} are dimensionless, and h_{22} has dimension of mho or siemen) so they are called hybrid or h-parameters.

1. *Meaning of h-parameters.* By assuming that the given two-port network has no reactive element and by applying open-circuit ($i_1 = 0$) or short-circuit ($v_2 = 0$) conditions to Eqs. (12.1) and (12.2), the h-parameters can be defined as below.

If the output terminals are short-circuited, (Fig. 12.2) output voltage v_2 becomes zero and Eqs. (12.1) and (12.2) become

$$v_1 = h_{11} i_1 + h_{12} \times 0 = h_{11} i_1$$
and $$i_2 = h_{21} i_1 + h_{22} \times 0 = h_{21} i_1$$
or $$h_{11} = \frac{v_1}{i_1}\Big|_{v_2=0}$$
and $$h_{21} = \frac{i_2}{i_1}\Big|_{v_2=0}$$

Fig. 12.2

Fig. 12.3

Since h_{11} is the ratio of input voltage and input current with output terminals short-circuited, it is called the *input impedance with output short-circuited*. The subscript 11 of h_{11} defines the fact that the parameter is determined by the ratio of quantities measured at the input terminals. Its unit is ohm.

Similarly h_{21} is the ratio of output and input currents (i.e. i_2/i_1) with output terminals short-circuited, so it is called the *forward transfer current gain with output short-circuited*. Obviously it is dimensionless quantity.

If the input terminals are open-circuited and we drive the output terminals with voltage v_2, as shown in Fig. 12.3, input current i_1 becomes zero and Eqs. (12.1) and (12.2) become

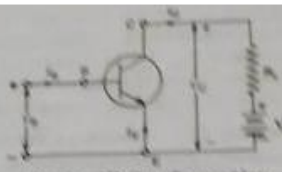
$$v_1 = h_{11} \times 0 + h_{12} v_2 = h_{12} v_2$$
and $$i_2 = h_{21} \times 0 + h_{22} v_2 = h_{22} v_2$$
or $$h_{12} = \frac{v_1}{v_2}\Big|_{i_1=0}$$
and $$h_{22} = \frac{i_2}{v_2}\Big|_{i_1=0}$$

Thus the parameter h...

ARTICLE 6.7: SIMPLIFIED h-PARAMETER OF TRANSISTOR

$$v_B = f_1(i_B, v_C) \quad \text{...(12.3)}$$
$$i_C = f_2(i_B, v_C) \quad \text{...(12.4)}$$

Making a Taylor's series expansion of Eqs. (12.3) and (12.4) about the zero signal operating point (I_B, V_C) and neglecting higher order terms we have



Basic CE Configuration

Fig. 12.7

$$\Delta v_B = \left.\frac{\delta f_1}{\delta i_B}\right|_{V_C} \Delta i_B + \left.\frac{\delta f_1}{\delta v_C}\right|_{I_B} \Delta v_C \quad \text{...(12.5)}$$

$$\Delta i_C = \left.\frac{\delta f_2}{\delta i_B}\right|_{V_C} \Delta i_B + \left.\frac{\delta f_2}{\delta v_C}\right|_{I_B} \Delta v_C \quad \text{...(12.6)}$$

where partial derivatives $\frac{\delta f_1}{\delta i_B}$ and $\frac{\delta f_2}{\delta i_B}$ are taken keeping collector voltage V_C constant while partial derivates $\frac{\delta f_1}{\delta v_C}$ and $\frac{\delta f_2}{\delta v_C}$ are taken keeping base current I_B constant.

The quantities Δv_B, Δv_C, Δi_B and Δi_C represent the small-signal (incremental) base and collector voltages and currents and may be represented as v_b, v_c, i_b, and i_c respectively as per standard notations. We may now write Eqs. (12.5) and (12.6) as below

$$v_b = h_{ie}\, i_b + h_{re}\, v_c \quad \text{...(12.7)}$$
$$i_c = h_{fe}\, i_b + h_{oe}\, v_c \quad \text{...(12.8)}$$

$$\text{where } h_{ie} = \left.\frac{\delta f_1}{\delta i_B}\right|_{V_C} = \left.\frac{\delta v_B}{\delta i_B}\right|_{V_C} = \left.\frac{v_b}{i_b}\right|_{V_C = 0} \quad \text{...(12.9a)}$$

S.No.	h-parameter	Common Base Configuration	Common Emitter Configuration	Common Collector Configuration
1.	h_{11}	h_{ib}	h_{ie}	h_{ic}
2.	h_{12}	h_{rb}	h_{re}	h_{rc}
3.	h_{21}	h_{fb}	h_{fe}	h_{fc}
4.	h_{22}	h_{ob}	h_{oe}	h_{oc}

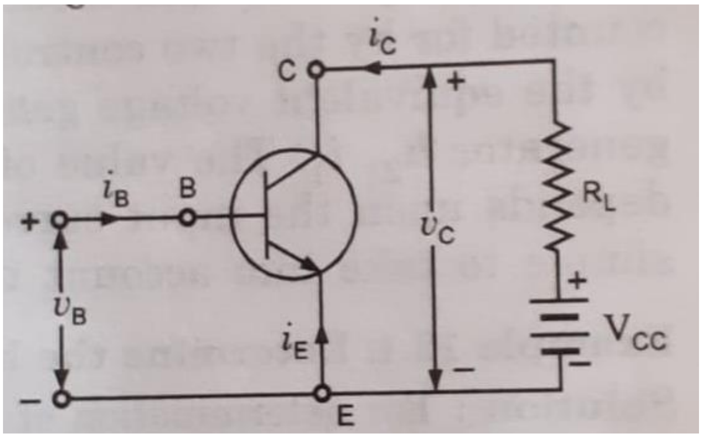
Since the two-port network (or the device) described by Eqs. (12.1) and (12.2) is assumed to have no
reactive elements, the four parameters h_{11}, h_{12}, h_{21} and h_{22} are real numbers and voltages and currents v_1,
v_2, and i_1, i_2 are functions of time. However, if the reactive elements had been included in the device, the
excitation would be considered to be sinusoidal, the h-parameters would in general be functions of frequency,
and the voltages and currents would be represented by phasors V_1, V_2, and I_1, I_2

ARTICLE 6.8: GENERALIZE APPROXIMATION MODEL

In a hybrid parameter model, the transistor parameters can be considered constant over a small range of operation above operating point or the quiescent point.

A set of parameters is specified for the transistor by the manufacturers

Let us consider the basic CE amplifier circuit given in the below figure.



The variables i_B, i_C, v_B, v_C, represent the total instantaneous values of current and voltage

Th input voltage v_B is a function of i_B, and v_C .

Similarly, output current i_C is a function of i_B, and v_C.

Hence, we can write

$v_B = h_{ie} * i_B + h_{re} * v_C$

and $i_C = h_{fe} * i_B + h_{oe} * v_C$

In other words;

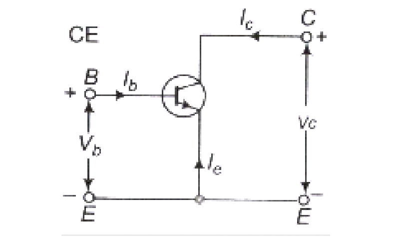
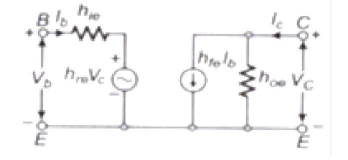
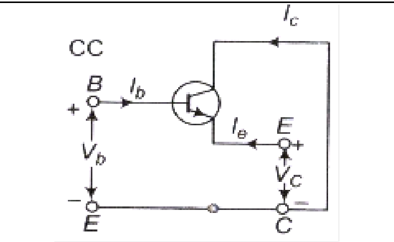
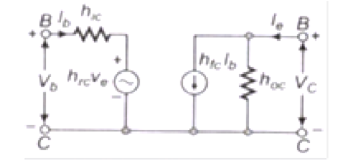
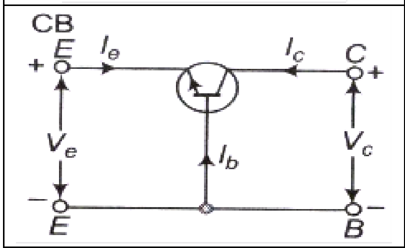
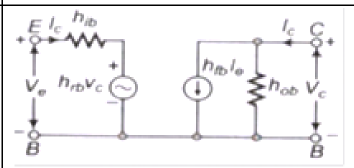
$h_{ie} = v_B / i_B$ (when v_C is 0)

$h_{re} = v_B / v_C$ (when i_B is 0)

$h_{fe} = i_C / i_B$ (when v_C is 0)

$h_{oe} = i_C / v_C$ (when i_B is 0)

ARTICLE 6.9: ANALYSIS OF CB, CE, CC AMPLIFIERS USING GENERALIZED APPROXIMATION MODEL

Circuit Schematic	Hybrid Model	Equations
		$V_b = h_{ie}I_b + h_{re}V_c$ $I_c = h_{fe}I_b + h_{oe}V_c$
		$V_b = h_{ic}I_b + h_{rc}V_e$ $I_e = h_{fc}I_b + h_{oc}V_e$
		$V_e = h_{ib}I_e + h_{rb}V_c$ $I_c = h_{fb}I_e + h_{ob}V_c$

ARTICLE 6.10: MULTI STAGE TRANSISTOR AMPLIFIER

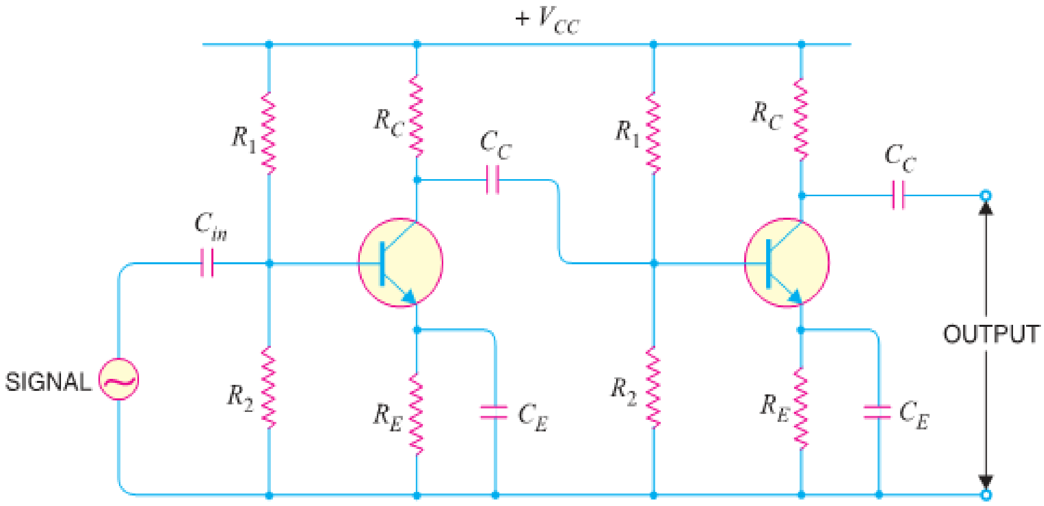
- The output from a single stage amplifier is usually insufficient to drive an output device. In other words, the gain of a single amplifier is inadequate for practical purposes.
- A transistor circuit containing *more than one stage of amplification* is known as *multistage transistor amplifier*.
- In a multistage amplifier, a number of single amplifiers are connected in cascade arrangement i.e. output of first stage is connected to the input of the second stage through a suitable coupling device and so on.
- The purpose of **coupling device** (e.g. a capacitor, transformer etc.) is
  - (i) to transfer A.C. output of one stage to the input of the next stage and
  - (ii) to isolate the D.C. conditions of one stage from the next stage.
- The name of the amplifier is usually given after the type of coupling used. e.g.

Name of coupling	*Name of multistage amplifier*
RC coupling	R-C coupled amplifier
Transformer coupling	Transformer coupled amplifier
Direct coupling	Direct coupled amplifier

ARTICLE 6.10.1: R-C COUPLED TRANSISTOR AMPLIFIER

- This is the most popular type of coupling

- Fig shows two stages of an RC coupled amplifier. A coupling capacitor C_C is used to connect the output of first stage to the base (i.e. input) of the second stage and so on.
- The resistances R_1, R_2 and R_E form the *biasing* and *stabilization* network. The emitter bypass capacitor offers *low reactance path* to the signal. Without it, the voltage gain of each stage would be lost.
- The coupling capacitor C_C transmits A.C. signal but blocks D.C. This prevents D.C. interference between various stages and the shifting of operating point.



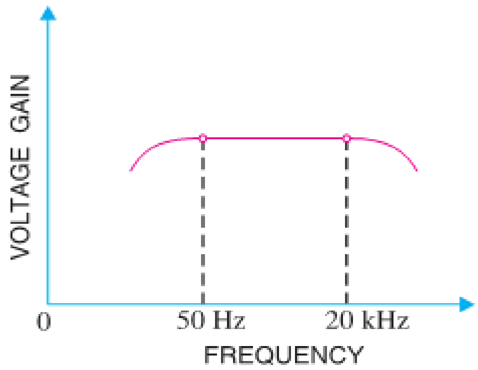
[Circuit Diagram of RC Coupled Transistor Amplifier]

OPERATION: -

- When A.C. signal is applied to the base of the first transistor, it appears in the amplified form across its collector load R_C.
- The amplified signal developed across RC is given to base of next stage through coupling capacitor C_C. The second stage does further amplification of the signal.
- In this way, the cascaded (one after another) stages amplify the signal and the overall gain is considerably increased.
- It may be mentioned here that total gain is less than the product of the gains of individual stages.
- It is because when a second stage is made to follow the first stage, the effective load resistance of first stage is reduced due to the shunting effect of the input resistance of second stage.
- This reduces the gain of the stage which is loaded by the next stage

FREQUENCY RESPONSE R-C COUPLED TRANSISTOR AMPLIFIER:

- Fig shows the frequency response of a typical RC coupled amplifier.
- **(i) At low frequencies** (< 50 Hz):- At this stage the reactance of coupling capacitor C_C is quite high and hence very small part of signal will pass from one stage to the next stage. Moreover, C_E cannot shunt the emitter resistance R_E effectively because of its large reactance at low frequencies. These two factors cause a falling of voltage gain at low frequencies.
- **(ii) At high frequencies** (> 20 kHz):-At this stage the reactance of C_C is very small and it behaves as a short circuit. These increases the loading effect of next stage and serves to reduce the voltage gain.



Moreover, at high frequency, capacitive reactance of base-emitter junction is low which increases the base current. This reduces the current amplification factor β. Due to these two reasons, the voltage gain drops off at high frequency.

(iii) At mid-frequencies (50 Hz to 20 kHz):- At this stage the voltage gain of the amplifier is constant. The effect of coupling capacitor in this frequency range is such so as to maintain a uniform voltage gain. Thus, as the frequency increases in this range, reactance of CC decreases which tends to increase the gain. However, at the same time, lower reactance means higher loading of first stage and hence lower gain. These two factors almost cancel each other, resulting in a uniform gain at mid-frequency.

- **ADVANTAGES:-**

(i) It has excellent frequency response. The gain is constant over the audio frequency range which is the region of most importance for speech, music etc.

(ii) It has lower cost since it employs resistors and capacitors which are cheap.

(iii) The circuit is very compact as the modern resistors and capacitors are small and extremely light.

- **DISADVANTAGES:-**

(i) The RC coupled amplifiers have low voltage and power gain. It is because the low resistance presented by the input of each stage to the preceding stage decreases the effective load resistance (R_{AC}) and hence the gain.

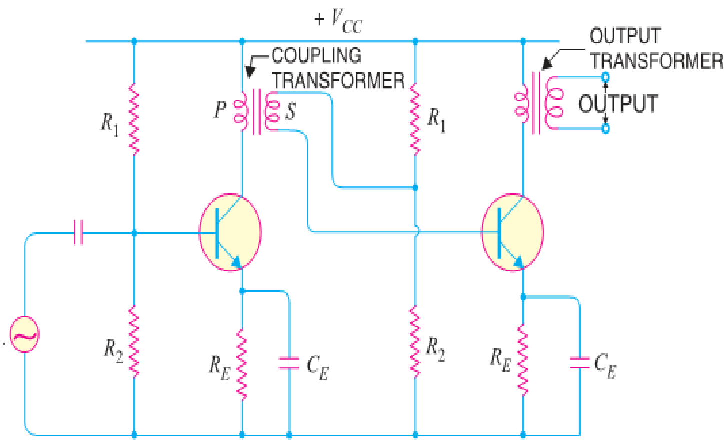
(ii) They have the tendency to become noisy with age, particularly in moist climates.

(iii) Impedance matching is poor. It is because the output impedance of RC coupled amplifier is several hundred ohms whereas the input impedance of a speaker is only a few ohms. Hence, little power will be transferred to the speaker.

- **APPLICATIONS:-**

- The RC coupled amplifiers have excellent audio fidelity over a wide range of frequency. Therefore, they are widely used as **voltage amplifiers** e.g. in the initial stages of public address system.
- If other type of coupling (e.g. transformer coupling) is employed in the initial stages, this results in frequency distortion which may be amplified in next stages.
- However, because of poor impedance matching, RC coupling is rarely used in the final stages.

ARTICLE 6.10.2: TRANSFORMER COUPLED AMPLIFIER



- A two-stage transformer coupled amplifier using N-P-N transistor (CE) is shown in the adjacent diagram
- The transformer coupled amplifier is shown in the adjacent figure
- In this case, the collector resistance (Rc/ load) of first transistor (T1) is replaced by a transformer whose primary side s connected to input transistor
- Secondary side of the transformer is connected to the base of the second / next transistor and the other side is connected to the joint of two base resistors of second transistor (T2).
- Similarly, another transformer is connected at the output of second transistor (T2)
- The output is taken from the secondary side of that transformer
- **Advantages:**
    - All the DC voltages supplied by Vcc is available at the collector due to absence of collector resistance Rc
    - Efficiency is more as there is no load resistance
    - It provides excellent impedance matching
    - The coupling is effective when the final output is fed to a low impedance load
- **Disadvantages**
    - Poor frequency response
    - It is bulky and costly system because of use of transformer
    - Transformer coupling tends to introduce hum in the output
- **Application:** It is used in the low frequency/ audio frequency signals

Comparison of Different Types of Coupling:-

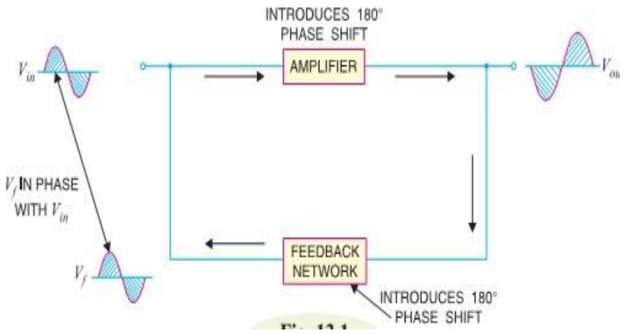
S. No	Particular	*RC* coupling	Transformer coupling	Direct coupling
1.	*Frequency response*	Excellent in the audio frequency range	Poor	Best
2.	*Cost*	Less	More	Least
3.	*Space and weight*	Less	More	Least
4.	*Impedance matching*	Not good	Excellent	Good
5.	*Use*	For voltage amplification	For power amplification	For amplifiying extremely low frequencies

ARTICLE 6.11: FEEDBACK AMPLIFIER

- **The process of injecting a fraction of output energy of some device back to input is known as feedback.**

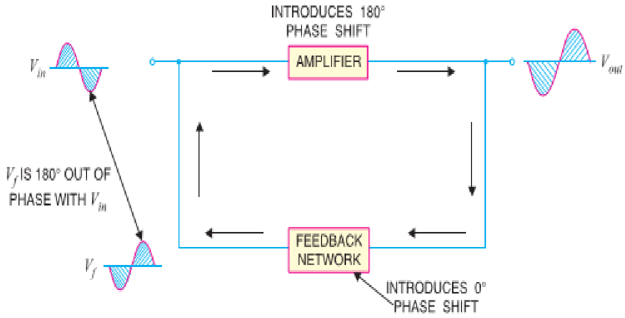
ARTICLE 6.11.1: GENERAL THEORY OF FEEDBACK

- Depending upon whether the feedback energy aids or opposes the input signal, there are two basic types of feedback in amplifiers viz Positive Feedback and Negative Feedback.
- **Positive Feedback**. When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called *positive feedback*. This is illustrated in Fig.



- Both amplifier and feedback network introduce a phase shift of 180°. The result is a 360° phase shift around the loop, causing the feedback voltage V_f to be in phase with the input signal V_{in}.
- The positive feedback increases the gain of the amplifier. However, it has the disadvantages of increased distortion and instability.

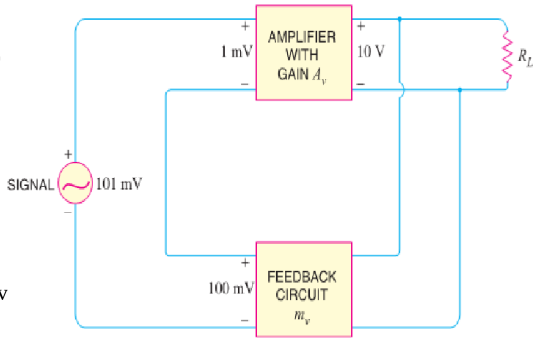
- One important use of positive feedback is in oscillators. If positive feedback is sufficiently large, it leads to oscillations. As a matter of fact, an oscillator is a device that converts d.c. power into a.c. power of any desired frequency.
- **(ii) Negative Feedback.** When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called *negative feedback*. This is illustrated in Fig.



- The amplifier introduces a phase shift of 180° into the circuit while the feedback network is so designed that it introduces no phase shift (i.e., 0° phase shift). The result is that the feedback voltage V_f is 180° out of phase with the input signal V_{in}.
- Negative feedback reduces the gain of the amplifier. However, the advantages of negative feedback are: reduction in distortion, stability in gain, increased bandwidth & improved input and output impedances.

- It is due to these advantages that negative feedback is frequently employed in amplifiers.

ARTICLE 6.11.2: NEGATIVE FEEDBACK CIRCUIT



- A feedback amplifier has main two parts such as an amplifier and a feedback circuit.
- The feedback circuit usually consists of resistors and returns a fraction of output energy back to the input.
- The following points are worth noting:-

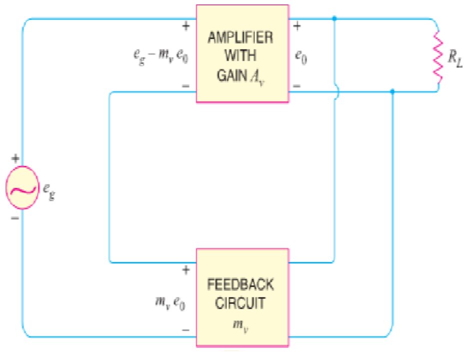
♣ In a negative voltage feedback circuit, the feedback fraction m_v is always between 0 and 1.

♣ The gain with feedback is sometimes called **closed-loop gain** while the gain without feedback is called ***open-loop gain***. These terms come from the fact that amplifier and feedback circuits form a "loop".

♣ When loop is "opened" by disconnecting feedback circuit from I/P, amplifier's gain $\mathbf{A_v}$,[open-loop gain]

♣ When the loop is "closed" by connecting the feedback circuit, gain decreases to $\mathbf{A_{vf}}$ ["closed-loop" gain]

- **GAIN OF NEGATIVE VOLTAGE FEEDBACK AMPLIFIER:-**



- Consider the negative voltage feedback amplifier shown in Fig.
- The gain of the amplifier without feedback is $\mathbf{A_v}$.
- Negative feedback is then applied by feeding a fraction $\mathbf{m_v}$ of the output voltage $\mathbf{e_0}$ back to amplifier input.
- Therefore, the actual input to the amplifier is the signal voltage $\mathbf{e_g}$ minus feedback voltage $\mathbf{m_v\, e_0}$ i.e.,

  Actual input to amplifier = $(e_g - m_v e_0)$

The output e_0 must be equal to the input voltage $(e_g - m_v e_0)$ multiplied by gain A_v of the amplifier

i.e. $(e_g - m_v e_0) A_v = e_0$ ➔ $A_v e_g - A_v m_v e_0 = e_0$

➔ $e_0 + A_v m_v e_0 = A_v e_g$ ➔ $e_0 (1 + A_v m_v) = A_v e_g$

$$\frac{e_0}{e_g} = \frac{A_v}{1+A_v m_v}$$

But $\mathbf{e_0/e_g}$ is the voltage gain of the amplifier with feedback.

∴ Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1+A_v m_v}$$

- It may be seen that the gain of the amplifier without feedback is A_v. However, when negative voltage feedback is applied, the gain is reduced by a factor $1 + A_v m_v$.
- It may be noted that negative voltage feedback does not affect the current gain of the circuit.

ARTICLE 6.11.3: ADVANTAGES OF NEGATIVE VOLTAGE FEEDBACK

- The following are the advantages of negative voltage feedback in amplifiers:-

♣ **Gain Stability**. An important advantage of negative voltage feedback is that the resultant gain of the amplifier can be made independent of transistor parameters or the supply voltage variations.

$$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

- For negative voltage feedback in an amplifier to be effective, the designer deliberately makes the product $A_v m_v$ much greater than unity. Therefore, in the above relation, 1 can be neglected as compared to $A_v m_v$ and the expression becomes:

$$A_{vf} = \frac{A_v}{A_v m_v} = \frac{1}{m_v}$$

- It may be seen that the gain now depends only upon feedback fraction m_v i.e., on the characteristics of feedback circuit. As feedback circuit is usually a voltage divider (a resistive network), therefore, it is unaffected by changes in temperature, variations in transistor parameters and frequency. Hence, the gain of the amplifier is extremely stable.

♣ **(ii) Reduces non-linear Distortion.** The negative voltage feedback reduces the nonlinear distortion in large signal amplifiers.

It can be proved mathematically that:

$$D_{vf} = \frac{D}{1 + A_v m_v}$$

Where D = distortion in amplifier without feedback

D_{vf} = distortion in amplifier with negative feedback

- Thus by applying negative voltage feedback to an amplifier, distortion is reduced by a factor $\mathbf{1 + A_v m_v}$.

(iii)Improves Frequency Response. As feedback is usually obtained through a resistive network, therefore, voltage gain of the amplifier is independent of signal frequency.

- The result is that voltage gain of the amplifier will be substantially constant over a wide range of signal frequency. The negative voltage feedback, therefore, improves the frequency response of the amplifier.

(iv)Increases Circuit Stability. The output of an ordinary amplifier is easily changed due to variations in ambient temperature, frequency and signal amplitude.

- This changes the gain of the amplifier, resulting in distortion. However, by applying negative voltage feedback, voltage gain of the amplifier is stabilized or accurately fixed in value.

(iv) Variation of input and output impedance: Depending upon the feedback circuit configuration, i.e. voltage series/ shunt feedback, current series / shunt feedback etc., the impedance can be changed accordingly.

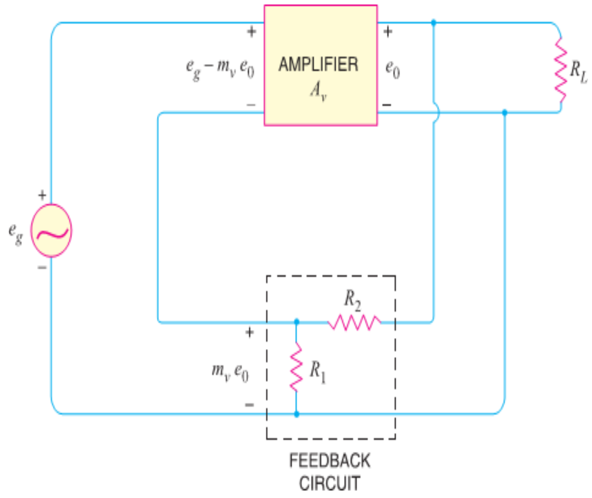
- **FEEDBACK CIRCUIT:-**

➢ The function of the feedback circuit is to return a fraction of the output voltage to the input of the amplifier.

➢ Fig. shows the feedback circuit of negative voltage feedback amplifier.

➢ It is essentially a potential divider consisting of resistances R_1 and R_2.

➢ The output voltage of the amplifier is fed to this potential divider which gives the feedback voltage to the input.



- **INPUT & OUTPUT IMPEDANCE OF NEGATIVE FEEDBACK AMPLIFIER :-**

♣ **(a) Input impedance.** The increase in input impedance with negative voltage feedback can be explained by referring to Fig.

➢ Suppose the input impedance of the amplifier is Z_{in} without feedback and Z'_{in} with negative feedback. Let us further assume that input current is i_1.

➢ Referring to Fig., we have,

$e_g - m_v e_0 = i_1 Z_{in}$

Now $e_g = (e_g - m_v e_0) + m_v e_0$

$= (e_g - m_v e_0) + A_v m_v (e_g - m_v e_0)$ [$\because e_0 = A_v (e_g - m_v e_0)$]

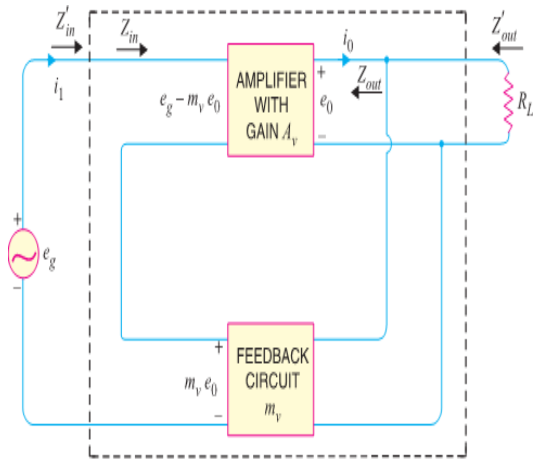
$= (e_g - m_v e_0)(1 + A_v m_v)$

$= i_1 Z_{in} (1 + A_v m_v)$ [$\because e_g - m_v e_0 =$

$i_1 Z_{in}$] Or — $= Z_{in} (1 + A_v m_v)$

But — $= Z'_{in}$, the input impedance of the amplifier with negative voltage feedback.

$$\therefore \; \mathbf{Z'_{in} = Z_{in} (1 + A_v m_v)}$$



➢ It is clear that by applying negative voltage feedback, the input impedance of the amplifier is increased by a factor $1 + A_v m_v$. As $A_v m_v$ is much greater than unity.

➢ Therefore, input impedance is increased considerably. This is an advantage, since the amplifier will now present less of a load to its source circuit.

♣ **(b) Output impedance.** Following similar line, we can show that output impedance with negative voltage feedback is given by :

$$\therefore \; \mathbf{Z'_{out} = Z_{out} / (1 + A_v m_v)}$$

Where Z'_{out} = output impedance with negative voltage feedback

Z_{out} = output impedance without feedback

➢ It is clear that by applying negative feedback, the output impedance of the amplifier is decreased by a factor $1 + A_v m_v$.

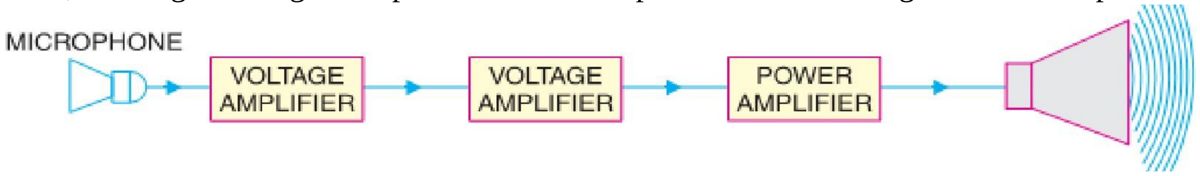
➢ This is an added benefit of using negative voltage feedback.

➢ With lower value of output impedance, the amplifier is much better suited to drive low impedance loads.

ARTICLE 6.12: POWER AMPLIFIERS

INTRODUCTION:-

- A practical amplifier always consists of a number of stages that amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device.
- The first few stages in this multistage amplifier have the function of only voltage amplification. However, last stage is designed to provide maximum power. This final stage is known as power stage.



- **Transistor Audio Power Amplifier: -**

- A transistor amplifier which raises the power level of signals having audio frequency range is known as transistor **Audio Power Amplifier**. Generally last stage of a multistage amplifier is the power stage.
- The power amplifier differs from all the previous stages in that here a concentrated effort is made to obtain maximum output power.
- A transistor that is suitable for power amplification is generally called a *power transistor*.

CLASSIFICATION OF POWER AMPLIFIERS

- Transistor power amplifiers handle large signals. Many of them are driven by the input large signal that collector current is either cut-off or is in the saturation region during a large portion of the input cycle.
- Therefore, such amplifiers are generally classified according to their mode of operation i.e. the portion of the input cycle during which the collector current is expected to flow. On this basis, they are classified as:
  - Class A
  - Class B
  - Class AB
  - Class C
  - Class D
- **Class A amplifier**: In this case the transistor is so biased that the output current flows for the entire cycle of input signal. Thus, the transistor operates only over the linear region of its load line.
- **Class B amplifier**: In this case the transistor is so biased that the output current flows during positive half cycle of input signal. Thus, the transistor operates at cut-off region of load line.
- **Class AB amplifier**: In this case the transistor is so biased that the output current flows for more than half cycle and less than full cycle of input signal. It operates at above the zero base current.
- **Class C amplifier**: In this case the transistor is so biased that the output current flows for less than the half cycle of input signal, and will operate only with a tuned or resonant circuit which provides a full cycle of operation.
- **Class D amplifier**: Class D power amplifier is designed to operate with digital or pulse type signals.

ARTICLE 6.12.1: DIFFERENCE BETWEEN VOLTAGE AND POWER AMPLIFIERS

- The difference between the two types is really one of degree; it is a question of how much voltage and how much power.
- A voltage amplifier is designed to achieve maximum voltage amplification. It is, however, not important to raise the power level.
- On the other hand, a power amplifier is designed to obtain maximum output power.

1) **Voltage Amplifier.** The voltage gain of an amplifier is given by : $\mathbf{A_v = \beta \times \frac{R_C}{R_{in}}}$

- In order to achieve high voltage amplification, the following features are incorporated in such amplifiers:
  - ♣ The transistor with high β(>100) is used in the circuit. i.e. Transistors are employed having thin base.
  - ♣ The input resistance R_{in} of transistor is sought to be quite low as compared to the collector load R_C.
  - ♣ A relatively high load R_C is used in the collector. To permit this condition, voltage amplifiers are always operated at low collector currents (≈ mA). If the collector current is small, we can use large R_C in the collector circuit

2) **Power Amplifier.** A power amplifier is required to deliver a large amount of power and as such it has to handle large current.

- In order to achieve high power amplification, the following features are incorporated in such amplifiers:
  - ♣ The size of power transistor is made considerably larger in order to dissipate the heat produced in the transistor during operation.
  - ♣ The base is made thicker to handle large currents. In other words, transistors with comparatively smaller β are used.
  - ♣ Transformer coupling is used for impedance matching.

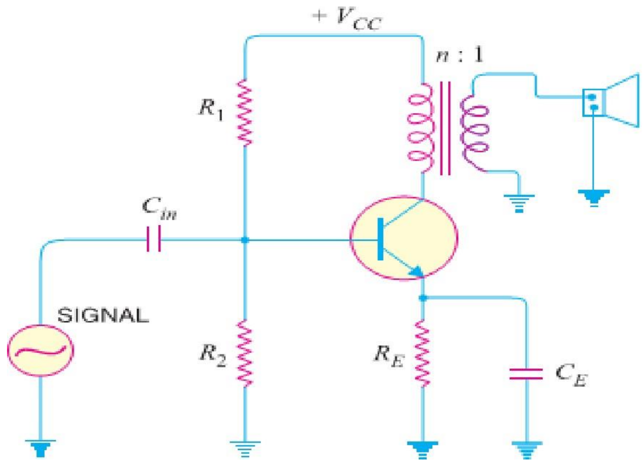
The comparison between voltage and power amplifiers is given below in the tabular form :

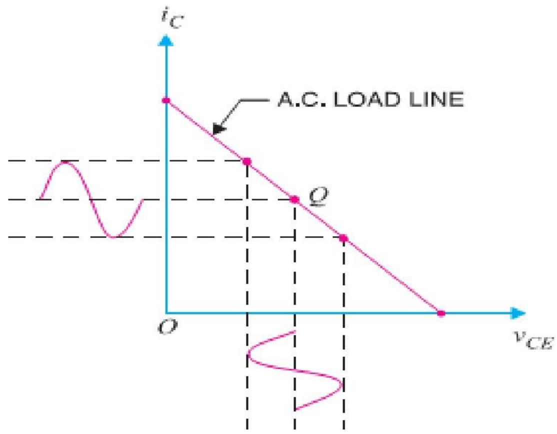
S. No.	Particular	Voltage amplifier	Power amplifier
1.	β	High (> 100)	low (5 to 20)
2.	R_C	High (4 – 10 kΩ)	low (5 to 20 Ω)
3.	*Coupling*	usually *R – C* coupling	Invariably transformer coupling
4.	*Input voltage*	low (a few mV)	High (2 – 4 V)
5.	*Collector current*	low (≃ 1 mA)	High (> 100 mA)
6.	*Power output*	low	high
7.	*Output impedance*	High (≃ 12 kΩ)	low (200 Ω)

ARTICLE 6.12.2: TRANSFORMER COUPLED CLASS A AMPLIFIER

If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as *class A power amplifier*.

- The power amplifier must be biased in such a way that no part of the signal is cut off. Fig (i) shows circuit of class A power amplifier. Note that collector has a transformer as the load which is most common for

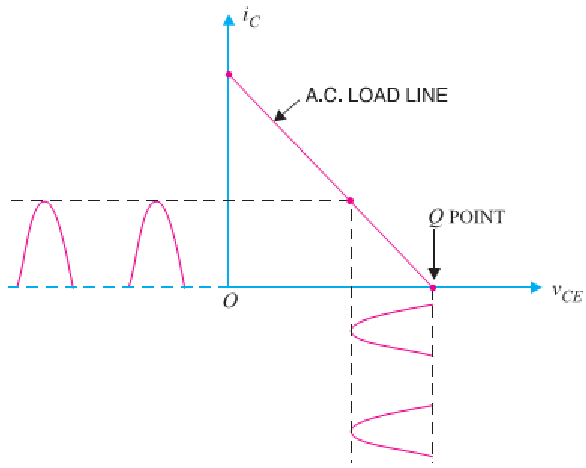




all classes of power amplifiers.

- The use of transformer permits impedance matching, resulting in the transference of maximum power to the load e.g. loudspeaker. Fig (ii) shows the class A operation in terms of a.c. load line.
- The operating point Q is so selected that collector current flows at all times throughout the full cycle of the applied signal. As the output wave shape is exactly similar to the input wave shape, therefore, such amplifiers have least distortion.
- However, they have the disadvantage of low power output and low collector efficiency (about 35%).
- **CLASS B POWER AMPLIFIER**: - If the collector current flows only during the positive half-cycle of the input signal, it is called a *class B power amplifier*.
- In class B operation, the transistor bias is so adjusted that zero signal collector current is zero i.e. no biasing circuit is needed at all.
- During the positive half-cycle of the signal, the input circuit is forward biased and hence collector current flows. However, during the negative half-cycle of the signal, the input circuit is reverse biased and no collector current flows.

- Fig. shows the class B operation in terms of a.c. load line.
- The operating point Q shall be located at collector cut off voltage.
- It is easy to see that output from a class B amplifier is amplified half-wave rectification.
- In a class B amplifier, the negative half-cycle of the signal is cut off and hence a severe distortion occurs.
- However, class B amplifiers provide higher power output and collector efficiency (50 − 60%).
- Such amplifiers are mostly used for power amplification in push-pull arrangement.
- In such an arrangement, 2 transistors are used in class B operation. One transistor amplifies the positive half cycle of the signal while the other amplifies the negative half-cycle.



- **CLASS C POWER AMPLIFIER**. If the collector current flows for less than half-cycle of the input signal, it is called *class C power amplifier*.
- In class C amplifier, the base is given some negative bias so that collector current does not flow just when the positive half-cycle of the signal starts.
- Such amplifiers are never used for power amplification. However, they are used as tuned amplifiers i.e. to amplify a narrow band of frequencies near the resonant frequency.

IMPORTANT POINTS ABOUT CLASS-A POWER AMPLIFIER : -

- **(i)** A Transformer coupled class A power amplifier has a maximum collector efficiency of 50% i.e., maximum of 50% d.c. supply power is converted into a.c. power output.
- In practice, the efficiency of such an amplifier is less than 50% (about 35%) due to power losses in the output transformer, power dissipation in the transistor etc.
- **(ii)** The power dissipated by a transistor is given by :

$$P_{dis} = P_{dc} - P_{ac}$$

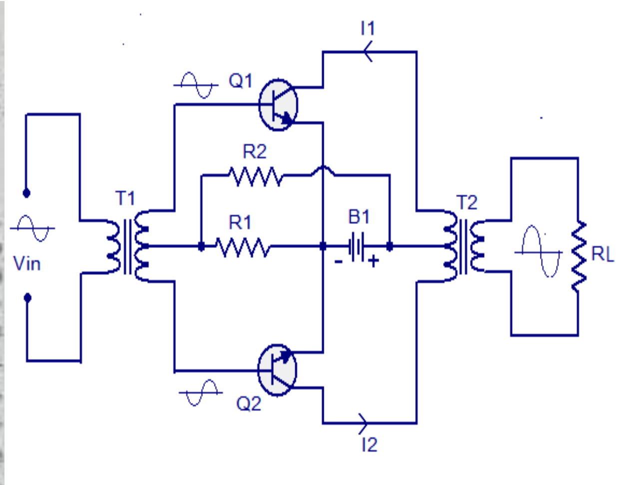
Where P_{dc}= available d.c. power

& P_{ac} = available a.c. power

- So, In class A operation, Transistor must dissipate less heat when signal is applied therefore runs cooler.
- **(iii)** When no signal is applied to a class A power amplifier, P_{ac}= 0. ∴ P_{dis}= Pdc
- Thus in class A operation, maximum power dissipation in the transistor occurs under zero signal conditions.
- Therefore, the power dissipation capability of a power transistor (for class A operation) must be at least equal to the zero signal rating.
- **(iv)** When a class A power amplifier used in final stage, it is called single ended class A power amplifier.

ARTICLE 6.12.3: CLASS A PUSH – PULL AMPLIFIER

A class A push-pull amplifier circuit is shown in Fig. By class A push-pull amplifier means that current flows in the output of the active device (each transistor) for the whole of the input cycle.

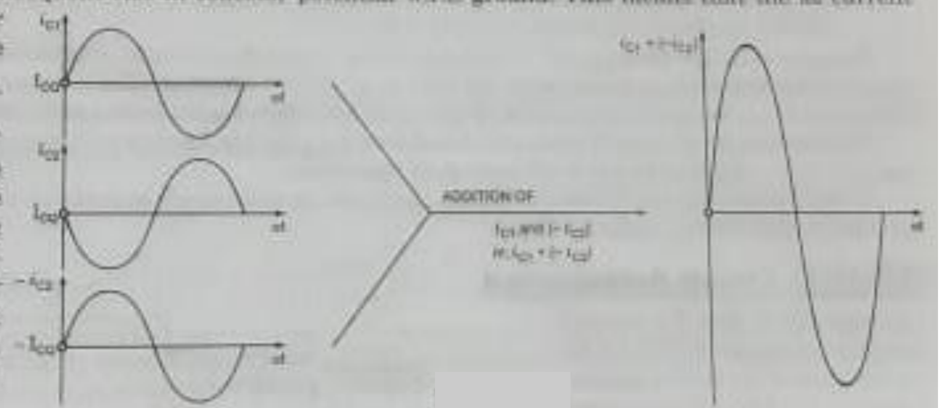


Circuit Arrangement

The circuitry of a typical push-pull amplifier is shown in Fig. 18.24. As already mentioned, push-pull amplifier uses two identical transistors, say Q_1 and Q_2. The emitter terminals of the two transistors Q_1 and Q_2 connected together. The input signal is applied to the inputs of two transistors through centre-tapped step-up transformer T_1, which provides opposite polarity signals to the two transistors. The collector terminals of both the transistors are connected to end terminals of centre-tapped primary of output transformer T_2. The power supply V_{CC} is connected between the emitter terminals and the centre-tap of primary of output transformer. Resistors R_1 and R_2 are used to provide the proper bias for the circuit. The load R_L is connected across the secondary of the output transformer T_2. The turn-ratio ($2N_1 : N_2$) of the output transformer is chosen so as to match the load with the output impedance of the amplifier and therefore, transfer maximum power. The quiescent currents of the two transistors, which are equal in magnitude, flow in opposite directions through each half of primary of the output transformer T_2, so no saturation of the magnetic core occurs.

Circuit Operation

When the base current of one transistor is being driven positive with respect to the quiescent point Q, the collector current increases, thus causing a decrease in collector potential relative to ground. At the same time, however, a reverse action takes place in the base circuit of the second transistor, *i.e.* base current decreases causing a drop in the collector current with a consequent rise in collector potential w.r.t. ground. This means that the ac current flowing through the transformer primary winding is in the same direction. As I_{C_1} increases (*i.e.* pulls), the current I_{C_2} decreases (*i.e.* pushes). Hence the name ***push-pull amplier***. The overall operation results in ac voltage induced in the secondary of the output transformer and thus ac power is delivered to the load. The difference of two collector currents is illustrated in .



EFFICIENCY:

and overall efficiency becomes equal to collector efficiency and

$$= \frac{P_{out\,(ac)}}{V_{CC}\, I_{CQ}}$$

Under condition of development of maximum ac power, voltage swings from $V_{CE\ max}$ to zero and collector current from $I_{C\ max}$ to zero. So

$$V_{rms} = \frac{1}{\sqrt{2}}\left[\frac{V_{CE\,max} - V_{CE\,min}}{2}\right] = \frac{V_{CE\,max}}{2\sqrt{2}} = \frac{2\,V_{CC}}{2\sqrt{2}} = \frac{V_{CC}}{\sqrt{2}}$$

$$\text{and } I_{rms} = \frac{1}{\sqrt{2}}\left[\frac{I_{C\,max} - I_{C\,min}}{2}\right] = \frac{I_{C\,max}}{2\sqrt{2}} = \frac{2\,I_{CQ}}{2\sqrt{2}} = \frac{I_{CQ}}{\sqrt{2}}$$

AC power developed across the load, $P_{out\,(ac)} = V_{rms}\, I_{rms} = \frac{V_{CC}}{\sqrt{2}} \cdot \frac{I_{CQ}}{\sqrt{2}} = \frac{V_{CC}\, I_{CQ}}{2}$

$$\text{Collector efficiency, } \eta_{collector} = \frac{P_{out\,(ac)}}{V_{CC}\, I_{CQ}} = \frac{V_{CC}\, I_{CQ}/2}{V_{CC}\, I_{CQ}} = 0.5 \text{ or } 50\% \qquad \text{...(18.17)}$$

Thus for a transformer coupled class A power amplifier the maximum theoretical efficiency is 50%. In practice, the efficiency of such an amplifier is somewhat less than 50%. It is about 30%.

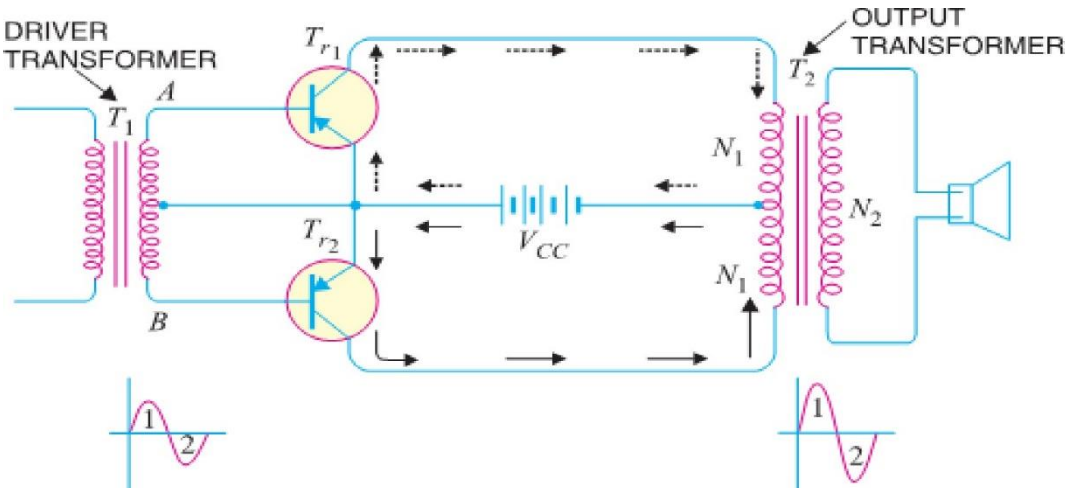
ADVANTAGES:

- Here even harmonics are eliminated, so more output is obtained
- Due to the presence of the transformer winding, the ripple voltage will not appear in the load

DISADVANTAGES:

- We may not get identical transformers
- It required bulky and expensive transformers

ARTICLE 6.12.4: CLASS B PUSH-PULL AMPLIFIER



- The push-pull amplifier is a power amplifier and is frequently employed in the output stages of electronic circuits. It is used whenever high output power at high efficiency is required. Fig. shows the circuit of a push-pull amplifier.
- Two transistors T_{r1} and T_{r2} placed back to back are employed. Both transistors are operated in class B operation i.e. collector current is nearly zero in the absence of the signal.
- The centre tapped secondary of driver transformer T_1 supplies equal and opposite voltages to the base circuits of two transistors. The output transformer T_2 has the centre-tapped primary winding. The supply voltage V_{CC} is connected between the bases and this centre tap.
- The loudspeaker is connected across the secondary of this transformer.

CIRCUIT OPERATION.

- The input signal appears across the secondary AB of driver transformer. Suppose during the first half-cycle (marked 1) of the signal, end A becomes positive and end B negative.
- This will make the base-emitter junction of T_{r1} reverse biased and that of T_{r2} forward biased. The circuit will conduct current due to T_{r2} only and is shown by solid arrows.
- Therefore, this half-cycle of the signal is amplified by T_{r2} and appears in the lower half of the primary of output transformer. In the next half cycle of the signal, T_{r1} is forward biased whereas T_{r2} is reverse biased. Therefore, T_{r1} conducts and is shown by dotted arrows.
- Consequently, this half-cycle of the signal is amplified by T_{r1} and appears in the upper half of the output transformer primary. The centre-tapped primary of the output transformer combines two collector currents to form a sine wave output in the secondary.
- It may be noted here that push-pull arrangement also permits a maximum transfer of power to the Load through impedance matching. If R_L is the resistance appearing across secondary of output transformer, then resistance R'_L of primary shall become:

$$\mathbf{R'_L = \left(\frac{2N_1}{N_2}\right)^2 R_L}$$

Where N_1 = Number of turns between either end of primary winding and centre-tap
N_2 = Number of secondary turns

EFFICIENCY

Input DC power is given by:

$P_{dc} = V_{CC} I_{dc}$ where I_{dc} is the average or direct current taken from the dc supply V_{CC}.
In class B operation the current drawn from a single power supply is a full-wave rectified signal, thus

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_{C\,max} \sin\theta \, d\theta = \frac{2 I_{C\,max}}{\pi}$$

$$\text{Thus } P_{dc\,(in)} = \frac{2}{\pi} V_{CC} I_{C\,max} \qquad \text{...(18.42)}$$

$$\text{AC power output, } P_{ac\,(out)} = V_{rms} I_{rms} = \frac{V_{CC}}{\sqrt{2}} \cdot \frac{I_{C\,max}}{\sqrt{2}} = \frac{V_{CC} I_{C\,max}}{2} \qquad \text{...(18.44)}$$

Total collector power dissipation for the two transistors,

$$= P_{dc\,(in)} - P_{ac\,(out)} = \frac{2}{\pi} V_{CC} I_{C\,max} - \frac{V_{CC} I_{C\,max}}{2} = 2 I_{C\,max}\left(\frac{V_{CC}}{\pi} - \frac{V_{CC}}{4}\right)$$

$$\text{Overall efficiency, } \eta_{overall} = \frac{P_{ac\,(out)}}{P_{dc\,(in)}} = \frac{V_{CC} I_{C\,max}/2}{2 V_{CC} I_{C\,max}/\pi} = \frac{\pi}{4} = 0.785 \text{ or } 78.5\% \qquad \text{...(18.45)}$$

ADVANTAGES

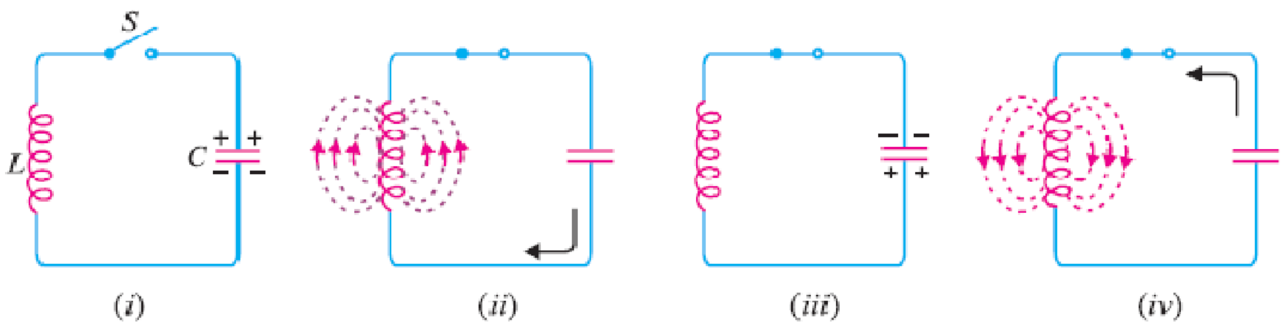
1) The efficiency of the circuit is quite high (≈ 75%) due to class B operation.
2) A high a.c. output power is obtained.

DISADVANTAGES

1) Two transistors have to be used.
2) It requires two equal and opposite voltages at the input. Therefore, push-pull circuit requires the use of driver stage to furnish these signals.
3) If the parameters of the two transistors are not the same, there will be unequal amplification of the two halves of the signal.
4) The circuit gives more distortion.
5) Transformers used are bulky and expensive.

ARTICLE 6.13: OSCILLATOR

- An electronic device that generates oscillations of desired frequency is known as a **oscillator**. Although we speak of an oscillator as "generating" a frequency, it should be noted that it does not create energy, but merely acts as an energy converter.
- It receives D.C. energy and changes it into A.C. energy of our desired frequency.
- The frequency of oscillations depends upon the constants of the device.



♣ A transistor amplifier with proper positive feedback will work as an oscillator.

♣ In order to get continuous undamped output from the circuit, the following condition must be met:

$$\mathbf{m_v A_v = 1}$$

Where $\mathbf{A_v}$ = Voltage Gain of Amplifier without Feedback and $\mathbf{m_v}$ = Feedback Fraction

♣ This relation is called **Barkhausen Criterion**.

ARTICLE 6.13.1: TYPES OF OSCILLATORS

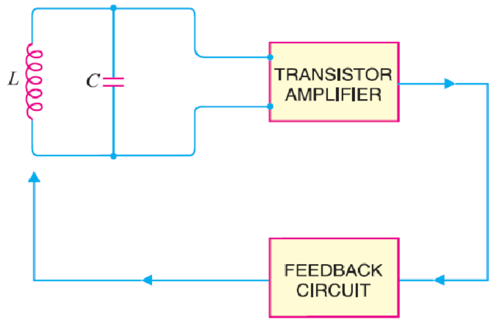
(i) Tuned Collector Oscillator (ii) Colpitt's Oscillator
(iii) Hartley Oscillator (iv) Phase Shift Oscillator
(v) Wien Bridge Oscillator (vi) Crystal Oscillator

ARTICLE 6.13.2: ESSENTIALS OF TRANSISTOR OSCILLATOR: -

- Fig shows the block diagram of an oscillator. Its essential components are : -

♣ **Tank circuit**. It consists of inductance coil (L) connected in parallel with capacitor (C).

- The frequency of oscillations circuit depend upon the values of inductance of the coil and capacitance of the capacitor.

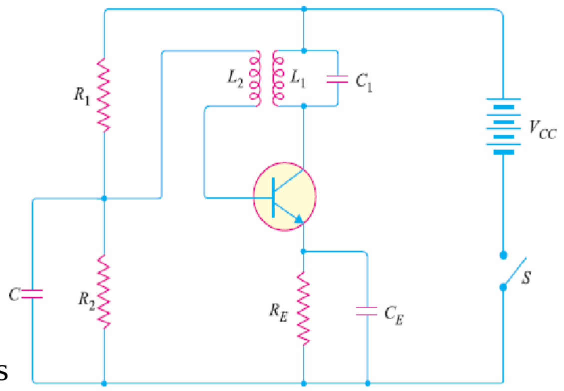


♣ **(ii) Transistor Amplifier.** The transistor amplifier receives D.C. power from the battery and changes it into a.c. power for supplying to the tank circuit.

- The oscillations occurring in the tank circuit are applied to the input of the transistor amplifier. Because of the amplifying properties of the transistor, we get increased output of these oscillations.
- This amplified output of oscillations is due to the D.C. power supplied by the battery.
- The output of the transistor can be supplied to the tank circuit to meet the losses.

♣ **(iii) Feedback Circuit**. The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillations i.e. it provides positive feedback.

ARTICLE 6.13.3: TUNED COLLECTOR OSCILLATOR:-



- Fig shows circuit of tuned collector oscillator. It contains tuned circuit L1 - C1 in the collector and hence the name.
- The frequency of oscillations depends upon the values of L1 and C1 and is given by :

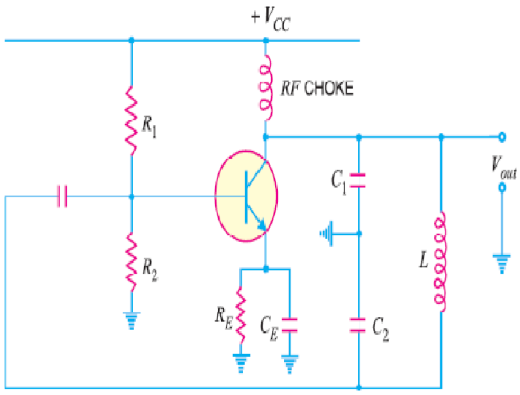
$$f = \frac{1}{2\Pi(L_1C_1)^{2}}$$

- The feedback coil L_2 in the base circuit is magnetically coupled to the tank circuit coil L_1. In practice, L_1 and L_2 form the primary and secondary of the transformer respectively.
- The biasing is provided by potential divider arrangement. The capacitor C connected in the base circuit provides low reactance path to the oscillations.

♣ **Circuit Operation**. When switch S is closed, collector current starts increasing and charges the capacitor C_1. When this capacitor is fully charged, it discharges through coil L_1, setting up oscillations of frequency determined by above equation.

- These oscillations induce some voltage in coil L2 by mutual induction. The frequency of voltage in coil L2 is the same as that of tank circuit but its magnitude depends upon the number of turns of L2 and coupling between L1 and L2.
- The voltage across L2 is applied between base and emitter and appears in the amplified form in the collector circuit, thus overcoming the losses occurring in the tank circuit.
- The number of turns of L2 and coupling between L1 and L2 are so adjusted that oscillations across L2 are amplified to a level just sufficient to supply losses to the tank circuit.
- It may be noted that the phase of feedback is correct i.e. energy supplied to the tank circuit is in phase with the generated oscillations. A phase shift of 180° is created between the voltages of L1 and L2 due to transformer action.
- A further phase shift of 180° takes place between base-emitter and collector circuit due to transistor properties. As a result, the energy feedback to the tank circuit is in phase with the generated oscillations.

- **COLPITT'S OSCILLATOR:-**



- Fig shows a Colpitt's oscillator. It uses two capacitors and placed across a common inductor L and the centre of the two capacitors is tapped.
- The tank circuit is made up of C_1, C_2 and L. The frequency of oscillations is determined by the values of C_1, C_2 and L and is given by ;

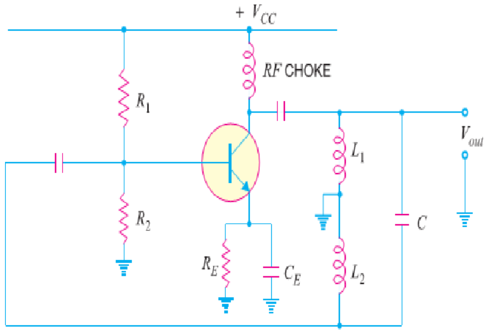
$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC_1}+\frac{1}{LC_2}}$$

✡ Note that **$C_1 - C_2 - L$** is also the feedback circuit that produces a phase shift of 180°.

♣ **Circuit Operation.** When the circuit is turned on, the capacitors C_1 and C_2 are charged. The capacitors discharge through L, setting up oscillations of frequency determined by exp.(i).

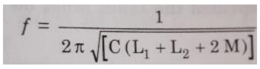
- Output voltage of the amplifier appears across C_1 and feedback voltage is developed across C_2. The voltage across it is 180° out of phase with the voltage developed across C_1 (V_{out}) as shown in Fig.
- It is easy to see that voltage feedback (voltage across C_2) to the transistor provides positive feedback.
- A phase shift of 180° is produced by transistor and a further phase shift of 180° is produced by $C_1 - C_2$ voltage divider. In this way, feedback is properly phased to produce continuous undamped oscillation.

- **HARTLEY OSCILLATOR:-**



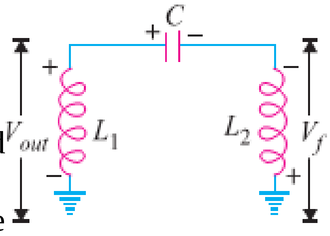
✍ The Hartley oscillator is similar to Colpitt's oscillator with minor modifications. Instead of using tapped capacitors, two inductors L_1 and L_2 are placed across a common capacitor C and the centre of the inductors is tapped as shown in Fig.

✍ The tank circuit is made up of L_1, L_2 and C.



$$f = \frac{1}{2\pi\sqrt{[C(L_1 + L_2 + 2M)]}} \quad \text{(i)}$$

Where $\mathbf{L_T = L_1 + L_2 + 2M}$ & M= Mutual inductance between L_1 & L_2



♣ **<u>Circuit Operation</u>**. When the circuit is turned on, the capacitor is charged. When this capacitor is fully charged, it discharges through coils L_1 and L_2 setting up oscillations of frequency determined by equ(i).

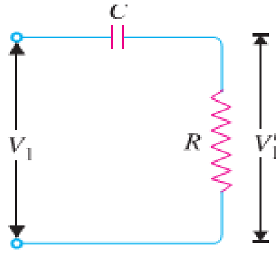
✍ The output voltage of the amplifier appears across L_1 and feedback voltage across L_2. The voltage across L_2 is 180° out of phase with the voltage developed across L_1 (V_{out}) as shown in Fig.

✍ It is easy to see that voltage feedback (i.e., voltage across L_2) to transistor provides positive feedback.

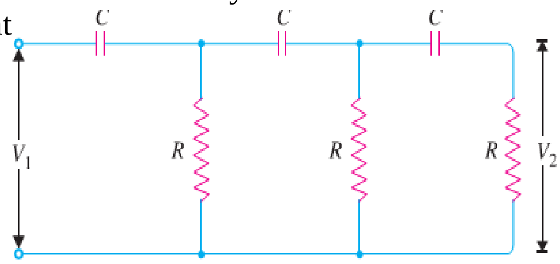
✍ A phase shift of 180° is produced by the transistor & further phase shift of 180° is produced by L_1 – L_2 voltage divider. In this way, feedback is properly phased to produce continuous undamped oscillations.

- **PRINCIPLE OF PHASE SHIFT OSCILLATORS:-**

- One desirable feature of an oscillator is that it should feedback energy of correct phase to the tank circuit to overcome the losses occurring in it.
- In the oscillator circuits discussed so far, the tank circuit employed inductive (L) and capacitive (C) elements. In such circuits, a phase shift of 180° was obtained due to inductive or capacitive coupling and a further phase shift of 180° was obtained due to transistor properties.
- In this way, energy supplied to the tank circuit was in phase with the generated oscillations. The oscillator circuits employing L-C elements have two general drawbacks.
- **Firstly**, they suffer from frequency instability and poor waveform. **Secondly**, they cannot be used for very low frequencies because they become too much bulky and expensive.
- Good frequency stability and waveform can be obtained from oscillators employing resistive and capacitive elements. Such amplifiers are called R-C or phase shift oscillators and have the additional advantage that they can be used for very low frequencies.



- In a phase shift oscillator, a phase shift of 180° is obtained with a phase shift circuit instead of inductive or capacitive coupling.
- A further phase shift of 180° is introduced due to the transistor properties. Thus energy supplied back to the tank circuit is assured of correct phase.
- **Phase shift Circuit.** A phase-shift circuit essentially consists of an R-C network. Fig (i) shows a single section of RC network. From the elementary theory of electrical engineering, it can be shown that alternating voltage V'_1 across R leads the applied voltage V_1 by φ°. The value of φ depends upon the values of R and C.



- If resistance R is varied, the value of φ also changes. If R were reduced to zero, V'_1 will lead V_1 by 90° i.e. φ= 90°.
- However, adjusting R to zero would be impracticable because it would lead to no voltage across R.
- Therefore, in practice, R is varied to such a value that makes V'_1 to lead V_1 by 60°.
- Fig (ii) shows the three sections of RC network. Each section produces a phase shift of 60°. Consequently, a total phase shift of 180° is produced i.e. voltage V_2 leads the voltage V_1 by 180°.

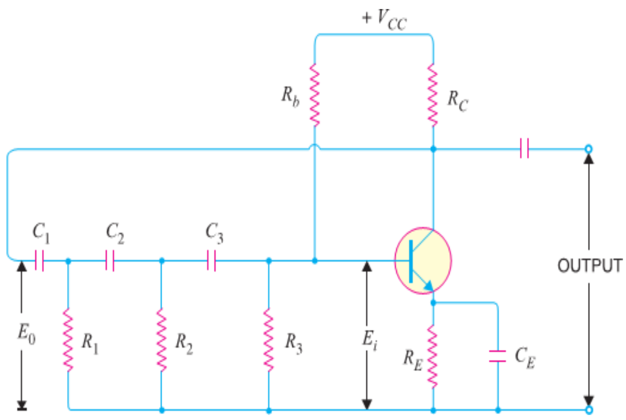
- **PHASE SHIFT OSCILLATOR:-**

- Fig. shows the circuit of a phase shift oscillator. It consists of a conventional single transistor amplifier and a RC phase shift network.
- The phase shift network consists of three sections R_1C_1, R_2C_2 and R_3C_3. At some particular frequency f0, the phase shift in each RC section is 60° so that total phase-shift produced by the RC network is 180°.
- The frequency of oscillations is given by:

$$f = \frac{1}{2\pi RC\sqrt{6}}$$

Circuit Operation. When the circuit is switched on, it produces oscillations of frequency determined by exp. (i). The output E_0 of the amplifier is fed back to RC feedback network.

- This network produces a phase shift of 180º and a voltage Ei appears at its output which is applied to the transistor amplifier.
- Obviously, the feedback fraction $\beta = E_i/E_0 = 1/29$; So loop gain $A\beta = 1$
- The feedback phase is correct.
- A phase shift of 180º is produced by the transistor amplifier.
- A further phase shift of 180º is produced by the RC network. As a result, the phase shift around the entire loop is 360º.



♣ Advantages

- It does not require transformers or inductors.
- It can be used to produce very low frequencies.
- The circuit provides good frequency stability.

♣ Disadvantages

- It is difficult for the circuit to start oscillations as the feedback is generally small.
- The circuit gives small output.

- **WIEN BRIDGE OSCILLATOR:-**

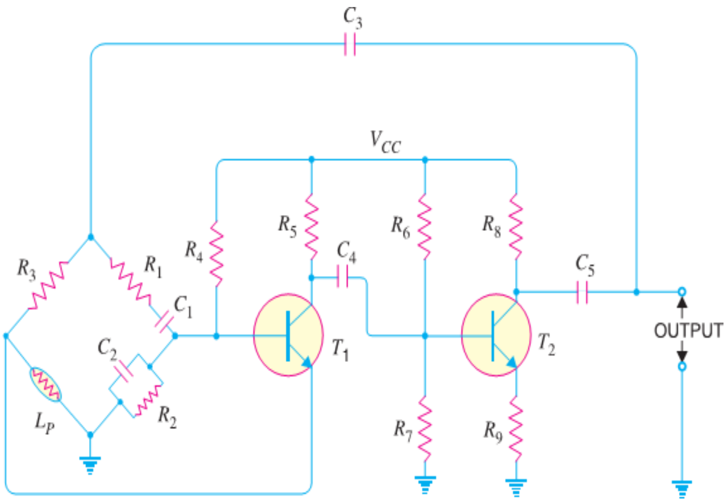
- The Wien-bridge oscillator is the standard oscillator circuit for all frequencies in the range of 10 Hz to about 1 MHz. It is the most frequently used type of audio oscillator as the output is free from circuit fluctuations and ambient temperature.
- Fig. shows the circuit of Wien bridge oscillator. It is essentially a two-stage amplifier with R-C bridge circuit. The bridge circuit has the arms R1C1, R3, R2C2 and tungsten lamp L_p.
- Resistances R_3 and L_p are used to stabilize the amplitude of the output. The transistor T_1 serves as an oscillator and amplifier while the other transistor T2 serves as an inverter (to produce 180º phase shift).
- The circuit uses positive and negative feedbacks. The positive feedback is through R1C1, C2R2 to the transistor T_1. The negative feedback is through the voltage divider to the input of transistor T_2.
- The frequency of oscillations is determined by the series element R1C1 and parallel element R2C2 of the bridge.

$$f = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$,

$$f = \frac{1}{2\pi CR}$$

- When the circuit is started, bridge circuit produces oscillations of frequency determined.
- The two transistors produce a total phase shift of 360º so that proper positive feedback is ensured.
- The negative feedback in the circuit ensures constant output. This is achieved by the temperature sensitive tungsten lamp L_p. Its resistance increases with current.
- Should the amplitude of output tend to increase, more current would provide more negative feedback.
- The result is that the output would return to original value.



- A reverse action would take place if the output tends to decrease.

♣ **Advantages**

(i) It gives constant output.
(ii) It works quite easily.
(iii) Overall gain is high due to two transistors.
(iv) The frequency of oscillations can be easily changed by using a potentiometer.

♣ **Disadvantages**

(v) It requires two transistors & large number of components.
(vi) It cannot generate very high frequencies.

PRACTICE QUESTIONS

Probable short questions with answers

1. Draw an DC equivalent circuit of a CE amplifier
2. Draw an AC equivalent circuit of a CE amplifier
3. Draw the simplified H-parameter of CB transistor
4. What is the function of $C_{in,}$ C_{out} and C_c in practical amplifier circuit
5. What is feedback
6. Write down advantages of negative feedback (W2007)
   Ans: *The advantages of negative feedback are as follows:*
   - Reduces non-linear distortion
   - Increases circuit stability
   - Improve frequency response
   - Improve gain stability
   - Increase bandwidth

7. Write down difference between the voltage amplifier and power amplifier
8. Write down the essentials of transistor oscillations
9. Write down the barkhausen criteria for oscillation
10. Name the different types of power amplifier
11. Why power amplifiers are used in final stage of an amplifier circuit (W2011)
    Ans: *Power amplifier is used to increase the power of an output signal*

Probable long questions

1. Draw the practical circuit of transistor amplifier and explain in detail
2. With neat diagram explain working of a transformer coupled amplifier (W2015)
3. With neat circuit diagram, explain RC coupled amplifier with frequency response (W2019)
4. Derive the voltage gain of a negative feedback amplifier (W2018)
5. With neat circuit diagram explain the Class B push-pull amplifier and derive its efficiency (W2007, 2008, 2009, 2011, 2014, 2015, 2016, 2017,2018, 2019, S2019)
6. State the difference between voltage and power amplifier with example (W2016, 2017)
7. Write down the principle of operations of colpitt oscillator
8. With neat circuit diagram, write down the principle of operations of RC phase shift oscillator
9. Write down the principle of operations of Wein Bridge oscillator
10. Derive collector efficiency of class A and class B power amplifier (W2011)

CHAPTER -7

---------------------------[FIELD EFFECT TRANSISTOR (FET)]------------------------

LEARNING OBJECTIVE

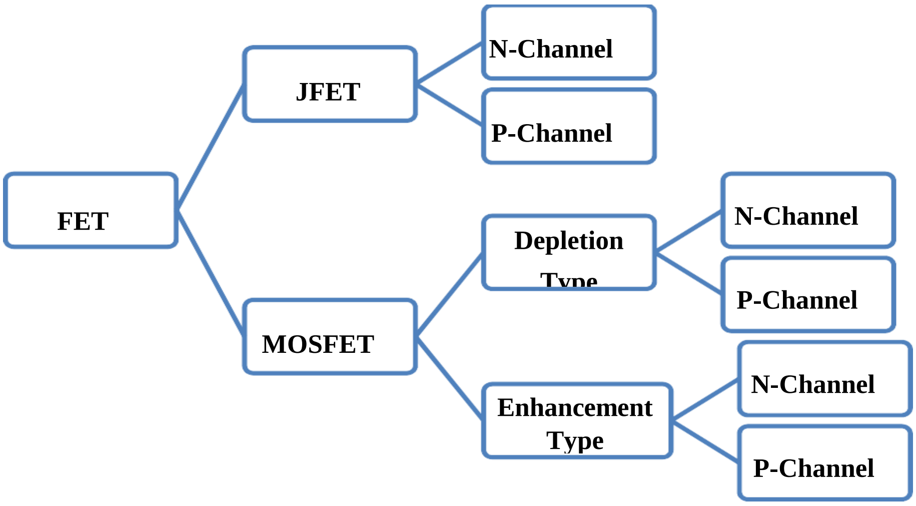
7.1 Classification of FET
7.2 Advantages of FET over BJT
7.3 Principle of operation of BJT
7.4 FET parameters (no mathematical derivation)
7.4.1 DC drain resistance
7.4.2 AC drain resistance
7.4.3 Trans-conductance
7.5 Biasing of FET

6.1 Practical circuit of transistor amplifier

- **INTRODUCTION: -**

- In BJT, both holes and electrons play part in the conduction process. For this reason, it is sometimes called a **Bipolar Transistor.**
- It has two principal disadvantages.
  - **First**, it has low input impedance because of forward biased emitter junction
  - **Secondly**, it has considerable noise level
- The FET is generally much less noisy than the ordinary or bipolar transistor. The rapidly expanding FET market has led many semiconductor marketing managers to believe that this device will soon become the most important electronic device, primarily because of its integrated-circuit applications.

ARTICLE 7.1: CLASSIFICATION OF FET



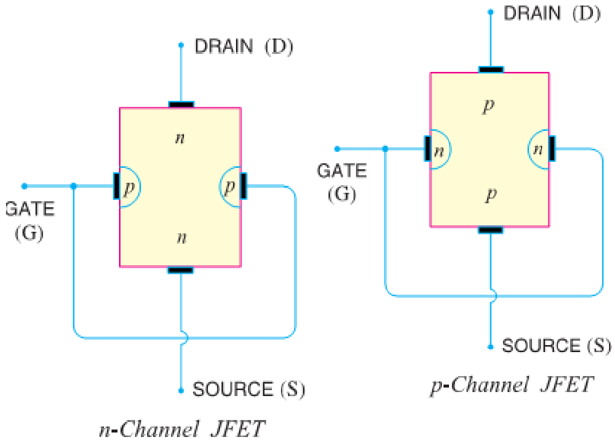
ARTICLE 7.2: ADVANTAGES OF FET OVER BJT

- **COMPARISON BETWEEN BJT & FET : -**

FET	BJT
✂ It means Field Effect Transistor	✂ Means Bipolar Junction Transistor
✂ Its three terminals are Source, Gate & Drain	✂ Its terminals are Emitter, Base & Collector.
✂ It is Unipolar devices i.e. Current in the device is carried either by electrons or holes.	✂ It is Bipolar devices i.e. Current in the device is carried by both electrons and holes.
✂ It is Voltage controlled device. i.e. Voltage at the gate or drain terminal controls the amount of current flowing through the devices.	✂ It is Current controlled device. i.e. Base Current controls the amount of collector current flowing through the devices.
✂ It has very High Input Resistance and Low Output Resistance.	✂ It has very Low Input Resistance and High Output Resistance.
✂ **Low noisy operation**	✂ **High noisy operation**
✂ **It is Longer Life & High Efficiency.**	✂ **It is Shorter Life & Low Efficiency.**
✂ **It is much simpler to fabricate as IC and occupies less space on IC.**	✂ **It is comparatively difficult to fabricate as IC and occupies more space on IC then FET.**
✂ **It has Small gain bandwidth product.**	✂ **It has Large gain bandwidth product.**
✂ **It has higher switching speed.**	✂ **It has higher switching speed.**

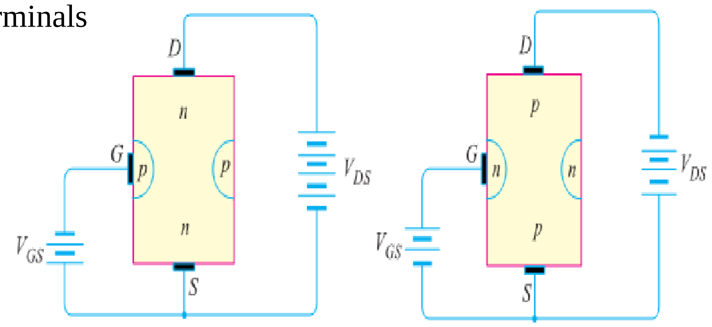
ARTICLE 7.3: PRINCIPLE OF OPERATION OF FET

- A junction field effect transistor is a three terminal semiconductor device in which current conducts through either electrons or holes.
- The current conduction is controlled by means of an electric field between the gate electrode and the conducting channel of the device.
- The JFET has high input impedance and low noise level.



- **CONSTRUCTIONAL DETAILS.**
- A JFET consists of a p-type or n-type silicon bar containing two pn junctions at the sides as shown in Fig.
- The bar forms the conducting channel for the charge carriers. If the bar is of n-type, it is called n-channel JFET as shown in Fig (i) and if the bar is of p-type, it is called a p-channel JFET as shown in Fig (ii).
- The two pn junctions forming diodes are connected internally & a common terminal called **gate** is taken out.
- Other terminals are **source** and **drain** taken out from the bar as shown. Thus a JFET has essentially three terminals viz., Gate (G), Source (S) & Drain (D).

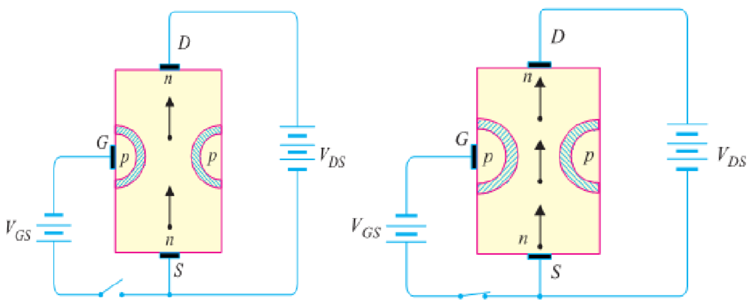
- **JFET POLARITIES: -**
- Fig (i) shows n-channel JFET polarities whereas Fig (ii) shows the p-channel JFET polarities.
- Note that in each case, voltage between gate and source is such that the gate is reversing biased.
- The drain & source terminals are interchangeable i.e., either end can be used as source and the other end as drain.



- The following points may be noted:
    - ❖ The input circuit (i.e. gate to source) of a JFET is reverse biased. This means that the device has high input impedance.
    - ❖ The drain is so biased w.r.t. source that drain current I_D flows from the source to drain.
    - ❖ In all JFETs, source current I_S is equal to the drain current i.e. $I_S = I_D$.

- **WORKING PRINCIPLE OF JFET:-**

Principle: - Fig. shows the circuit of n-channel JFET with normal polarities.



- The two pn junctions at the sides form two depletion layers. The current conduction by free electrons, which travels through the channel between the two depletion layers and from source to the drain.
- The width and hence resistance of this channel can be controlled by changing the input voltage V_{GS}.
- The greater the reverse voltage V_{GS}, the wider will be the depletion layers and narrower will be the conducting channel. The narrower channel means greater resistance and hence source to drain current decreases. Reverse will happen should V_{GS} decrease.
- Thus JFET operates on the principle that width and hence resistance of the conducting channel can be varied by changing the reverse voltage V_{GS}.

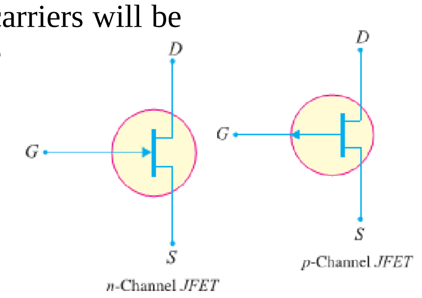
Working: - The working of JFET is as under :

- **(i)** When voltage V_{DS} is applied between drain & source terminals and voltage on the gate is zero [See the above Fig (i)], the two pn junctions at the sides of the bar establish depletion layers.
- The electrons will flow from source to drain through a channel between the depletion layers.

- The size of these layers determines width of the channel & hence current conduction through the bar.
- **(ii)** When a reverse voltage V_{GS} is applied between the gate and source [See Fig (ii)], the width of the

depletion layers is increased.

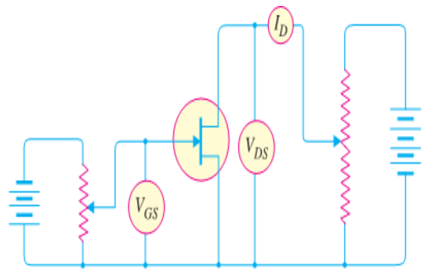
- This reduces the width of conducting channel, thereby increasing the resistance of n-type bar. Consequently, the current from source to drain is decreased.
- On the other hand, if the reverse voltage on the gate is decreased, the width of the depletion layers also decreases. This increases the width of the conducting channel and hence source to drain current.
- It is clear from the above discussion that current from source to drain can be controlled by the application of potential (i.e. electric field) on the gate.
- For this reason, the device is called field effect transistor. It may be noted that a p-channel JFET operates in the same manner as an n-channel JFET except that channel current carriers will be the holes instead of electrons and the polarities of V_{GS} and V_{DS} are reversed.



- **JFET SYMBOL & CIRCUIT CONNECTION:-**

- For the proper operation of JFET, the gate must be negative w.r.t. source i.e., input circuit should always be reverse biased.
- This is achieved either by inserting a battery V_{GG} in the gate circuit or by a circuit known as biasing circuit.
- In the present case, we are providing biasing by the battery V_{GG}. A small change in the reverse bias on the gate produces a large change in drain current.
- **In the FET, since the input is reverse biased (open circuit), hence there is no input characteristics curve.**

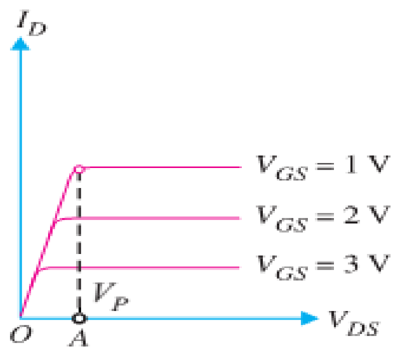
- **OUTPUT CHARACTERISTICS OF JFET**



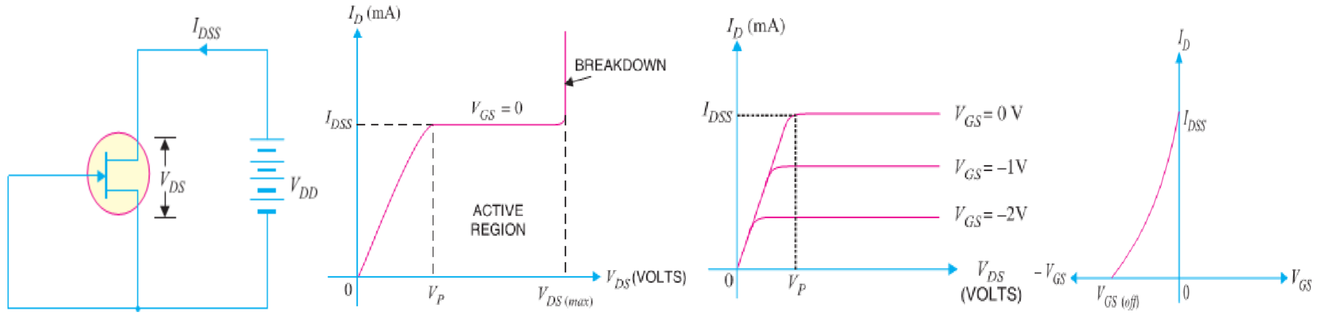
- The curve between drain current (I_D) and drain-source voltage (V_{DS}) of a JFET at constant gate source voltage (V_{GS}) is known as output characteristics of JFET.
- Fig shows circuit for determining output characteristics of JFET.
- Keeping V_{GS} fixed at some value, say 1V, the drain source voltage is changed in steps.
- Corresponding to each value of V_{DS}, the drain current I_D is noted.
- A plot of these values gives output characteristic of JFET at V_{GS}= 1V.
- Repeating similar procedure, output characteristics at other gate-source voltages can be drawn. Fig. shows a family of output characteristics.

The following points may be noted from the characteristics:

- **(i)** At first, the drain current I_D rises rapidly with drain-source voltage V_{DS} but then becomes constant.
- The drain-source voltage above which drain current becomes constant is known as pinch off voltage. Thus in Fig. OA is the pinch off voltage V_P.
- **(ii)** After pinch off voltage, the channel width becomes so narrow that depletion layers almost touch each other.
- The drain current passes through the small passage between these layers.
- Thus increase in drain current is very small with VDS above pinch off voltage.
- If we further increase V_{DS}, the junction breaks down and the current rises rapidly.



ARTICLE 7.4: FET PARAMETERS



1. Shorted-Gate Drain Current (I_{DSS}): -

- It is the drain current with source short-circuited to gate (i.e. $V_{GS} = 0$) and drain voltage (V_{DS}) equal to pinch off voltage. It is sometimes called zero-bias current.

2. Pinch Off Voltage (V_P) : -

- It is the minimum drain-source voltage at which the drain current essentially becomes constant.

3. Gate-Source Cut Off Voltage V_{GS} (off): -

- It is the gate-source voltage where the channel is completely cut off & the drain current becomes zero.

ARTICLE 7.4.1: DC DRAIN RESISTANCE (R_d)

- It is the ratio of drain-source voltage (V_{DS})to the drain current(I_D) at constant gate-source voltage i.e.

D.C. Drain Resistance, $R_d = \frac{V_{DS}}{I_D}$ at constant V_{GS}

ARTICLE 7.4.2: AC DRAIN RESISTANCE (r_d)

- It is the ratio of change in drain-source voltage (ΔV_{DS})to the change in drain current(ΔI_D) at constant gate-source voltage i.e.

A.C. Drain Resistance, $r_d = \frac{\Delta V_{DS}}{\Delta I_D}$ at constant V_{GS}

ARTICLE 7.4.3: TRANS-CONDUCTANCE

- It is the ratio of change in drain current (ΔI_D) to the change in gate-source voltage(ΔV_{GS}) at constant drain-source voltage i.e.

Transconductance, $g_{fs} = \frac{\Delta I_D}{\Delta V_{GS}}$ at constant V_{DS}

- The transconductance of a JFET is usually expressed either in mA/volt or micro mho.

♣ **Amplification Factor (μ)**. It is the ratio of change in drain-source voltage (ΔV_{DS}) to the change in gate-source voltage(ΔV_{GS}) at constant drain current i.e.

Amplification Factor, $\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}}$ at constant I_D

- Amplification factor of a JFET indicates how much more control the gate voltage has over drain current than has the drain voltage.

- **RELATION AMONG JFET PARAMETERS: -**

- The relationship among JFET parameters can be established as under :

We know $\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}}$

- Multiplying the numerator and denominator on R.H.S. by ΔI_D, we get,

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \times \frac{\Delta I_D}{\Delta I_D} = \frac{\Delta V_{DS}}{\Delta I_D} \times \frac{\Delta I_D}{\Delta V_{GS}} \Rightarrow \mu = r_d \times g_{fs}$$

➔ Amplification Factor = A.C. Drain Resistance × Transconductance

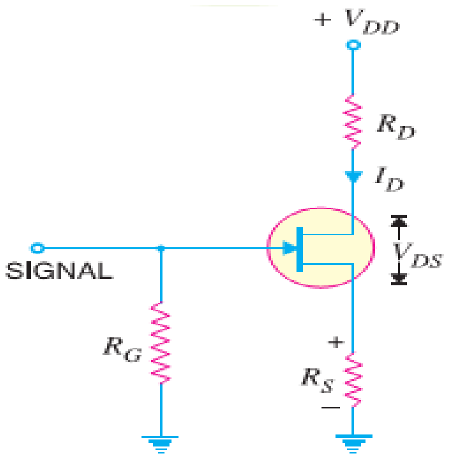
ARTICLE 7.5: BIASING OF FET

- For the proper operation of n-channel JFET, gate must be negative w.r.t. source. This can be achieved either by inserting a battery in the gate circuit or by a circuit known as biasing circuit.
- The latter method is preferred because batteries are costly and require frequent replacement.

1. Bias Battery: - In this method, JFET is biased by a bias battery V_{GG}. This battery ensures that gate is always negative w.r.t. source during all parts of the signal.

2. Biasing circuit: -The biasing circuit uses supply voltage $V_{DD}$to provide the necessary bias. Two most commonly used methods are **(i) Self-Bias (ii) Potential Divider Method**.

- **SELF-BIAS FOR JFET : -**



- Fig shows the self-bias method for n-channel JFET. The resistor RS is the bias resistor.
- The d.c. component of drain current flowing through R_S produces the desired bias voltage.

Voltage across R_S, $V_S = I_D R_S$

- Since gate current is negligibly small, the gate terminal is at d.c. ground i.e., $V_G = 0$.

$\therefore \quad V_{GS} = V_G - V_S = 0 - I_D R_S \quad$ or $\quad V_{GS} = - I_D R_S$

- Thus bias voltage V_{GS} keeps gate negative w.r.t. source.

Operating point: -

- The operating point (i.e., zero signals I_D & V_{DS}) can be easily determined. Since the parameters of the JFET are usually known, zero signal I_D can be calculated from the following relation :

$$\mathbf{I_D = I_{DSS} \left(1 - \frac{AVGS}{AV_{GS(of\ f)}}\right)^2}$$

Also $\qquad V_{DS} = V_{DD} - I_D (R_D + R_S)$

- Thus d.c. conditions of JFET amplifier are fully specified i.e. operating point for the circuit is (V_{DS}, I_D).

Also, $\qquad \mathbf{R_S} = \frac{|VGS|}{|I_D|}$

- Note that gate resistor R_G does not affect bias because voltage across it is zero.

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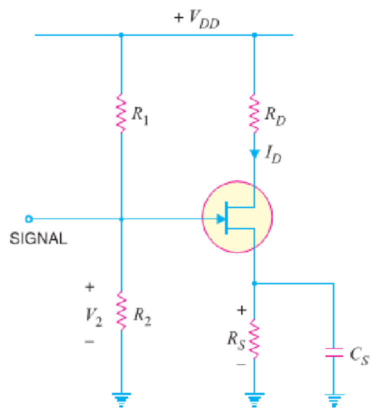
- **JFET with Voltage-Divider Bias :-**



- Fig shows potential divider method of biasing a JFET. This circuit is identical to that used for a transistor.
-
- The resistors R1 and R2 form a voltage divider across drain supply VDD. The voltage V2 (= VG) across R2 provides the necessary bias.

$$V_2 = V_G = \frac{VDD}{R_1 + R_2} \times R_2$$

Now $\qquad V_2 = V_{GS} + I_D R_S \qquad$ Or $\qquad \mathbf{V_{GS} = V_2 - I_D R_S}$

- The circuit is so designed that $I_D R_S$ is larger than V_2 so that V_{GS} is negative. This provides correct bias voltage. We can find the operating point as under:

$$I_D = \frac{V_2 - V_{GC}}{R_c} \quad \text{and} \quad V_{DS} = V_{DD} - I_D (R_D + R_S)$$

- The input impedance Z_i of this circuit is given by ; $Z_i = R_1 \parallel R2$

JFET Applications : -

- The high input impedance and low output impedance and low noise level make JFET far superior to the bipolar transistor. Some of the circuit applications of JFET are :
  - ♣ As a Buffer amplifier
  - ♣ As Phase-shift oscillators
  - ♣ As RF amplifier

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PRACTICE QUESTIONS

Probable short questions with answers

1. Write down the difference of JFET over BJT (W2011, 2016, 2017, 2018, 2019)
   Ans:

FET	BJT
✂ It means Field Effect Transistor	✂ Means Bipolar Junction Transistor
✂ Its three terminals are Source, Gate & Drain	✂ Its terminals are Emitter, Base & Collector.
✂ It is Unipolar devices i.e. Current in the device is carried either by electrons or holes.	✂ It is Bipolar devices i.e. Current in the device is carried by both electrons and holes.
✂ It is Voltage controlled device. i.e. Voltage at the gate or drain terminal controls the amount of current flowing through the devices.	✂ It is Current controlled device. i.e. Base Current controls the amount of collector current flowing through the devices.
✂ It has very High Input Resistance and Low Output Resistance.	✂ It has very Low Input Resistance and High Output Resistance.
✂ **Low noisy operation**	✂ **High noisy operation**
✂ **It is Longer Life & High Efficiency.**	✂ **It is Shorter Life & Low Efficiency.**
✂ **It is much simpler to fabricate as IC and occupies less space on IC.**	✂ **It is comparatively difficult to fabricate as IC and occupies more space on IC then FET.**
✂ **It has Small gain bandwidth product.**	✂ **It has Large gain bandwidth product.**
✂ **It has higher switching speed.**	✂ **It has higher switching speed.**

2. Define a.c. drain resistance
3. Define trans-conductance of FET (W2017, 2018)
   ***Ans**: It is also called as forward trans-conductance. It is defined as the ratio of small change in drain current to the corresponding small change in gate to source voltage for a constant drain to source voltage. Mathematically, it is as follows:*

   g_{m} = change in I_d/ change in V_{GS} (at const. V_{ds})

4. Derive the relation between amplification factor, trans-conductance and drain resistance of FET

Probable long questions

1. Explain the principle of operation of N-channel FET with neat diagram
2. With neat circuit diagram, explain the output characteristics of JFET (W2017, 2018, 2019)
3. Explain voltage divider biasing of JFET

CHAPTER - 8

OPERATIONAL AMPLIFIERS

LEARNING OBJECTIVE

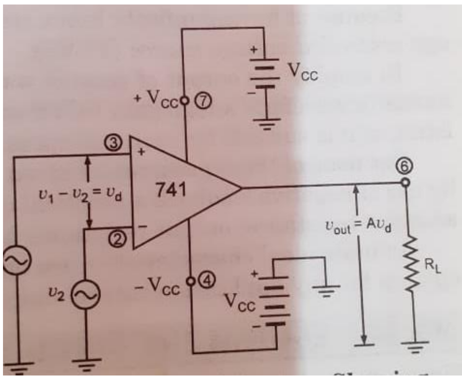
8.1 General circuit simple of OP-AMP and IC – CA – 741 OP AMP
8.2 Operational amplifier stages
8.3 Equivalent circuit of operational amplifier
8.4 Open loop OP-AMP configuration
8.5 OPAMP with fed back
8.6 Inverting OP-AMP
8.7 Non inverting OP-AMP
8.8 Voltage follower & buffer
8.9 Differential amplifier
8.9.1 Adder or summing amplifier
8.9.2 Sub tractor
8.9.3 Integrator
8.9.4 Differentiator
8.9.5 Comparator

ARTICLE 8.1: GENERAL CIRCUIT OF OP-AMP and IC-741

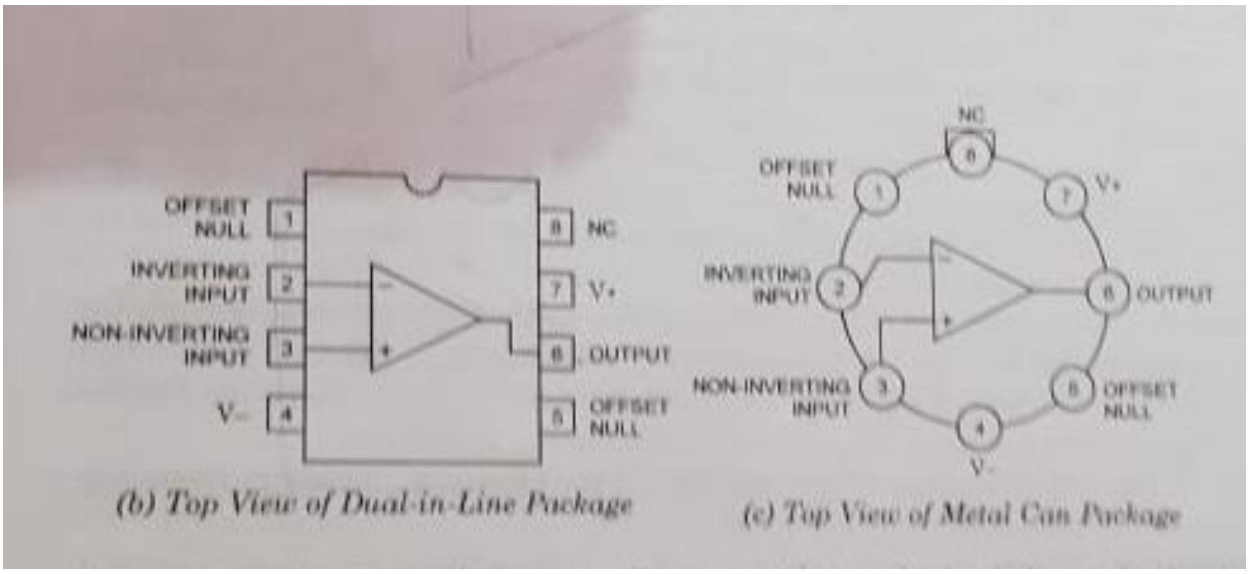
- ***It is a high gain differential amplifier which performs mathematical operations such as, addition, subtraction, multiplication etc.***
- The operational amplifier is an extremely efficient and versatile device. Its applications span the broad electronic industry filling requirements for signal conditioning, special transfer functions, analog instrumentation, analog computation, and special systems design. The analog assets of simplicity and precision characterize circuits utilizing operational amplifiers
- Op-amps are integrated circuits composed of many transistors & resistors such that the resulting circuit follows a certain set of rules

The schematic representation of an op-amp (μA- 741) is shown below. There are seven pins:

- Pin 1: offset null
- Pin 2: Inverting input
- Pin 3: Non-inverting input
- Pin 4: Negative power supply
- Pin 5: Offset null
- Pin 6: Output
- Pin 7: Positive power supply

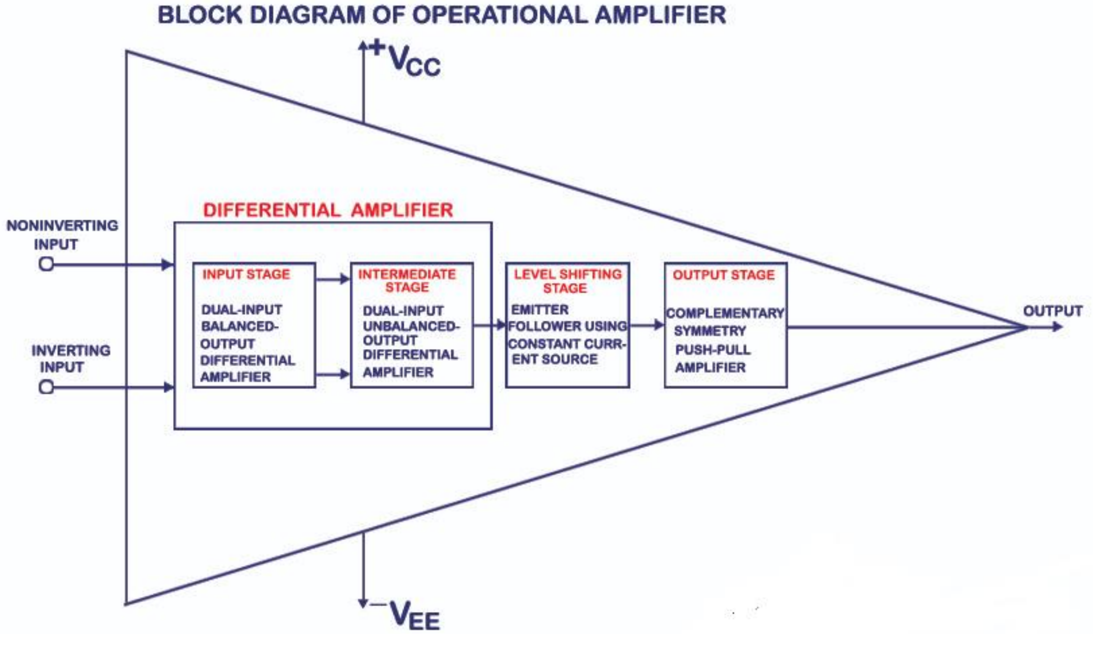


- Pin 8: Not connected (NC)



ARTICLE 8.2: OP-AMP STAGES

The following fig shows the typical operational amplifier stages:



First stage is double ended, high-gain, differential amplifier; known as dual input and balanced output

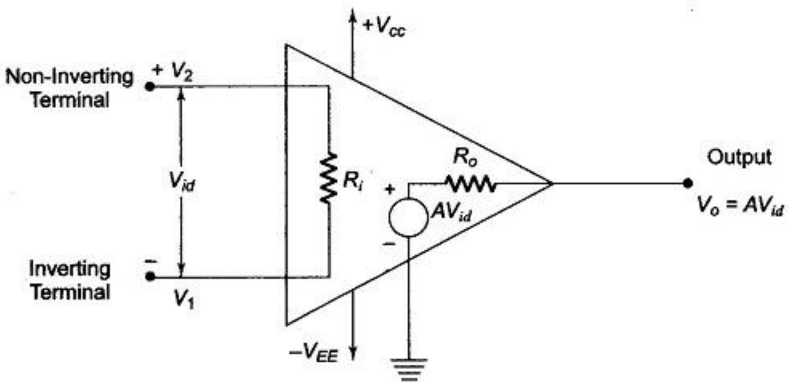
Second stage is called intermediate stage; It has dual inputs and a single output. It is driven by the output of first stage

Third stage is called level shifting stage is usually an emitter follower circuit. It order to shift the DC level at the output of the intermediate stage to 0 V with respect to ground

The final stage is called output stage is usually a push-pull complimentary amplifier. This stage increases the output voltage and current, so it acts as an amplifier

ARTICLE 8.3: EQUIVALENT CIRCUITS OF OP-AMP

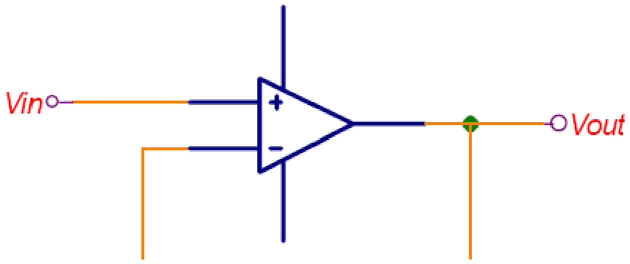
The figure shows the equivalent circuit of an OP-Amp, the voltage V_d is an equivalent differential input voltage. Rin is the input resistance between inverting and non-inverting terminal. AV_d is the equivalent output voltage looking back into the output terminal of the OP-AMP. Rout is the equivalent output resistance. So the output voltage Vout = $AV_d = A(V_1 - V_2)$



Equivalent Circuit of OpAmp

ARTICLE 8.4: OPEN LOOP OP-AMP

In open loop OP-AMP, there is no connection between input and output, and hence, there is no feedback resistance between input and output



ARTICLE 8.5: CONFIGURATION OF OP-AMP WITH FEEDBACK

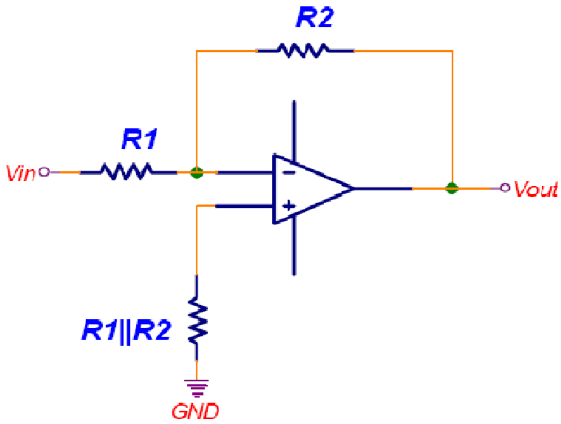
In this case, feedback resistance (R_f/ R_2) is connected between input and output. It is of 3 types

1. Inverting amplifier (when input signal is applied to inverting terminal (-ve) only)
2. Non-inverting (when input signal is applied to non-inverting terminal (+ve) only)
3. Differential amplifier (when input signal is applied to both inverting and non-inverting terminal)

ARTICLE 8.6: INVERTING OP-AMP

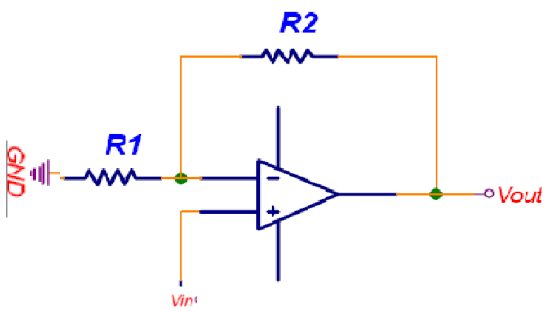
Because no current flows into the input pins there can't be any voltage drop across the R1 ‖ R2. Vin+ is therefore at 0V(this is called a virtual ground). The output will adjustsuch that Vin- is at zero volts. This makes **Rin = R1** (not ∞)**.** The current through R1 & R2 have to be the same since no current goes into the input pins.

Therefore I = Vin/R1. Vout = Vin+ - IR2 = 0 - (Vin/R1)R2. Therefore **Vout = -Vin(R2/R1)**

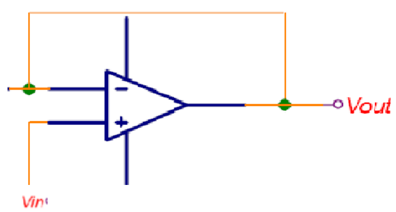


ARTICLE 8.7: NON-INVERTING AMPLIFIER

No current flows into the input, **Rin =** ∞ The output adjusts to bring Vin- to the same voltage as Vin+. Therefore Vin- = Vin and since no current flows into Vin- the same current must flow through R1 & R2. Vout is therefore VR1 + VR2 = Vin- + IR2 = Vin- + (Vin/R1)R2.



ARTICLE 8.8: VOLTAGE FOLLOWER AND BUFFER



Let the voltage at the inverting input with respect to the non-inverting input be E-.

By Kirchoff's voltage law:

$$(E-) + E_I = E_O$$

But by definition:

$$E_O = -A(E-)$$

where A is the gain of the operational amplifier

Then:

$$(E-) = \frac{-E_O}{A}$$

And substituting:

$$E_I - \frac{E_O}{A} = E_O$$

Letting A go to infinity, $\frac{E_O}{A}$ approaches zero, and:

$$E_O = E_I$$

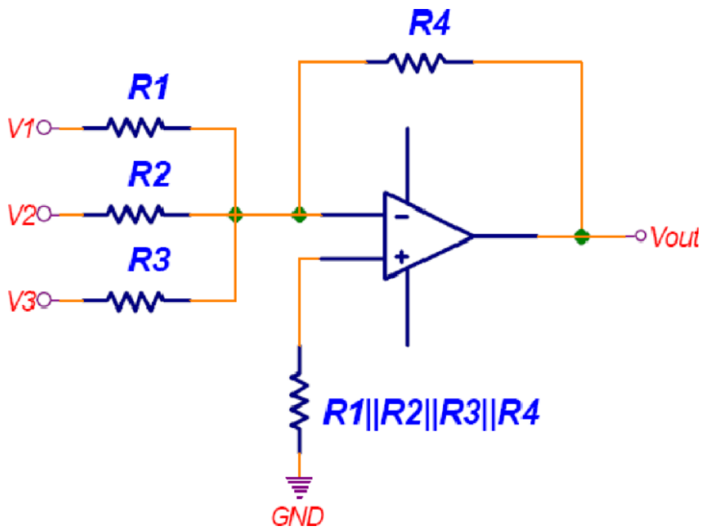
ARTICLE 8.9: DIFFERENTIAL AMPLIFIER

ARTICLE 8.9.1: ADDER/ SUMMING AMPLIFIER

Since Vin- is a virtual ground adding V2 and R2 (and V3 & R3) doesn't change the current flowing through R1 from V1. Each input contributes to the output using the following equation:

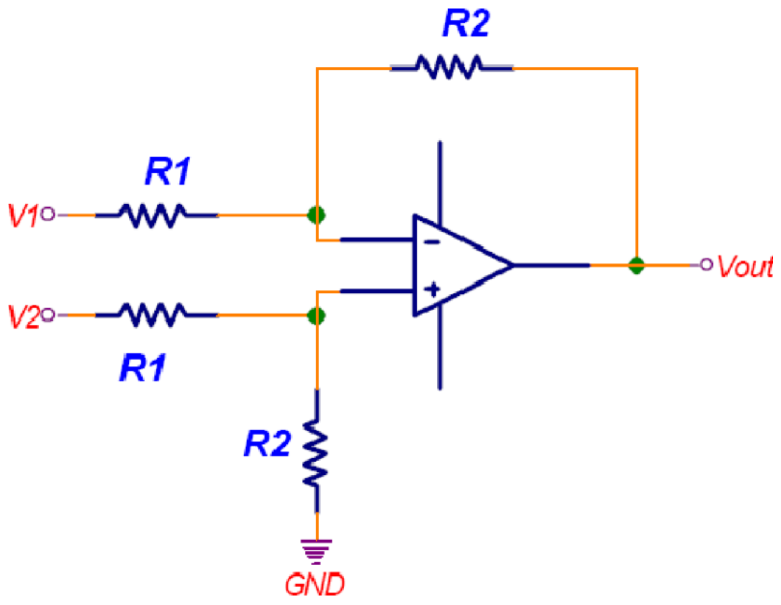
Vout = -V1(R4/R1) - V2(R4/R2) - V3(R4/R3).

The input impedance for the V1 input is still R1, similarly V2's input impedance is R2 and V3's is R3. Most of the time the parallel combination of R1-R4 isn't used and Vin+ is grounded.

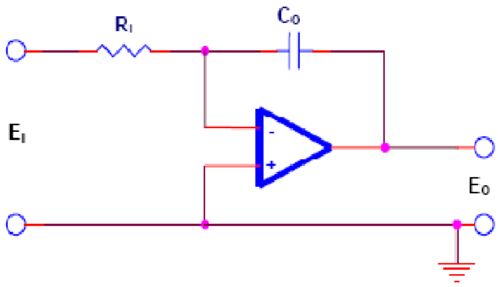


ARTICLE 8.9.2: SUBTRACTOR

You can work out the gain as before using the two rules (no current flows into the inputs, and the output will adjust to bring Vin- to Vin+). The result is **Vout = 2(V2-V1)*(R2/R1).** Also, **Rin(-) = R1, Rin(+) = R1 + R2**.



CLE 8.9.3: INTEGRATOR

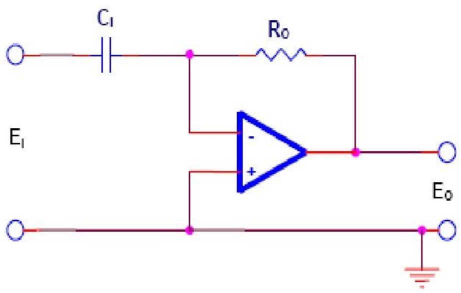


$$E_O = \frac{-1}{R_I C_O} \quad E_I dt$$

Figure 21. Integrator Circuit

If a capacitor is used as the feedback element in the inverting amplifier, shown in figure 21, the result is an integrator. An intuitive grasp of the integrator action may be obtained from the statement under the section, "Current Output," that current through the feedback loop charges the capacitor and is stored there as a voltage from the output to ground. This is a voltage input current integrator.

ARTICLE 8.9.4: DIFFERENTIATOR



$$E_O = -R_O C_I \frac{dE_1}{dt}$$

Figure 22. Differentiator Circuit

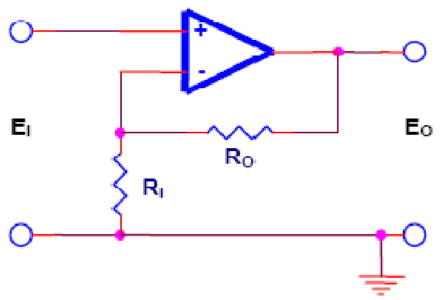
Using a capacitor as the input element to the inverting amplifier, figure 22, yields a differentiator circuit. Consideration of the device in figure 23 will give a feeling for the differentiator circuit.

ARTICLE 8.9.5: COMPARATOR

In OPAMP, we know Vo = A V_d = A ($V_1 - V_2$), where V_1 is non-inverting input terminal voltage and V_2 is inverting input terminal voltage. If V_1 is greater than V_2, then Vo is positive. Similarly, when V_1 is less than V_2 then Vo is negative. This is how the circuit compares both the input voltages.
It is used in accurate measurement of time, amplitude distribution analyzer, ADC converter, conversion of sinusoidal wave form into square wave form etc.

- **OPERATIONAL - AMPLIFIER WITH FEEDBACK**

Non-Inverting Amplifier



$$E_O = \left(1 + \frac{R_O}{R_I}\right) \cdot E_I$$

The same voltage must appear at the inverting and non-inverting inputs, so that:

$$(E-) = (E+) = E_I$$

From the voltage division formula:

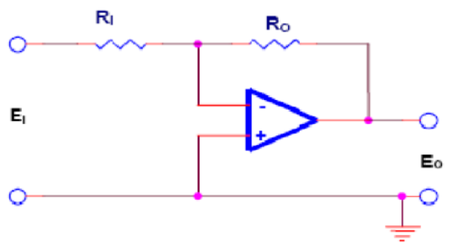
$$E_I = \frac{R_I}{R_I + R_O} \cdot E_O$$

$$\frac{E_O}{E_I} = \frac{R_I + R_O}{R_I} = 1 + \frac{R_O}{R_I}$$

The input impedance of the non-inverting amplifier circuit is infinite since no current flows into the inverting input. Output impedance is zero since output voltage is ideally independent of output current. Closed loop gain is $1 + \frac{R_O}{R_I}$ hence can be any desired value above unity.

Such circuits are widely used in control and instrumentation where non-inverting gain is required.

INVERTING AMPLIFIER



$$\frac{E_O}{E_I} = \frac{-R_O}{R_I}$$

Figure 17. Inverting Amplifier

The inverting amplifier appears in figure 17. This circuit and its many variations form the bulk of commonly used operational amplifier circuitry. Single ended input and output versions were first used, and they became the basis of analog computation. Today's modern differential input amplifier is used as an inverting amplifier by grounding the non-inverting input and applying the input signal to the inverting input terminal.

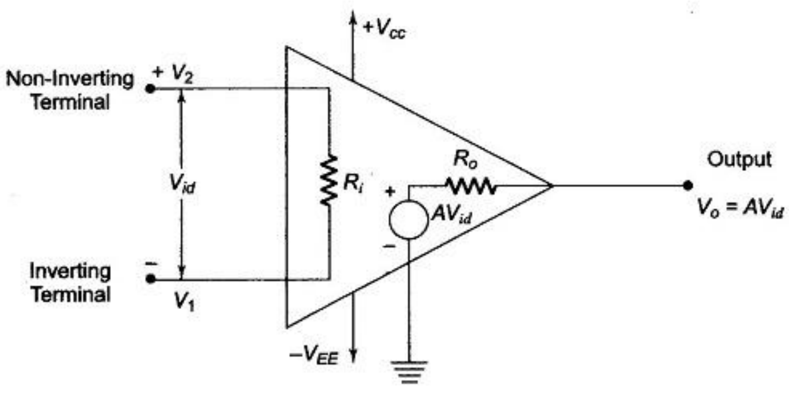
Since the amplifier draws no input current and the input voltage approaches zero when the feedback loop is closed (the two summing point restraints), we may write:

$$\frac{E_I}{R_I} = \frac{E_O}{R_O} = 0$$

PRACTICE QUESTIONS

Probable short questions with answers

1. Write down the name of different stages of OP-AMP
   ***Ans**: It has four (4) stages as detailed below:*
   First stage is double ended, high-gain, differential amplifier; known as dual input and balanced output
   Second stage is called intermediate stage; It has dual inputs and a single output. It is driven by the output of first stage
   Third stage is called level shifting stage is usually an emitter follower circuit. It order to shift the DC level at the output of the intermediate stage to 0 V with respect to ground
   The final stage is called output stage is usually a push-pull complimentary amplifier. This stage increases the output voltage and current, so it acts as an amplifier
2. Draw an equivalent circuit of an OP-AMP (W2017, 2019)
   ***Ans**:*



Equivalent Circuit of OpAmp

3. Define voltage follower
4. Draw the circuit diagram of non-inverting OP-AMP and write down its gain
5. Define OP-AMP

Probable long questions:

1. Explain OP-AMP as an integrator with suitable circuit diagram (W2016, 2017, 2018, 2019)
2. Explain OP-AMP as an differentiator with suitable circuit diagram (W2016, 2017, 2018, 2019)
3. Why OP-AMP is called an Adder with circuit diagram
4. Describe the inverting and non-inverting OP-AMP (W2015)