MODULE-I

DIODE AND BIPOLAR TRANSISTOR CIRCUITS

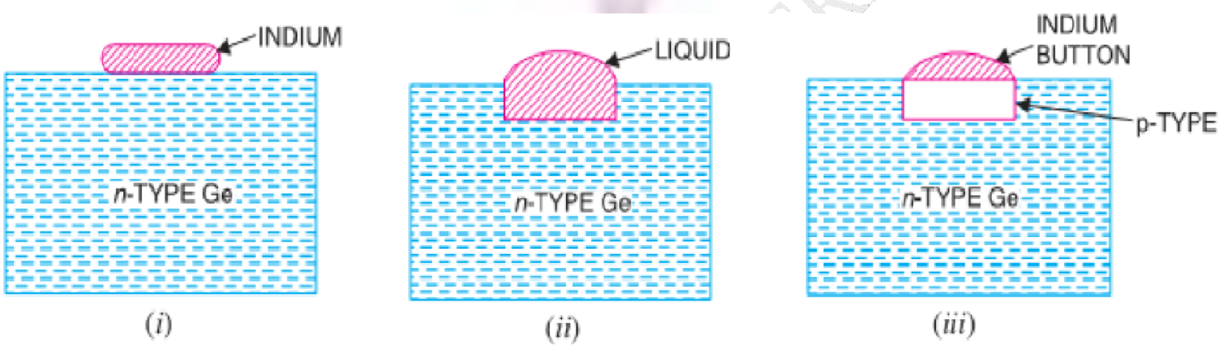
P-N junction diode, I-V characteristics of a diode; review of half-wave and full-wave rectifiers, clamping and clipping circuits. Input output characteristics of BJT in CB, CE, CC configurations, biasing circuits, Load line analysis, common-emitter, common-base and common collector amplifiers; Small signal equivalent circuits

1. DEFINITION:-

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

2. FORMATION OF PN JUNCTION

- In actual practice, the characteristic properties of PN junction will not be apparent if a p-type block is just brought in contact with n-type block.
- 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]

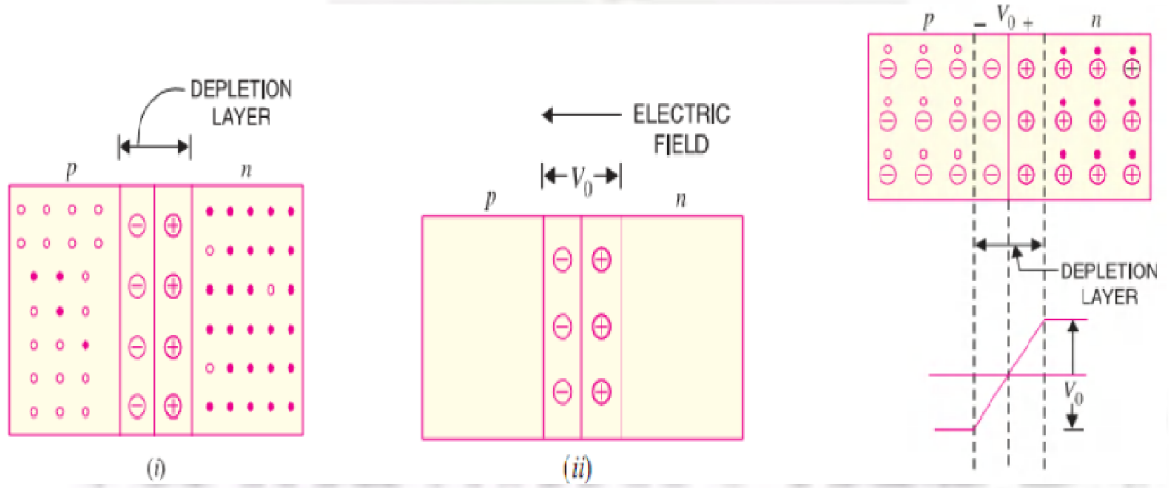
- In this method, a small block of indium (trivalent impurity) is placed on an n-type germanium slab as shown in Fig (i). The system is then heated to a temperature of about 500ºC. The indium and some of the germanium melt to form a small puddle of molten germanium-indium mixture as shown in Fig (ii). 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.
- The addition of indium overcomes the excess of electrons in the n-type germanium to such an extent that it creates a p-type region.
- As the process goes on, the remaining molten mixture becomes increasingly rich in indium. When all germanium has been re-deposited, the remaining material appears as indium but- ton which is frozen on to the outer surface of the crystallized portion as shown in Fig (iii).

3. PROPERTIES OF PN JUNCTION

- To explain PN junction, consider two types of materials: -
  - iii) P-Type-P-type semiconductor having –ive acceptor ions and +ive charged holes.
  - iv) N-Type -N-type semiconductor having +ive donor ions and –ive free electrons.

- 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.**

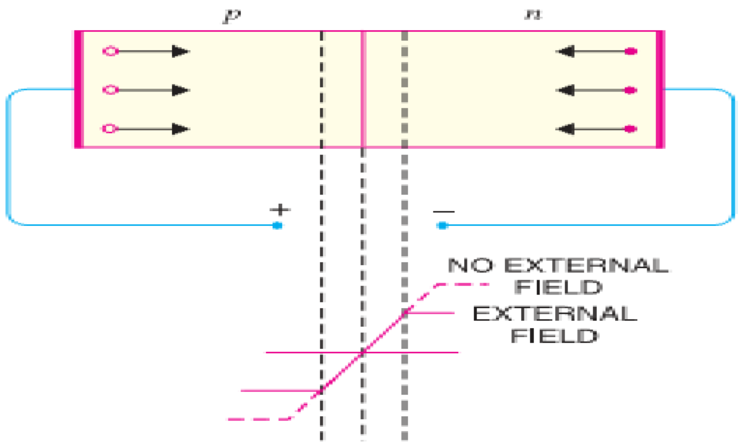
- When a free electron move across the junction from n-type to p-type, positive donor ions are removed by the force of electrons. Hence positive charge is built on the n-side of the junction. Similarly negative charge establish on p-side of the junction.
- When sufficient no of donor and accepter ions gathered at the junction, further diffusion is prevented.
- Since +ive charge on n-side repel holes to cross from p-side to n-side, similarly –ive 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 is hole or electrons.
- This barrier is called as **Potential Barrier/ Junction Barrier (V0)** 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.**
- 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 stops. In other words, the depletion region acts as a barrier to the further movement of free electrons across the junction.
- The positive and negative charges set up an electric field as shown in fig below.



- 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 (V0). 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 = 0.3 V.

4. 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 below.



- 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 and a low resistance path is established for the entire circuit.
- Therefore, current flows in the circuit. This is called Forward Current.
- With forward bias to PN junction, the following points are worth noting :

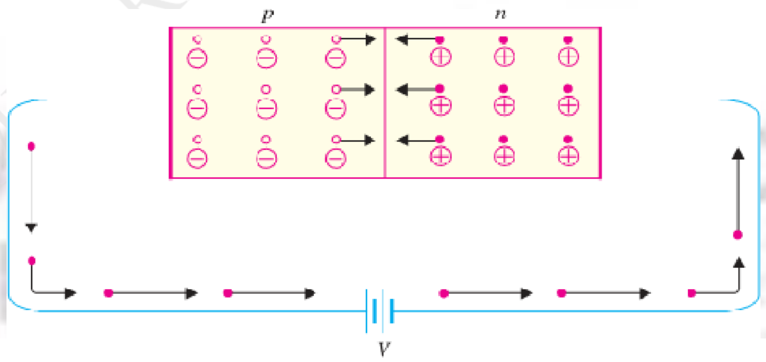
i) The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated altogether.

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

iii) Current flows in the circuit due to the establishment of low resistance path. The magnitude of current depends upon the applied forward voltage.

5. CURRENT FLOW IN A FORWARD BIASED PN JUNCTION:-

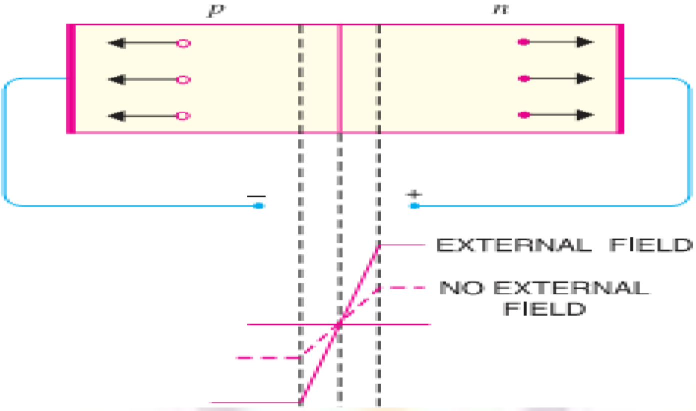
- It is concluded that in n-type region, current is carried by free electrons whereas in p-type region, it is carried by holes. However, in the external connecting wires, the current is carried by free electrons.



6. 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.

- It is clear that applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier.
- Therefore, the resultant field at the junction is strengthened and the barrier height is increased as shown in fig below .



- The increased potential barrier prevents the flow of charge carriers across the junction.
- Thus, a high resistance path is established for the entire circuit and hence the current does not flow.
- With reverse bias to PN junction, the following points are worth noting:
  - The potential barrier is increased.
  - 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.

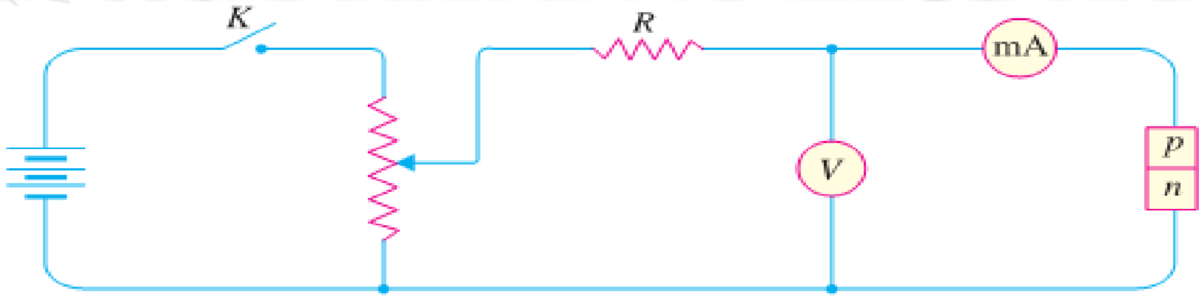
7. VOLT-AMPERE CHARACTERISTICS OF PN JUNCTION:-

- 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:
  - Zero external voltage
  - Forward Bias
  - Reverse Bias.

8. ZERO EXTERNAL VOLTAGE: -

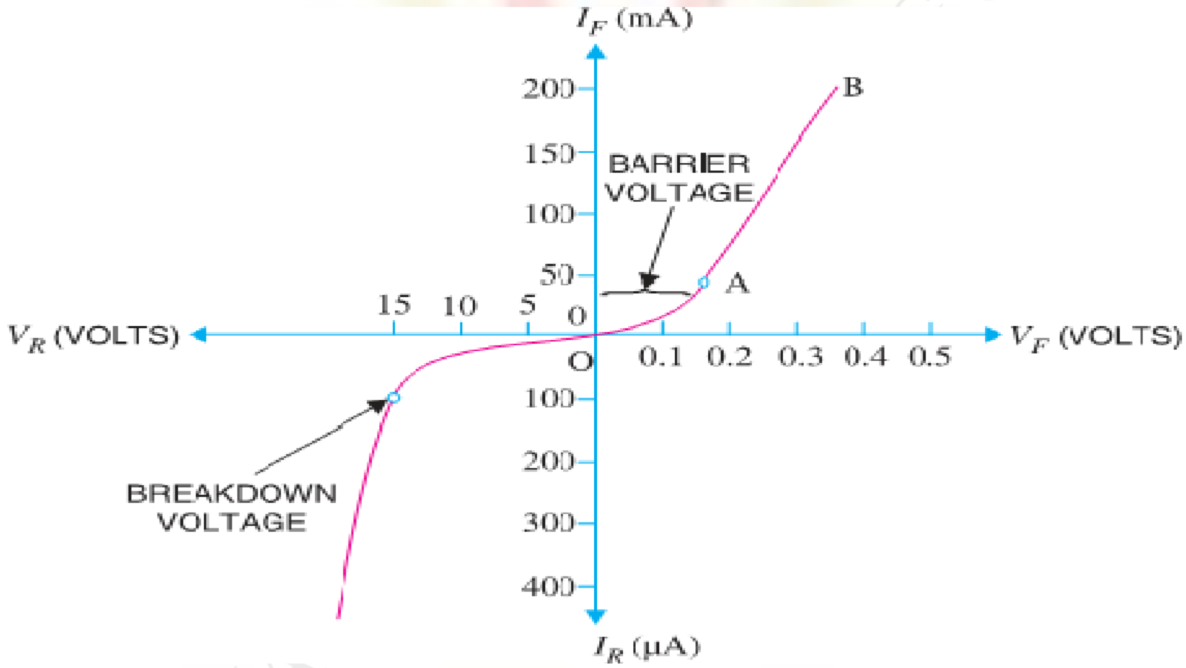
- When the external voltage is zero, i.e. circuit is open at K; the potential barrier at the junction does not permit current flow.

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



1) **FORWARD BIAS**: -

- With forward bias to the pn junction i.e. 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.



2) **REVERSE BIAS:-**

- With reverse bias to the pn junction i.e. 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 is due to the minority carriers.
- It may be recalled that there are a few free electrons in p-type material and a few holes in n-type material.
- 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 (minority carriers) 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.

9. <u>IMPORTANT TERMS:</u> -

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

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

3. **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. The peak inverse voltage is of particular importance in rectifier service.

4. **MAXIMUM FORWARD CURRENT**:- It is the highest instantaneous forward current that a pn junction can conduct without damage to the junction. Manufacturer's data sheet usually specifies this rating. If the forward current in a pn junction is more than this rating, the junction will be destroyed due to overheating.

5. **MAXIMUM POWER RATING**: - It is the maximum power that can be dissipated at the junction without damaging it. The power dissipated at the junction is equal to the product of junction current and the voltage across the junction. This is a very important consideration and is invariably specified by the manufacturer in the data sheet.

10. DC LOAD LINE:-

- The line obtained by joining the maximum values of I_c and V_{ce} in the output characteristics of a CE configuration transistor is known as the DC Load Line.

11. PN JUNCTION BREAKDOWN:-

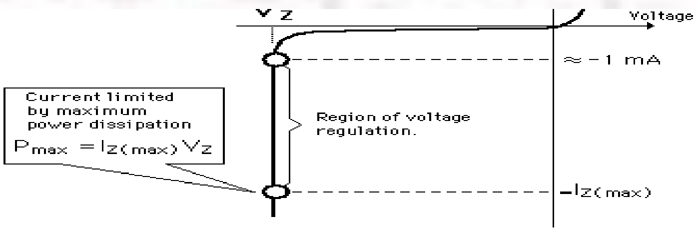
- Electrical break down of semiconductor can occur due to two different phenomena. Those two phenomena are

IV) Zener breakdown

V) Avalanche breakdown

12. ZENER BREAKDOWN:-

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

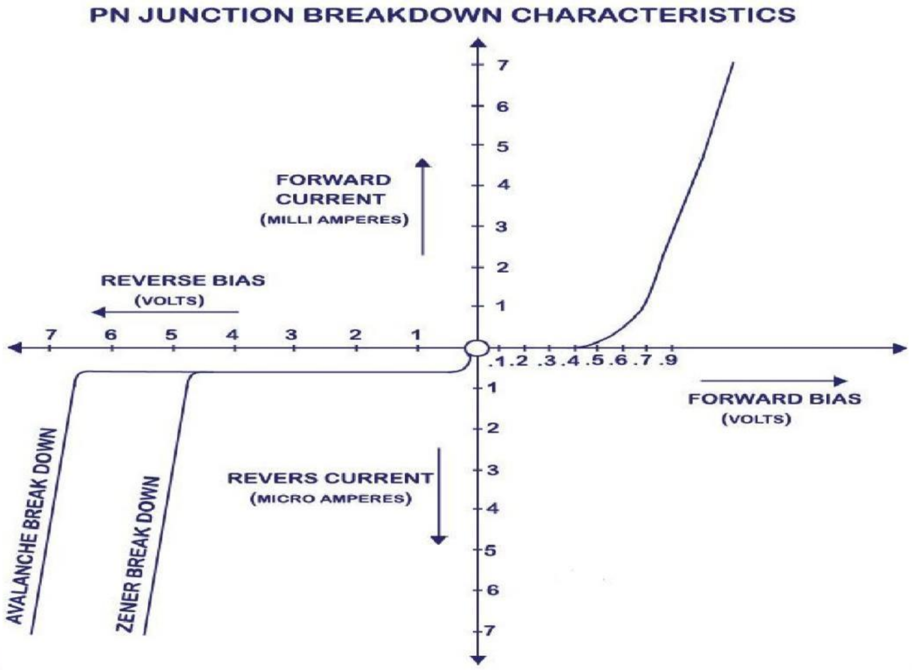


- It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called Breakdown Voltage is reached where the reverse current increases sharply to a high value.
- The breakdown region is the knee of the reverse characteristic as shown in Figure.
- The satisfactory explanation of this breakdown of the junction was first given by the American scientist C. Zener.
- The breakdown voltage is sometimes called Zener Voltage 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.

13. PROPERTIES OF ZENER DIODE:-

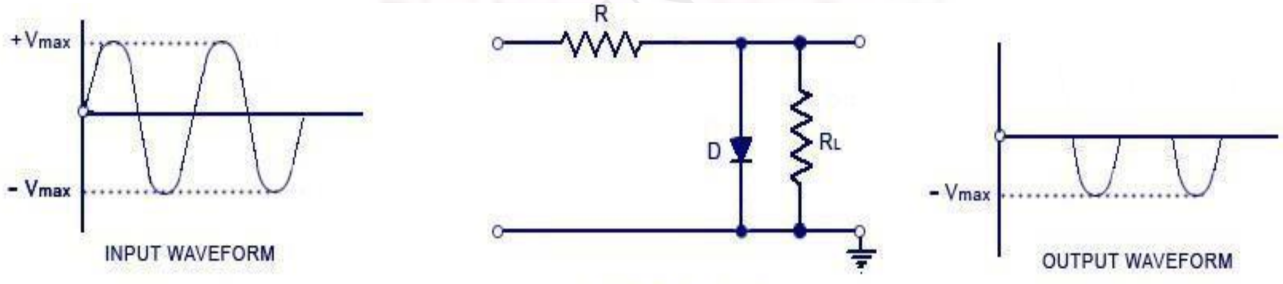
- The following points may be noted about the Zener diode:
- A Zener diode is like an ordinary diode except that it is properly doped to have a sharp breakdown voltage. A Zener diode is always reverse connected i.e. it is always reverse biased. A Zener diode has sharp breakdown voltage, called Zener voltage V_Z.
- When forward biased, its characteristics are just those of ordinary diode.
- 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.**
- **WORKING/OPERATION OF ZENER BREAKDOWN:-**
- When the reverse voltage across the pn junction diode increases, the electric field across the diode junction increases (both internal & external).
- 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 (means depletion layer width is very small).
- 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.

- **AVALANCHE BREAKDOWN:-**
- Avalanche breakdown occurs in a p-n junction diode which is moderately doped and has a thick junction (means its depletion layer width is high).
- 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).
- The electric field that occur due to applied reverse voltage (say V) can be calculated as $E = V/d$. So in a Zener breakdown, the electric field necessary to break electrons from covalent bond is achieved with lesser voltage than in avalanche breakdown due to thin depletion layer width.

- 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 (necessary enough to break electrons free).
- **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.
- Clippers find extensive use in radar, digital and other electronic systems.
- Although several clipping circuits have been developed to change the wave shape, we concentrate only on diode clippers.
- These clippers can remove signal voltages above or below a specified level.
- The important diode clippers are:-
  - Positive clipper and negative clipper
  - Biased positive clipper and biased negative clipper
  - 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
  - vi) Positive series clipper
  - vii) Positive shunt clipper
- The below Fig. shows the typical circuit of a positive shunt clipper using a diode.



Positive Shunt Clipper

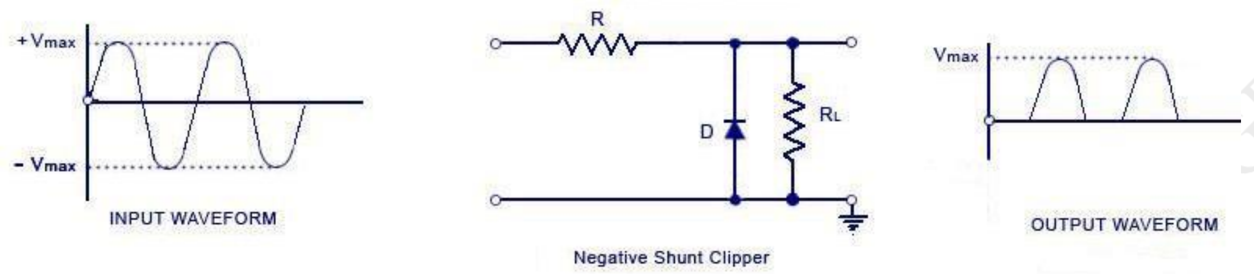
- Here the diode is kept in parallel with the load.
- During the positive half cycle, the diode 'D' is forward biased and the diode acts as a closed switch. This causes the diode to conduct heavily.
- This causes the voltage drop across the diode or across the load resistance R_L to be zero. Thus output voltage during the positive half cycles is zero.
- 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
- 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

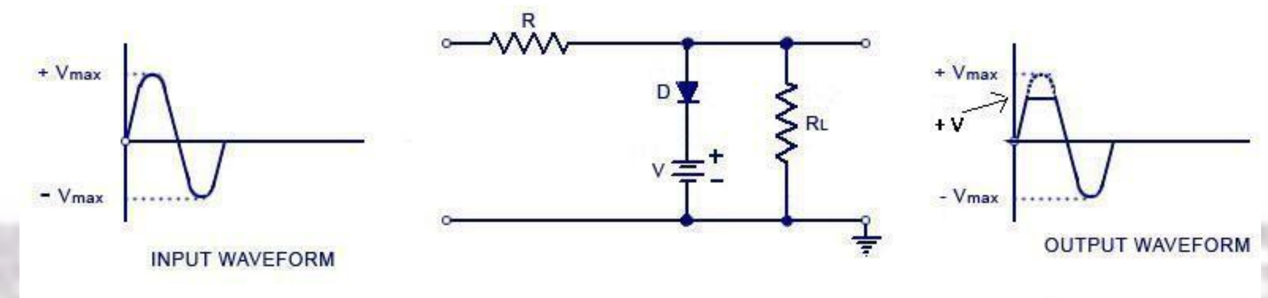
1) Negative series clipper
2) Negative shunt clipper

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



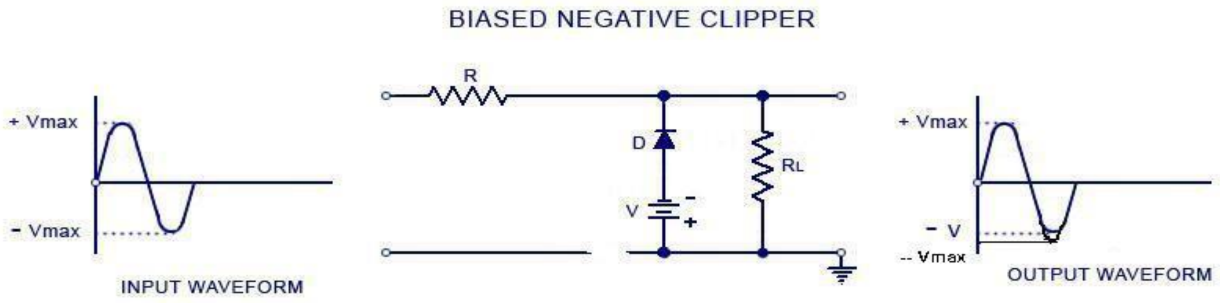
- During the negative half cycle, the diode 'D' is forward biased and the diode acts as a closed switch. This causes the diode to conduct heavily.
- This causes the voltage drop across the diode or across the load resistance R_L to be zero. Thus output voltage during the negative half cycles is zero.
- 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
- 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 $R_L >> R$).
- **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.

BIASED POSITIVE CLIPPER

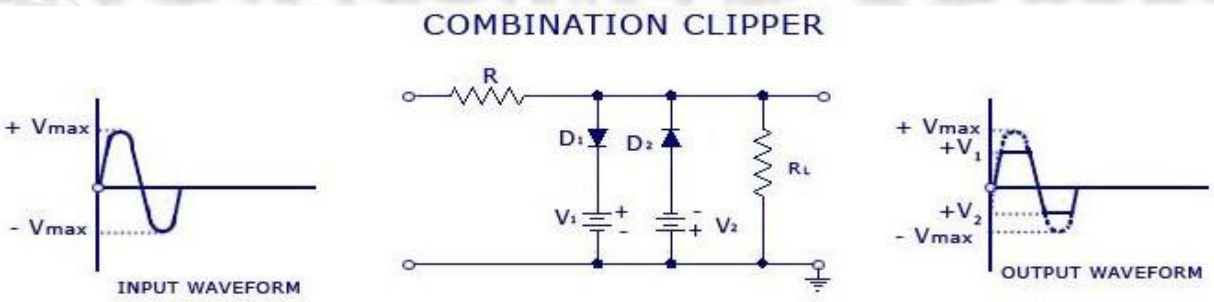


- During negative half cycle, when the input signal voltage is negative, the diode 'D' is reverse-biased. This causes it to act as an open-switch. Thus the entire negative half cycle appears across the load, as illustrated by output waveform.
- During positive half cycle, when the input signal voltage 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.

- 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.



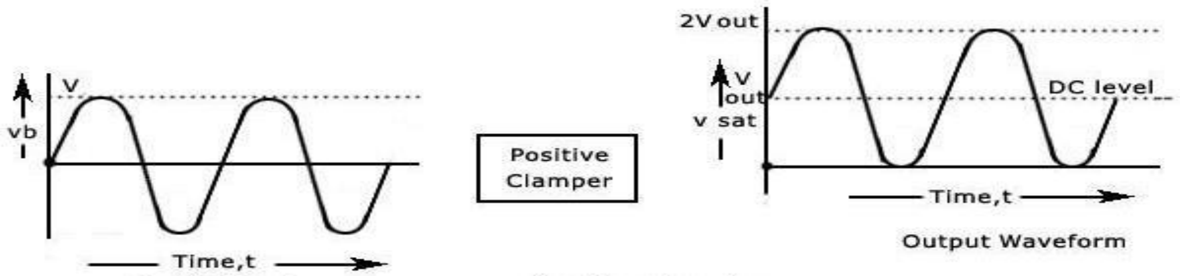
- For positive input voltage signal when input voltage exceeds battery voltage $+V_1$ diode D_1 conducts heavily while diode D_2 is reversed biased and so voltage $+V_1$ appears across the output. This output voltage $+V_1$ stays as long as input signal voltage exceeds $+V_1$.
- On the other hand for 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:-**
- There are numerous clipper applications however, in general, clippers are used to perform one of the following two functions:

1. **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.

2. **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.

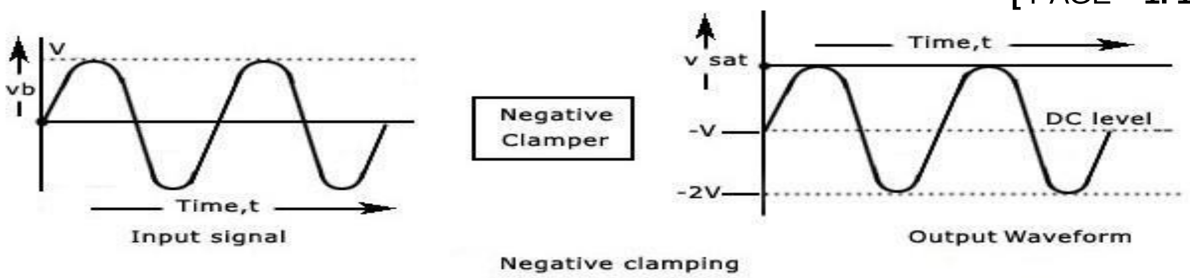
- **CLAMPER CIRCUITS:-**

- 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.
- A clamp circuit adds the positive or negative dc component to the input signal so as to push it either on the positive side.
- The clamper is of two types :-
  - Positive clamper
  - 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.



Positive clamping

- 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.

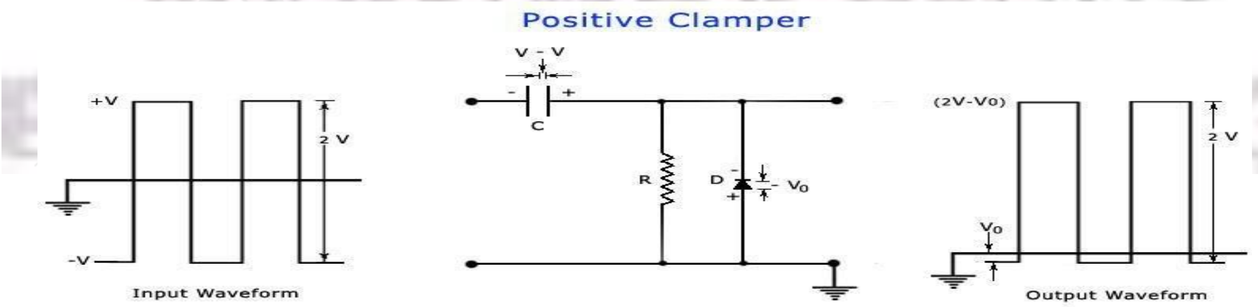


- For a clamping circuit at least three components — a diode, a capacitor and a resistor are required. Sometimes an independent dc supply is also required to cause an additional shift. The important points regarding clamping circuits are:

1. The shape of the waveform will be the same, but its level is shifted either upward or downward,
2. There will be no change in the peak-to-peak or r.m.s value of the waveform due to the clamping circuit. Thus, the input waveform and output waveform will have the same peak-to-peak value that is, $2V_{max}$. This is shown in the figure above. It must also be noted that same readings will be obtained in the ac voltmeter for the input voltage and the clamped output voltage.
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. It is advantageous to first consider the condition under which the diode becomes forward biased.

14. POSITIVE CLAMPER:-

- Consider a negative clamping circuit, a circuit that shifts the original signal in a vertical downward direction.

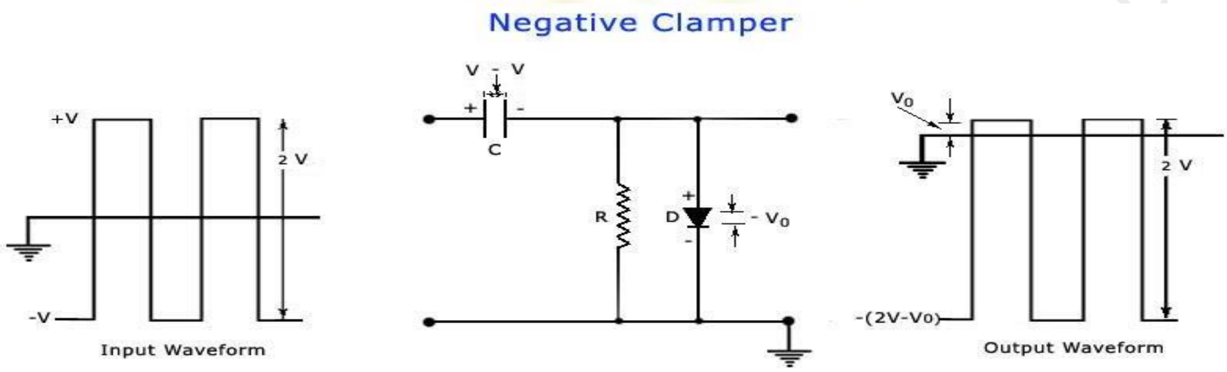


- The diode D will be forward biased and the capacitor C is charged with the polarity shown, when an input signal is applied.
- During the negative half cycle of input, the output voltage will be equal to the barrier potential of the diode, V_0 and capacitor is charged to $(V - V_0)$.

- 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 + (V — V_0) = +(2 V – V_0) .
- The value of the peak-to-peak output will be the difference of the negative and positive peak voltage levels is equal to (2V-V_0) - V_0 = 2 V.

15. NEGATIVE CLAMPER:-

- Consider a negative clamping circuit, a circuit that shifts the original signal in a vertical downward direction.



- The diode D will be forward biased and the capacitor C is charged with the polarity shown, when an input signal is applied.
- During the positive half cycle of input, the output voltage will be equal to the barrier potential of the diode, V_0 and capacitor is charged to (V – V_0).
- 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 – (V — V_0) = – (2 V – V_0) .
- 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 - [-(2V-V_0)] = 2 V.

16. APPLICATIONS OF CLAMPER:-

- Clamping circuits are often used in television receivers as dc restorers in the TV receiver

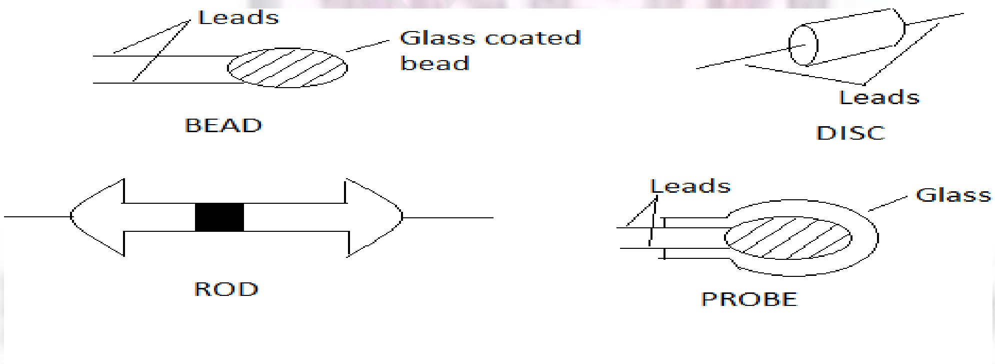
They also find applications in storage counters, analog frequency meter, capacitance meter, divider and stair-case waveform generator.

17. 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.

18. 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.
- The relation between resistance and absolute temperature of a thermistor can be represented as
    - $R_{T1}=R_{T2}$ exp[β(1/T1)-(1/T2)]
    - Where RT1=resistance of thermistor at absolute temperature T1 K
    - R_{T2}=resistance of thermistor at absolute temperature T2K
    - And β=a constant depending on the material of the thermistor (usually it ranges from 3500 K to 4500 K).



[Different Types Of Thermistors]

19. FEATURES

- These are compact, rugged and inexpensive and have good stability when properly aged.
- Measuring current is maintained at a value as low as possible so that self-heating of thermistors is avoided otherwise errors are introduced on account of changes of resistance caused by self-heating.

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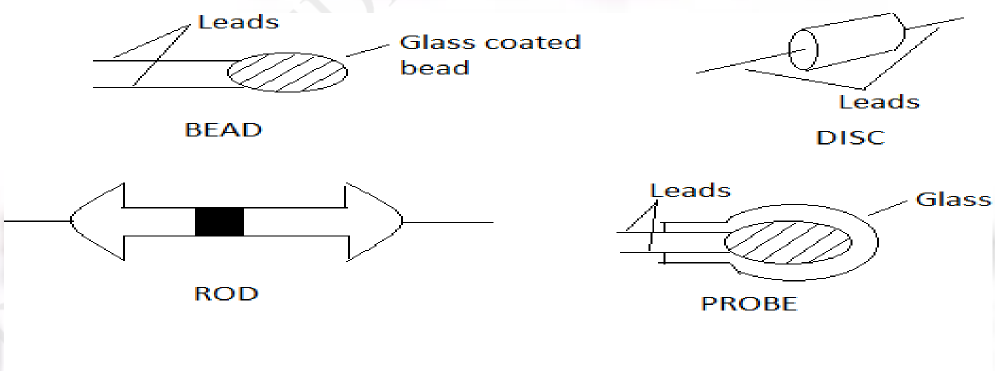


[Different Types Of Thermistors]

22. FEATURES

- These are compact, rugged and inexpensive and have good stability when properly aged.
- Measuring current is maintained at a value as low as possible so that self-heating of thermistors is avoided otherwise errors are introduced on account of changes of resistance caused by self-heating.

- The upper operating limit of temperature for thermistor is dependent on physical changes in the material.
- For thermistor the Response time can vary from fraction of second to minute depending on the size of detecting mass and thermal capacity of the thermistor.
- Response time varies inversely with dissipation factor.

23. 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.

24. <u>BARRETERS</u>

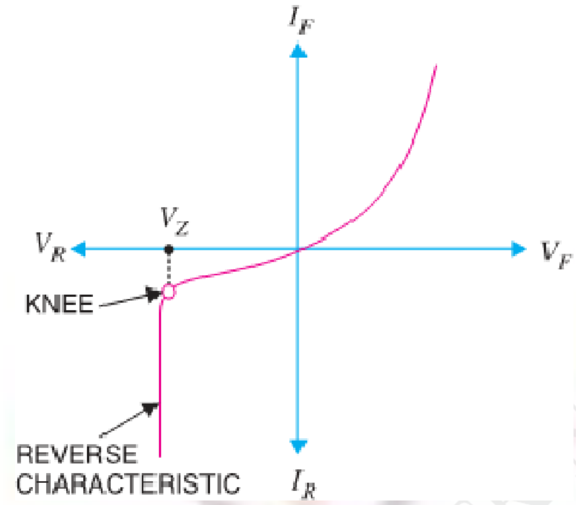
- Barreters are the short length wires with fine diameters with operating range around 1500C.

1) **<u>SENSORS</u>**

- 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.
- With advances in micro machinery and easy to use microcontroller platforms, the uses of sensors have expanded beyond the more traditional fields of temperature, pressure or flow measurement.
- Moreover, analog sensors such as potentiometers and force-sensing resistors are still widely used. Applications include manufacturing and machinery, airplanes and aerospace, cars, medicine and robotics.
- 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 .
- Sensors need to be designed to have a small effect on what is measured; making the sensor smaller often improves this and may introduce other advantages.
- Technological progress allows more and more sensors to be manufactured on a microscopic scale as microsensors using MEMS technology.
- In most cases, a microsensor reaches a significantly higher speed and sensitivity compared with macroscopic approaches.

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 satisfactory explanation of this breakdown of the junction was first given by the American scientist C. Zener.
- The breakdown voltage is sometimes called **Zener Voltage** 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.

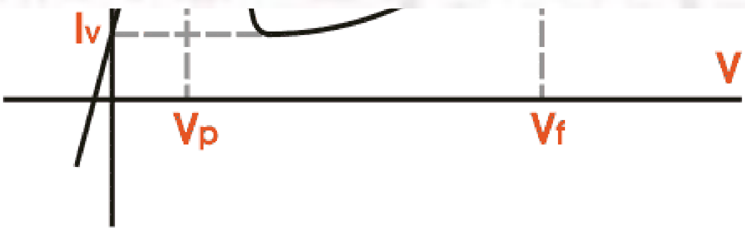
- The given figure shows the symbol of a Zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into z-shape.

  The following points may be noted about the Zener diode:
  - A Zener diode is like an ordinary diode except that it is properly doped to have a sharp breakdown voltage.
  - A Zener diode is always reverse connected i.e. it is always reverse biased.
  - A Zener diode has sharp breakdown voltage, called Zener voltage V_Z.
  - When forward biased, its characteristics are just those of ordinary diode.
  - 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.

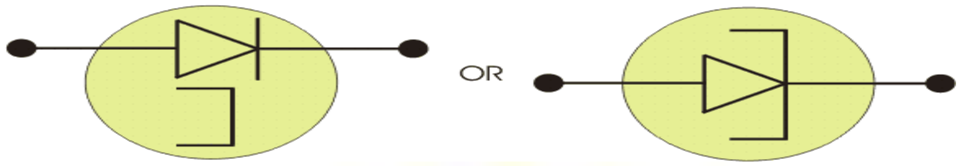
- Zener diode operated in this region will have a relatively constant voltage across it, regardless of the value of current through the device. This permits the Zener diode to be used as a **Voltage Regulator.**

25. TUNNEL DIODE:-

- Under normal forward bias operation, as voltage begins to increase, 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 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, 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**) and can act as fast rectifiers with zero offset voltage and extreme linearity for power signals (they have an accurate square law characteristic in the reverse direction).
- 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 a conventional semiconductor diode, conduction takes place while the p–n junction is forward biased and blocks current flow when the junction is reverse biased. This occurs up to a point known as the “reverse breakdown voltage” when conduction begins (often accompanied by destruction of the device).
- 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.
- However, when forward-biased, an odd effect occurs called quantum mechanical tunnelling which gives rise to a region where an *increase* in forward voltage is accompanied by a *decrease* in forward current.
- In the current voltage characteristics of **tunnel diode**, we can find a negative slope region when forward bias is applied.

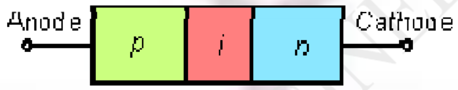


- Quantum mechanical tunneling is responsible for the phenomenon and thus this device is named as tunnel diode.
- The doping is very high so at absolute zero temperature the Fermi levels lies within the bias of the semiconductors. When no bias is applied any current flows through the junction.



26. PIN DIODE:-

- The PIN diode can be shown diagrammatically as being a PN junction, but with an intrinsic layer between the PN and layers.
- 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.
- In any PN junction, the P region contains holes as it has been doped to ensure that it has a predominance of holes.
- Similarly the N region has been doped to contain excess electrons.
- 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.
- This electric field helps in speeding up of the transport of charge carriers from p to n region, which results in faster operation of the diode, making it a suitable device for high frequency operations.
- A PIN diode obeys the standard diode equation for low frequency signals.

At higher frequencies, the diode looks like an almost perfect (very linear, even for large signals) resistor.

- There is a lot of stored charge in the intrinsic region.
- At low frequencies, the charge can be removed and the diode turns off.
- At higher frequencies, there is not enough time to remove the charge, so the diode never turns off. The PIN diode has a poor reverse recovery time.
- The high-frequency resistance is inversely proportional to the DC bias current through the diode.
- A PIN diode, suitably biased, therefore acts as a variable resistor.
- This high-frequency resistance may vary over a wide range (from 0.1 ohm to 10 kΩ in some cases the useful range is smaller, though).
- The wide intrinsic region also means the diode will have a low capacitance when reverse biased.
- In a PIN diode, the depletion region exists almost completely within the intrinsic region.
- This depletion region is much larger than in a PN diode, and almost constant-size, independent of the reverse bias applied to the diode.
- This increases the volume where electron-hole pairs can be generated by an incident photon.

27. PIN DIODE USES AND ADVANTAGES

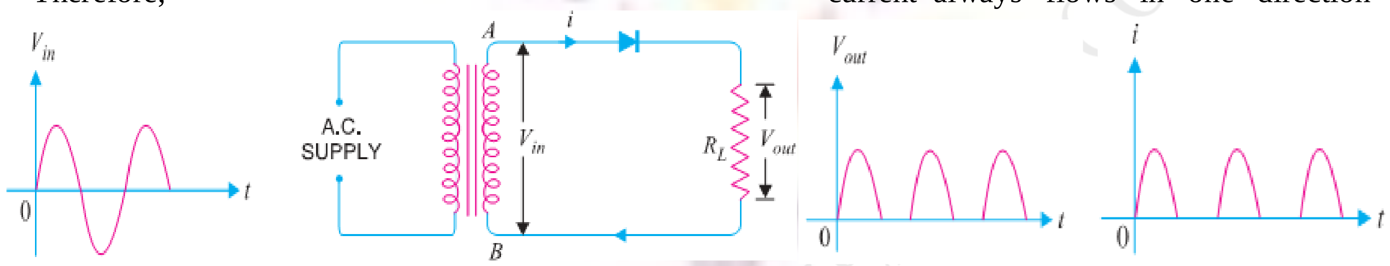
- The PIN diode is used in a number of areas as a result of its structure proving some properties which are of particular use.
    - **HIGH VOLTAGE RECTIFIER:** The PIN diode can be used as a high voltage rectifier. The intrinsic region provides a greater separation between the PN and N regions, allowing 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.

[RECTIFIERS]

- **INTRODUCTION: -**

1. 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
- **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.
    1) Firstly, it allows us to step up or step down the A.C. input voltage as the situation demands.
    2) 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 : -

- 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.
- 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.
- For the positive half- cycle of input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so ; current being always in the same direction through the load.
- Therefore, a full-wave rectifier utilizes both half-cycles of input A.C. voltage to produce the D.C. output.
- The following two circuits are commonly used for full-wave rectification: -
    - **(i)** Centre-tap full-wave rectifier **(ii)** Full-wave bridge rectifier

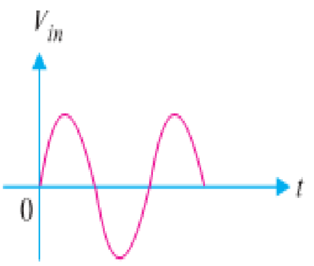
- **CENTRE-TAP FULL-WAVE RECTIFIER:-**

Circuit Details: -

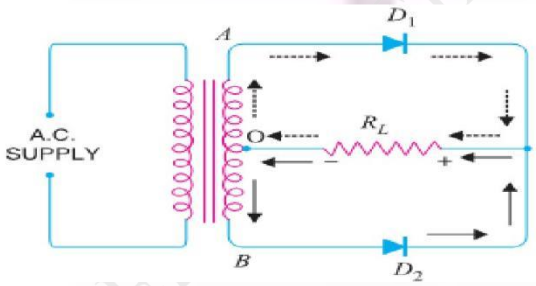
- The circuit employs two diodes D_1 and D_2 as shown in Fig below. A centre tapped secondary winding AB is used with two diodes connected so that each uses one half-cycle of input A.C. voltage.
- In other words, diode D_1 utilizes the A.C. voltage appearing across the upper half (OA) of secondary winding for rectification while diode D_2 uses the lower half winding OB.

Circuit Operation: -

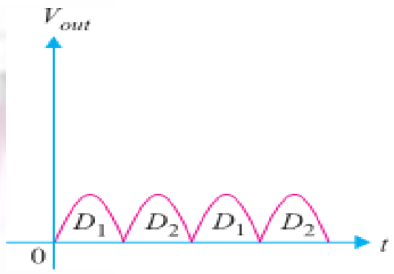
- During the positive half-cycle of secondary voltage, the end A of the secondary winding becomes positive and end B negative. This makes the diode D_1 forward biased and diode D_2 reverse biased.
- Therefore, diode D_1 conducts while diode D_2 does not. The conventional current flow is through diode 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:-

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

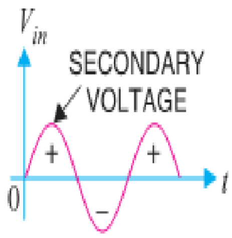
Disadvantages:-

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

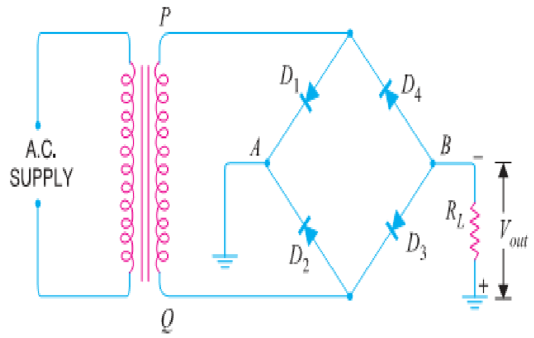
- **FULL-WAVE BRIDGE RECTIFIER: -**

Circuit Details: -

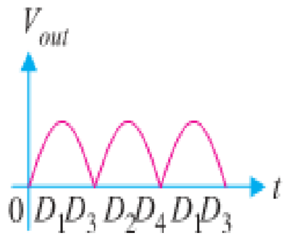
- The need for a centre tapped power transformer is eliminated in the bridge rectifier.
- It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in Fig below.
- The A.C. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer.
-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



(Input Wave Form)



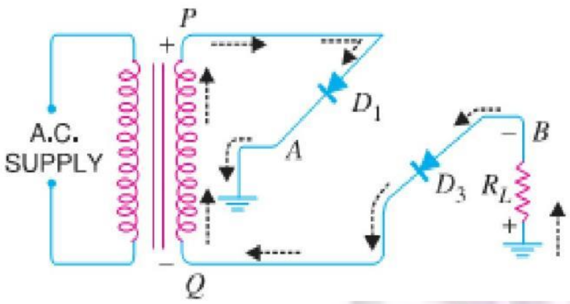
(Full-Wave Bridge Rectifier Circuit)



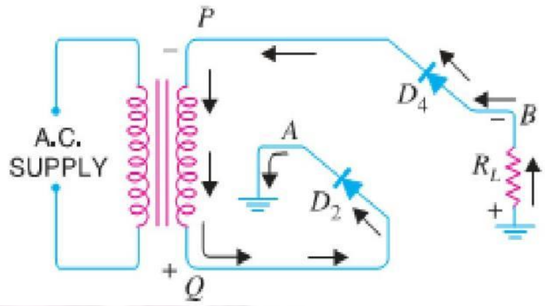
(Output wave form)

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: -**

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

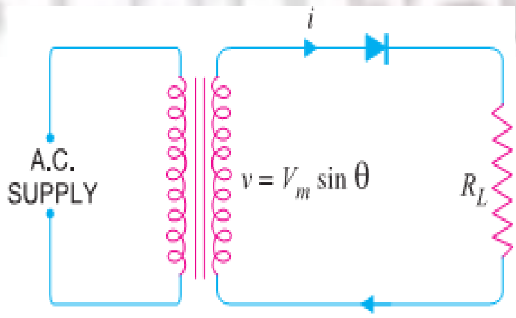
- **Disadvantages: -**

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

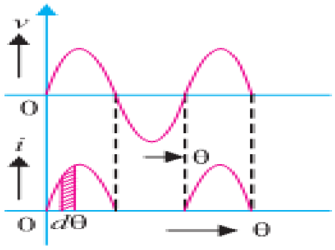
Mathematical Derivation for Rectification Efficiency for HALF WAVE rectifier : -

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

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



- 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.



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

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

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

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

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

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

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

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

$$\therefore \quad \text{Rectifier efficiency} = \frac{\text{d.C.output power}}{\text{a.C.input power}} = \left(\frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2 (r_f + R_L)}\right) = \frac{0.406 R_L}{r_f + R_L} = \frac{0.406 R_L}{1 + \frac{r_f}{R_L}}$$

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

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

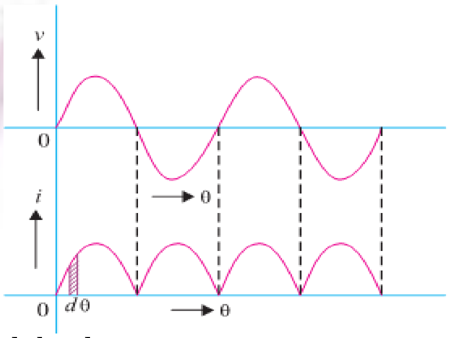
- It shows that in half-wave rectification, maximum of 40.6% of a. c. power is converted into d. c. power.

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

$$= \left[\frac{I_m^2}{4\pi}\left[\theta - \frac{\sin 2\theta}{2}\right]_0^{\pi}\right]^{½} = \left[\frac{I_m^2}{4\pi}\left[\pi - 0 - \frac{\sin 2\pi}{2} + \sin 0\right]\right]^{½} = \left[\frac{I_m^2}{4\pi} \times \pi\right]^{½} = \left[\frac{I_m^2}{4}\right]^{½} = \frac{I_m}{2} \rightarrow \mathbf{I_{rms}} = \frac{I_m}{2}$$

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

Mathematical Derivation for Rectification Efficiency for FULL WAVE Rectifier : -



- Fig. shows the process of full-wave rectification.
- Let $v = V_m \sin\theta$ be the a.c. voltage to be rectified. Let r_f and R_L be the diode resistance and load resistance respectively.
- Obviously, the rectifier will conduct current through the load in the same direction for both half-cycles of input a.c. voltage. The instantaneous current *i* is given by :

$$i = \frac{v}{(r_f + R_L)} = \frac{V_m \sin\theta}{(r_f + R_L)}$$

(a) D.C. OUTPUT POWER.

- The output current is pulsating direct current. Therefore, in order to find the d.c. power, average current has to be found out. For a full wave rectifier the average value or dc value can be found like half wave ,

$$\mathbf{I_{dc}} = \frac{2 I_m}{\pi}$$

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

(b) A.C. INPUT POWER.

- The a.c. input power is given by : $P_{ac} = I^2_{rms} (r_f + R_L)$

For a full-wave rectified wave, we have, $\mathbf{I_{rms} = I_m/\sqrt{2}}$ ∴ $\mathbf{P_{ac}} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)$

∴ Full-wave rectification efficiency is

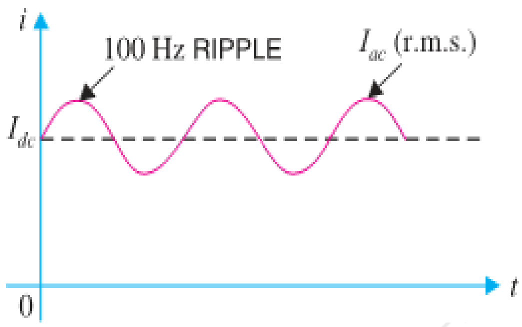
$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m/\pi)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)} = \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812\, R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

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.

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.



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

(c) **Mathematical Analysis**.

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

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

3. Dividing throughout by I_{dc}, we get,

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

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

1) For half-wave rectification: -

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

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

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

2) **For full-wave rectification**: -

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

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

7. 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.
8. For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

Peak Inverse Voltage (PIV) : -

- 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 : -
  - For Half Wave = V_m, **b)** For Center Tapped = $2V_m$ and **c)** For Bridge Rectifier = V_m.

Transformer Utilization Factor (TUF) : -

- 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.

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

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

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

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

Output Frequency of Half Wave Rectifier: -

- The output frequency of a half-wave rectifier is equal to the input frequency (50 Hz). Recall how a complete cycle is defined.
- A waveform has a complete cycle when it repeats the same wave pattern over a given time.
- Thus in Fig. (i), the a.c. input voltage repeats the same wave pattern over 0° – 360°, 360° – 720° and so on.
- In Fig. (ii), the output waveform also repeats the same wave pattern over 0° – 360°, 360° – 720° and so on.
- This means that when input a.c. completes one cycle, the output half wave rectified wave also completes one cycle.
- In other words, for the half wave rectifier the output frequency is equal to the input frequency i.e. $\mathbf{f_{out} = f_{in}}$
- For example, if the input frequency of sine wave applied to a half-wave rectifier is 100 Hz, then frequency of the output wave will also be 100 Hz.

Output Frequency of Full Wave Rectifier: -

- The output frequency of a full-wave rectifier is double the input frequency.
- As a wave has a complete cycle when it repeats the same pattern.
- In Fig. (i), the input a.c. completes one cycle from 0° – 360°.
- However, in Fig. (ii) full-wave rectified wave completes two cycles in this period.
- Therefore, output frequency is twice the input frequency i.e. $\mathbf{f_{out} = 2f_{in}}$
- For example, if the input frequency to a full-wave rectifier is 100 Hz, then the output frequency will be 200 Hz.
- **COMPARISON OF RECTIFIERS: -**

waveform:

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

(d) FILTER CIRCUITS:-

- Generally, a rectifier is required to produce pure D.C. supply for using at various places in the electronic circuits.
- However, 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.
- To do so, a filter circuit is used which removes (or filters out) the A.C. component and allows only the D.C. component to reach 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)

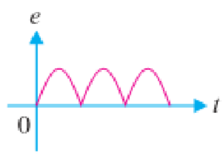
  ♣ ***Hence, a Capacitor does not allow d.c. to pass through it.***

- 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)

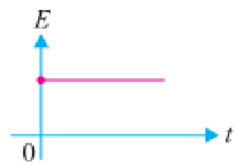
  ♣ ***Hence Inductor passes d.c. quite readily.***

- *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 : -

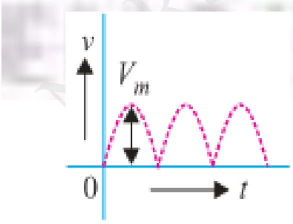
  ♣ <u>*Inductive Filter or Series Inductor*</u>,

  ♣ <u>*Capacitor Filter or Shunt Capacitor*</u>,

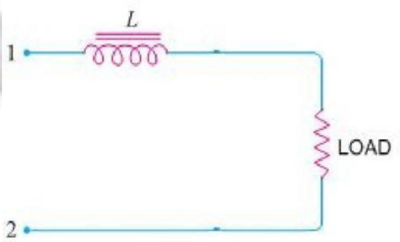
  ♣ <u>*Choke Input Filter or LC Filter*</u> and

  ♣ <u>*Capacitor Input Filter* or *π-Filter*</u>.

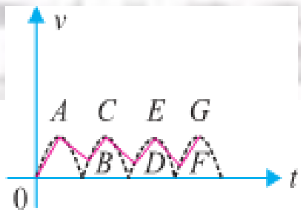
✓ **Inductive Filter Or Series Inductor:-**



(Rectified output Pulsating d.c)



(Inductive Filter Circuit)

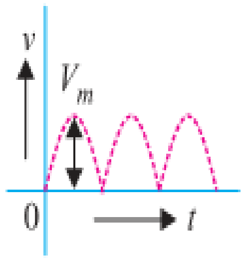


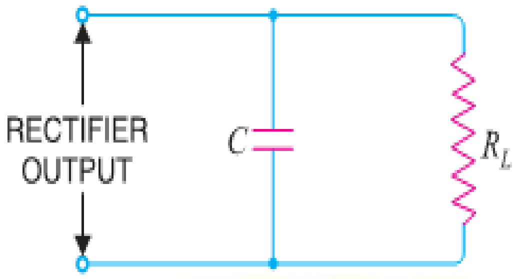
(Output of Inductive Filter)

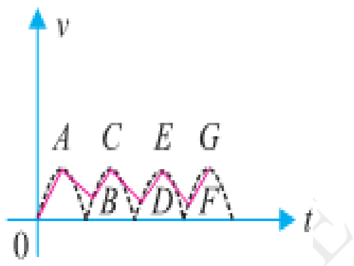
- Fig. (ii) Shows a typical Inductive filter circuit. It consists of an Inductor L placed across the rectifier output in series with load R_L.

- The choke (Inductor with iron core) offers high opposition to the passage of a.c. component but no opposition to the d.c. component.
- 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 Load resistance R_L.

✓ **Capacitor Filter Or Shunt Capacitor:-**



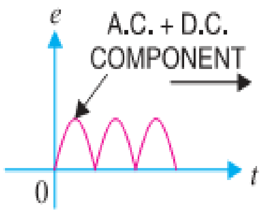


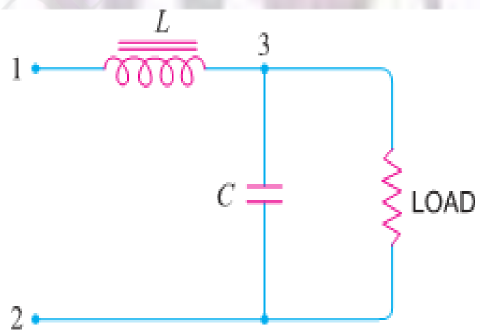


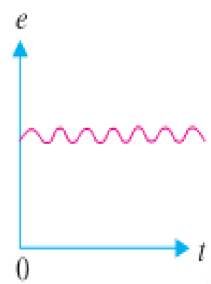
(Rectified output Pulsating d.c) (Capacitor Filter Circuit) (Output of Capacitor Filter)

- 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.
- Moreover, output voltage is higher as it remains substantially near the peak value of rectifier output voltage.
- The capacitor filter circuit is extremely popular because of its low cost, small size, little weight and good characteristics.

✓ **Choke Input Filter Or LC Filter:-**





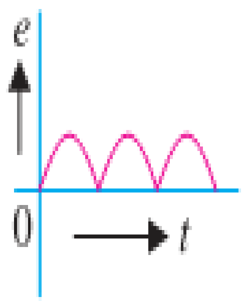


(Rectified output Pulsating d.c) (Choke Input Filter Circuit) (Output of Choke Input Filter)

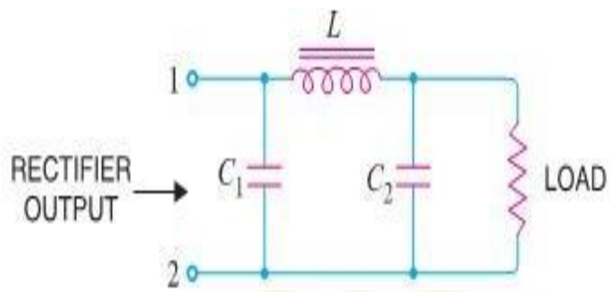
- Fig. shows a typical choke input filter circuit. It consists of a choke L connected in series with the rectifier output and a filter capacitor C across the load.
- Only a single filter section is shown, but several identical sections are often used to reduce the pulsations as effectively as possible.
- The pulsating output of the rectifier is applied across terminals 1 and 2 of the filter circuit.
- As discussed before, the pulsating output of rectifier contains a.c. and d.c. components. The choke offers high opposition to the passage of a.c. component but negligible opposition to the d.c. component.
- 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. componentto 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.

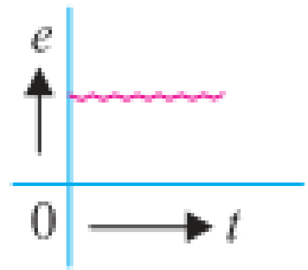
✓ **Capacitor Input Filter or π-Filter:-**



(Rectified output Pulsating d.c)



(Capacitor Input or π- Filter Circuit)



(Output of π-Filter)

i) 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.

ii) Only one filter section is shown but several identical sections are often used to improve the smoothing action. The pulsating output from the rectifier is applied across the input terminals (i.e. terminals 1 & 2) of the filter.

iii) The filtering action of the three components viz C_1 , L and C_2 of this filter is described below :

1. 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.
2. 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.
3. 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

MODULE-II

FET CIRCUITS

FET Structure and VI Characteristics, MOSFET structure and I-V characteristics. MOSFET as a switch. Small signal equivalent circuits-gain,input and output impedances, small-signal model and common-source, common-gate and common- drain amplifiers, trans conductance, high frequency equivalent circuit.

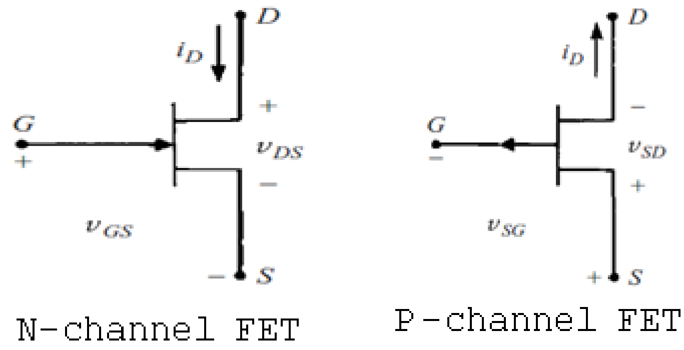
INTRODUCTION

- The Field effect transistor is abbreviated as FET , it is an another semiconductor device like a BJT which can be used as an amplifier or switch.
- The Field effect transistor is a voltage operated device. Whereas Bipolar junction transistor is a current controlled device. Unlike BJT a FET requires virtually no input current.
- This gives it an extremely high input resistance , which is its most important advantage over a bipolar transistor.
- FET is also a three terminal device, labeled as source, drain and gate.
- The source can be viewed as BJT's emitter, the drain as collector, and the gate as the counter part of the base.
- The material that connects the source to drain is referred to as the channel.
- FET operation depends only on the flow of majority carriers ,therefore they are called uni polar devices. BJT operation depends on both minority and majority carriers.
- As FET has conduction through only majority carriers it is less noisy than BJT.
- FETs are much easier to fabricate and are particularly suitable for ICs because they occupy less space than BJTs.
- FET amplifiers have low gain bandwidth product due to the junction capacitive effects and produce more signal distortion except for small signal operation.
- The performance of FET is relatively unaffected by ambient temperature changes. As it has a negative temperature coefficient at high current levels, it prevents the FET from thermal breakdown. The BJT has a positive temperature coefficient at high current levels which leads to thermal breakdown.

CLASSIFICATION OF FET:

There are two major categories of field effect transistors:
2. Junction Field Effect Transistors
3. MOSFETs
These are further sub divided in to P- channel and N-channel devices.
MOSFETs are further classified in to two types Depletion MOSFETs and Enhancement. MOSFETs
When the channel is of N-type the JFET is referred to as an N-channel JFET, when the channel is of P-type the JFET is referred to as P-channel JFET.

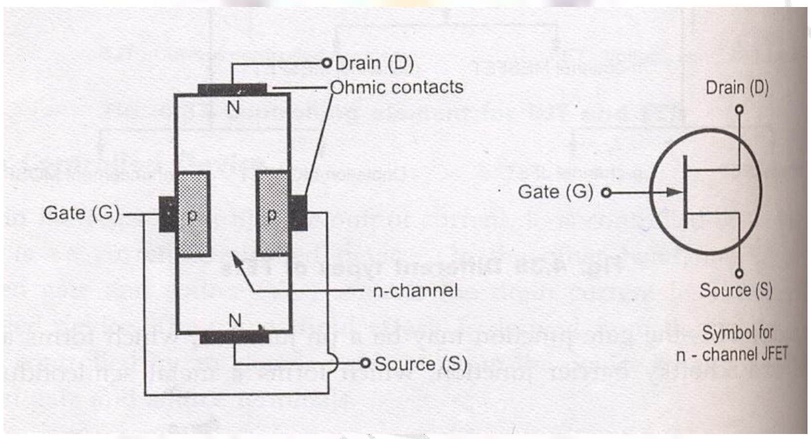
The schematic symbols for the P-channel and N-channel JFETs are shown in the figure.



CONSTRUCTION AND OPERATION OF N- CHANNEL FET

If the gate is an N-type material, the channel must be a P-type material.

CONSTRUCTION OF N-CHANNEL JFET



A piece of N- type material, referred to as channel has two smaller pieces of P-type material attached to its sides, forming PN junctions. The channel ends are designated as the drain and source . And the two pieces of P-type material are connected together and their terminal is called the gate. Since this channel is in the N-type bar, the FET is known as N-channel JFET.

OPERATION OF N-CHANNEL JFET:-

The overall operation of the JFET is based on varying the width of the channel to control the drain current.

A piece of N type material referred to as the channel, has two smaller pieces of P type material attached to its sites, farming PN –Junctions. The channel's ends are designated the drain and the source. And the two pieces of P type material are connected together and their terminal is called the gate. With the gate terminal not connected and the potential applied positive at the drain negative at the source a drain current Id flows. When the gate is biased negative with respective to the source the PN junctions are reverse biased and depletion regions are formed. The channel is more lightly doped than the P type gate blocks, so the depletion regions penetrate deeply into the channel. Since depletion region is a region depleted of charge carriers it behaves as an Insulator. The result is that the channel is narrowed. Its resistance is increased and Id is reduced. When the negative gate bias voltage is further increased, the depletion regions meet at the center and Id is cut off completely.

There are two ways to control the channel width

- By varying the value of Vgs
- And by Varying the value of Vds holding Vgs constant

1 By varying the value of Vgs :-

We can vary the width of the channel and in turn vary the amount of drain current.

This can be done by varying the value of Vgs. This point is illustrated in the fig below. Here we are dealing with N channel FET. So channel is of N type and gate is of P type that constitutes a PN junction. This PN junction is always reverse biased in JFET operation .The reverse bias is applied by a battery voltage Vgs connected between the gate and the source terminal i.e positive terminal of the battery is connected to the source and negative terminal to gate.

3) When a PN junction is reverse biased the electrons and holes diffuse across junction by leaving immobile ions on the N and P sides , the region containing these immobile ions is known as depletion regions.
4) If both P and N regions are heavily doped then the depletion region extends symmetrically on both sides.
5) But in N channel FET P region is heavily doped than N type thus depletion region extends more in N region than P region.
6) So when no Vds is applied the depletion region is symmetrical and the conductivity becomes Zero. Since there are no mobile carriers in the junction.
7) As the reverse bias voltage is increases the thickness of the depletion region also increases. i.e. the effective channel width decreases .
8) By varying the value of Vgs we can vary the width of the channel.

2 Varying the value of Vds holding Vgs constant :-

- When no voltage is applied to the gate i.e. Vgs=0 , Vds is applied between source and drain the electrons will flow from source to drain through the channel constituting drain current Id .
- With Vgs= 0 for Id= 0 the channel between the gate junctions is entirely open .In response to a small applied voltage Vds , the entire bar acts as a simple semi conductor resistor and the current Id increases linearly with Vds .
- The channel resistances are represented as rd and rs as shown in the fig.

- This increasing drain current Id produces a voltage drop across rd which reverse biases the gate to source junction,(rd> rs) .Thus the depletion region is formed which is not symmetrical .
- The depletion region i.e. developed penetrates deeper in to the channel near drain and less towards

source because Vrd >> Vrs. So reverse bias is higher near drain than at source.

- As a result growing depletion region reduces the effective width of the channel. Eventually a voltage

Vds is reached at which the channel is pinched off. This is the voltage where the current Id begins to level off and approach a constant value.

- So, by varying the value of Vds we can vary the width of the channel holding Vgs constant.

When both Vgs and Vds is applied:-

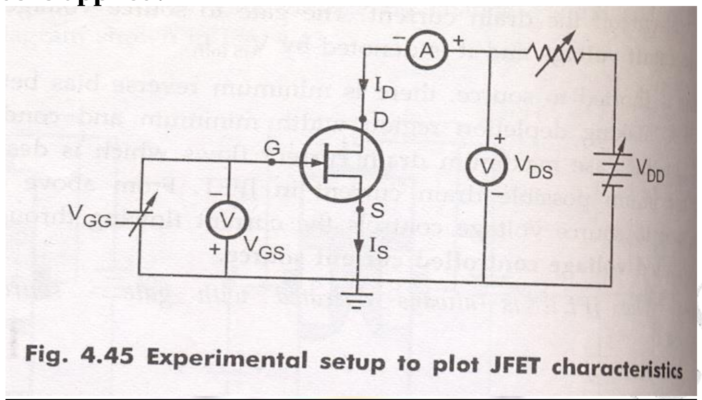
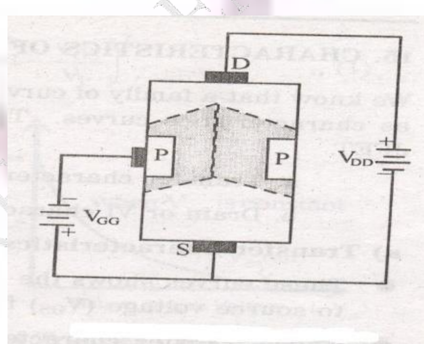


Fig. 4.45 Experimental setup to plot JFET characteristics

It is of course in principle not possible for the channel to close Completely and there by reduce the current Id to Zero for, if such indeed, could be the case the gate voltage Vgs is applied in the direction to provide additional reverse bias

- When voltage is applied between the drain and source with a battery Vdd, the electrons flow from source to drain through the narrow channel existing between the depletion regions. This constitutes the drain current Id, its conventional direction is from drain to source.
- The value of drain current is maximum when no external voltage is applied between gate and source and is designated by Idss.



- When Vgs is increased beyond Zero the depletion regions are widened. This reduces the effective width of the channel and therefore controls the flow of drain current through the channel.
- When Vgs is further increased a stage is reached at which to depletion regions touch each other that means the entire channel is closed with depletion region. This reduces the drain current to Zero.

CHARACTERISTICS OF N-CHANNEL JFET :-

The family of curves that shows the relation between current and voltage are known as characteristic curves.

There are two important characteristics of a JFET.

4) Drain or VI Characteristics
5) Transfer characteristics

- **Drain Characteristics:-**

Drain characteristics shows the relation between the drain to source voltage Vds and drain current Id. In order to explain typical drain characteristics let us consider the curve with Vgs= 0.V.

4. When Vds is applied and it is increasing the drain current ID also increases linearly up to knee

point.

5. This shows that FET behaves like an ordinary resistor. This region is called as ohmic region.
6. ID increases with increase in drain to source voltage. Here the drain current is increased slowly as compared to ohmic region.

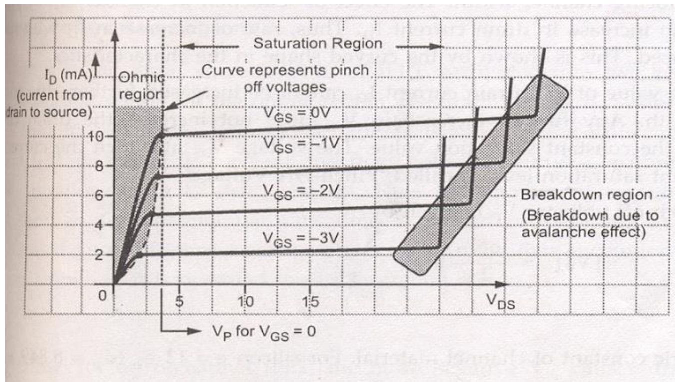


Fig. 4.44 Drain V-I characteristics of n-channel JFET

7) It is because of the fact that there is an increase in VDS .This in turn increases the reverse bias voltage across the gate source junction .As a result of this depletion region grows in size thereby reducing the effective width of the channel.
8) All the drain to source voltage corresponding to point the channel width is reduced to a minimum value and is known as pinch off.
9) The drain to source voltage at which channel pinch off occurs is called pinch off voltage(Vp).

PINCH OFF Region:-

1. This is the region shown by the curve as saturation region.
2. It is also called as saturation region or constant current region. Because of the channel is occupied with depletion region , the depletion region is more towards the drain and less towards the source, so the channel is limited, with this only limited number of carriers are only allowed to cross this channel from source drain causing a current that is constant in this region. To use FET as an amplifier it is operated in this saturation region.
3. In this drain current remains constant at its maximum value IDSS.
4. The drain current in the pinch off region depends upon the gate to source voltage and is given by the relation

$$I_d = I_{dss} [1-V_{gs/Vp}]^2$$

This is known as shokley’s relation.

BREAKDOWN REGION:-

- The region is shown by the curve .In this region, the drain current increases rapidly as the drain to source voltage is increased.
- It is because of the gate to source junction due to avalanche effect.
- The avalanche break down occurs at progressively lower value of VDS because the reverse bias gate voltage adds to the drain voltage thereby increasing effective voltage across the gate junction

This causes

- o The maximum saturation drain current is smaller
- o The ohmic region portion decreased.

- It is important to note that the maximum voltage VDS which can be applied to FET is the lowest voltage which causes available break down.

- **TRANSFER CHARACTERISTICS:-**

These curves shows the relationship between drain current ID and gate to source voltage VGS for different values of VDS.

i) First adjust the drain to source voltage to some suitable value , then increase the gate to source voltage in small suitable value.
ii) Plot the graph between gate to source voltage along the horizontal axis and current ID on the vertical axis. We shall obtain a curve like this.

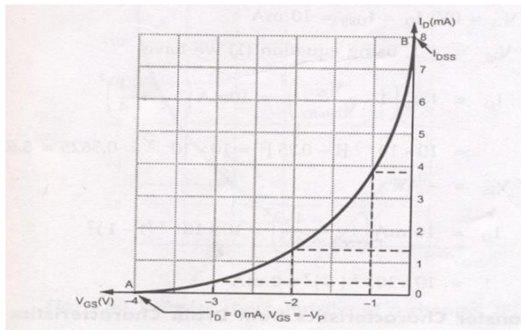


Fig. 4.48 Transfer characteristics of n-channel JFET

iii) As we know that if V_{gs} is more negative curves drain current to reduce . where V_{gs} is made sufficiently negative, I_d is reduced to zero. This is caused by the widening of the depletion region to a point where it is completely closes the channel. The value of V_{gs} at the cutoff point is designed as V_{gsoff}
iv) While the lower end is indicated by a voltage equal to V_{gsoff}
v) If Vg_s continuously increasing , the channel width is reduced , then I_d =0
vi) It may be noted that curve is part of the parabola; it may be expressed as

$I_d=I_{dss}[1-V_{gs}/V_{gsoff}]^2$

DIFFERENCE BETWEEN V_p AND V_{gsoff} –

Vp is the value of V_{gs} that causes the JFET to become constant current component, It is measured at V_{gs} =0V and has a constant drain current of I_d =I_{dss} .Where V_{gsoff} is the value of V_{gs} that reduces I_d to approximately zero.

<u>Why the gate to source junction of a JFET be always reverse biased ?</u>

The gate to source junction of a JFET is never allowed to become forward biased because the gate material is not designed to handle any significant amount of current. If the junction is allowed to become forward biased, current is generated through the gate material. This current may destroy the component. There is one more important characteristic of JFET reverse biasing i.e. J FET 's have extremely high characteristic gate input impedance. This impedance is typically in the high mega ohm range. With the advantage of extremely high input impedance it draws no current from the source. The high input impedance of the JFET has led to its extensive use in integrated circuits. The low current requirements of the component makes it perfect for use in ICs. Where thousands of transistors must be etched on to a single piece of silicon. The low current draw helps the IC to remain relatively cool, thus allowing more components to be placed in a smaller physical area.

JFET PARAMETERS

The electrical behavior of JFET may be described in terms of certain parameters. Such parameters are obtained from the characteristic curves.

<u>A C Drain resistance(r_d)</u>:

It is also called dynamic drain resistance and is the a.c resistance between the drain and source terminal, when the JFET is operating in the pinch off or saturation region. It is given by the ratio of small change in drain to source voltage ΔV_{ds} to the corresponding change in drain current ΔI_d for a constant gate to source voltage V_{gs}.

Mathematically it is expressed as $r_d = \Delta V_{ds} / \Delta I_d$ where V_{gs} is held constant.

TRANCE CONDUCTANCE (g_m):

It is also called forward transconductance . It is given by the ratio of small change in drain current (ΔI_d) to the corresponding change in gate to source voltage (ΔV_{ds})

Mathematically the transconductance can be written as

$$g_m = \Delta I_d / \Delta V_{ds}$$

AMPLIFICATION FACTOR (μ)

It is given by the ratio of small change in drain to source voltage (ΔV_{ds}) to the corresponding change in gate to source voltage (ΔV_{gs})for a constant drain current (I_d).

Thus $\mu = \Delta V_{ds} / \Delta V_{gs}$ when I_d held constant

The amplification factor μ may be expressed as a product of transconductance (g_m)and ac drain resistance (r_d)

$\mu = \Delta V_{ds} / \Delta V_{gs} = g_m r_d$

THE FET SMALL SIGNAL MODEL:-

The linear small signal equivalent circuit for the FET can be obtained in a manner similar to that used to derive the corresponding model for a transistor.

We can express the drain current iD as a function f of the gate voltage and drain voltage V_{ds}.

$I_d = f(V_{gs}, V_{ds})$------------------(1)

The transconductance g_m and drain resistance r_d:-

If both gate voltage and drain voltage are varied, the change in the drain current is approximated by using taylors series considering only the first two terms in the expansion

$$\Delta i_d = \frac{\partial id}{\partial V_{gs}}\Big|_{v_{ds}=constant} . \Delta v_{gs} + \frac{\partial id}{\partial V_{ds}}\Big|_{vgs=constant} \Delta v_{ds}$$

we can write $\Delta i_d = i_d$

$\Delta v_{gs} = v_{gs}$

$\Delta v_{ds} = v_{ds}$

$$I_d = g_m v_{gs} + \frac{1}{rd} V_{ds} \rightarrow (1)$$

Where $g_m = \frac{\partial id}{\partial V_{gs}}\Big|_{Vds} \quad \frac{\Delta id}{\Delta V_{gs}}\Big|_{Vds}$

$$g_m = \frac{id}{V_{gs}}\Big|_{Vds}$$

Is the mutual conductance or transconductance .It is also called as gfs or yfs common source forward conductance .

The second parameter r_d is the drain resistance or output resistance is defined as

$$r_d = \frac{\partial V ds}{\partial id}\Big|_{V_{gs}} \cong \frac{\Delta v ds}{\Delta ids}\Big|_{V_{gs}} = \frac{V ds}{id}\Big|_{V_{gs}}$$

$$r_d = \frac{V ds}{id}\Big|_{V_{gs}}$$

The reciprocal of the rd is the drain conductance gd .It is also designated by Yos and Gos and called the common source output conductance . So the small signal equivalent circuit for FET can be drawn in two different ways.

1.small signal current –source model

2.small signal voltage-source model.

This low frequency model for FET has a Norton's output circuit with a dependent current generator whose magnitude is proportional to the gate-to –source voltage. The proportionality factor is the transconductance 'g_m'. The output resistance is 'r_d'. The input resistance between the gate and source is infinite, since it is assumed that the reverse biased gate draws no current. For the same reason the resistance between gate and drain is assumed to be infinite.

These small signal models for FET can be used for analyzing the three basic FET amplifier configurations:

1.common source (CS) 2.common drain (CD) or source follower

3. common gate(CG).

(a) Small Signal Current source model for FET (b)Small Signal voltage source model for FET

MOSFET:-

We now turn our attention to the insulated gate FET or metal oxide semi conductor FET which is having the greater commercial importance than the junction FET.

Most MOSFETS however are triodes, with the substrate internally connected to the source. The circuit symbols used by several manufacturers are indicated in the Fig below.

(e) Depletion type MOSFET (b) Enhancement type MOSFET

Both of them are P- channel

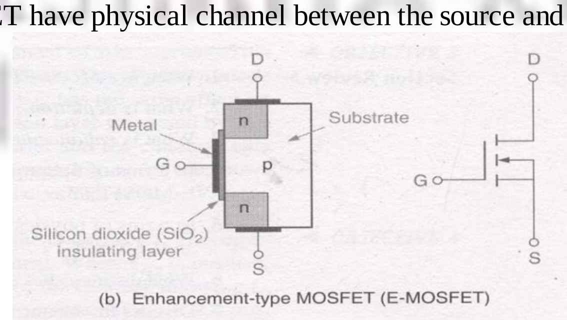
Here are two basic types of MOSFETS

(1) Depletion type (2) Enhancement type MOSFET.

D-MOSFETS can be operated in both the depletion mode and the enhancement mode. E MOSFETS are restricted to operate in enhancement mode. The primary difference between them is their physical construction.

The construction difference between the two is shown in the fig given below.

As we can see the D MOSFET have physical channel between the source and drain terminals(Shaded area)



(b) Enhancement-type MOSFET (E-MOSFET)

The E MOSFET on the other hand has no such channel physically. It depends on the gate voltage to form a channel between the source and the drain terminals.

Both MOSFETS have an insulating layer between the gate and the rest of the component. This insulating layer is made up of SIO_2 a glass like insulating material. The gate material is made up of metal conductor .Thus going from gate to substrate, we can have metal oxide semi conductor which is where the term MOSFET comes from. Since the gate is insulated from the rest of the component, the MOSFET is sometimes referred to as an insulated gate FET or IGFET. The foundation of the MOSFET is called the substrate. This material is represented in the schematic symbol by the center line that is connected to the source. In the symbol for the MOSFET, the arrow is placed on the substrate. As with JFET an arrow pointing in represents an N-channel device, while an arrow pointing out represents p-channel device.

CONSTRUCTION OF AN N-CHANNEL MOSFET:-

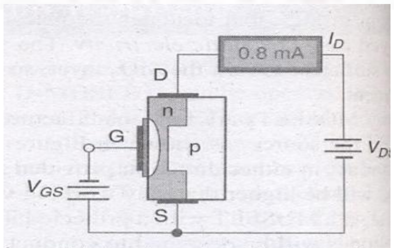
The N- channel MOSFET consists of a lightly doped p type substance into which two heavily doped n+ regions are diffused as shown in the Fig. These n+ sections, which will act as source and drain. A thin layer of insulation silicon dioxide (SIO_2) is grown over the surface of the structure, and holes are cut into oxide layer, allowing contact with the source and drain. Then the gate metal area is overlaid on the oxide, covering the entire channel region. Metal contacts are made to drain and source and the contact to the metal over the channel area is the gate terminal. The metal area of the gate, in conjunction with the insulating dielectric oxide layer and the semiconductor channel, forms a parallel plate capacitor. The insulating layer of sio2
Is the reason why this device is called the insulated gate field effect transistor. This layer results in an extremely high input resistance (10 10 to 10power 15ohms) for MOSFET.

DEPLETION MOSFET

The basic structure of D –MOSFET is shown in the fig. An N-channel is diffused between source and drain with the device an appreciable drain current IDSS flows foe zero gate to source voltage, Vgs=0.

Depletion mode operation:-

9. The above fig shows the D-MOSFET operating conditions with gate and source terminals shorted together(VGS=0V)
10. At this stage ID= IDSS where VGS=0V, with this voltage VDS, an appreciable drain current IDSS flows.
11. If the gate to source voltage is made negative i.e. VGs is negative .Positive charges are induced in the channel through the SIO2 of the gate capacitor.
12. Since the current in a FET is due to majority carriers(electrons for an N-type material) , the induced positive charges make the channel less conductive and the drain current drops as Vgs is made more negative.
13. The re distribution of charge in the channel causes an effective depletion of majority carriers , which accounts for the designation depletion MOSFET.
14. That means biasing voltage Vgs depletes the channel of free carriers This effectively reduces the width of the channel , increasing its resistance.
15. Note that negative Vgs has the same effect on the MOSFET as it has on the JFET.



(b) $I_D < I_{DSS}$ when V_{GS} is negative

16. As shown in the fig above, the depletion layer generated by Vgs (represented by the white space

between the insulating material and the channel) cuts into the channel, reducing its width. As a result ,Id<Idss. The actual value of ID depends on the value of Idss,Vgs(off) and Vgs.

Enhancement mode operation of the D-MOSFET:-

- This operating mode is a result of applying a positive gate to source voltage Vgs to the device.
- When Vgs is positive the channel is effectively widened. This reduces the resistance of the channel allowing ID to exceed the value of IDSS
- When Vgs is given positive the majority carriers in the p-type are holes. The holes in the p type substrate are repelled by the +ve gate voltage.
- At the same time, the conduction band electrons (minority carriers) in the p type material are attracted towards the channel by the +gate voltage.
- With the build up of electrons near the channel , the area to the right of the physical channel effectively becomes an N type material.
- The extended n type channel now allows more current, Id> Idss

Characteristics of Depletion MOSFET:-

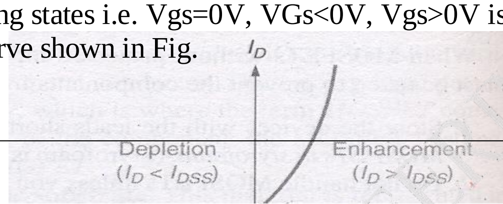
The fig. shows the drain characteristics for the N channel depletion type MOSFET

3) The curves are plotted for both Vgs positive and Vgs negative voltages
4) When Vgs=0 and negative the MOSFET operates in depletion mode when Vgs is positive ,the MOSFET operates in the enhancement mode.
5) The difference between JFET and D MOSFET is that JFET does not operate for positive values of Vgs.
6) When Vds=0, there is no conduction takes place between source to drain, if Vgs<0 and Vds>0 then Id increases linearly.
7) But as Vgs,0 induces positive charges holes in the channel, and controls the channel width. Thus the conduction between source to drain is maintained as constant, i.e. Id is constant.If Vgs>0 the gate induces more electrons in channel side, it is added with the free electrons generatedby source. again the potential applied to gate determines the channel width and maintains constant current flow through it as shown in Fig

6 MOSFET drain curves.

TRANSFER CHARACTERISTICS:-

The combination of 3 operating states i.e. Vgs=0V, VGs<0V, Vgs>0V is represented by the D MOSFET transconductance curve shown in Fig.

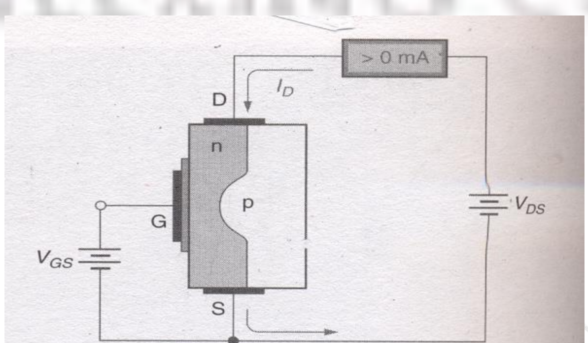


- Here in this curve it may be noted that the region AB of the characteristics similar to that of JFET.
- This curve extends for the positive values of Vgs
- Note that Id=Idss for Vgs=0V when Vgs is negative,Id< Idss when Vgs= Vgs(off) ,Id is reduced to approximately omA.Where Vgs is positive Id>Idss.So obviously Idss is not the maximum possible value of Id for a MOSFET.
- The curves are similar to JFET so thet the D MOSFET have the same transconductance equation.

E-MOSFETS

The E MOSFET is capable of operating only in the enhancement mode. The gate potential must be positive w.r.t to source.

- ✓ when the value of Vgs=0V, there is no channel connecting the source and drain materials.
- ✓ As aresult , there can be no significant amount of drain current.
- ✓ When Vgs=0, the Vdd supply tries to force free electrons from source to drain but the presence of p-region does not permit the electrons to pass through it. Thus there is no drain current at Vgs=0,
- ✓ If Vgs is positive, it induces a negative charge in the p type substrate just adjacent to the SIO2 layer.
- ✓ As the holes are repelled by the positive gate voltage, the minority carrier electrons attracted toward this voltage. This forms an effective N type bridge between source and drain providing a path for drain current.
- ✓ This +ve gate voltage forma a channel between the source and drain.
- ✓ This produces a thin layer of N type channel in the P type substrate. This layer of free electrons is called N type inversion layer.



(b) $I_D > 0$ mA when V_{GS} is sufficient to form a channel.

- ✓ The minimum Vgs which produces this inversion layer is called threshold voltage and is designated by Vgs(th).This is the point at which the device turns on is called the threshold voltage Vgs(th)
- ✓ When the voltage Vgs is <Vgs (th) no current flows from drain to source.
- ✓ How ever when the voltage Vgs > Vgs (th) the inversion layer connects the drain to source and we get significant values of current.

CHARACTERISTICS OF E MOSFET:-

- **DRAIN CHARACTERISTICS**

The volt ampere drain characteristics of an N-channel enhancement mode MOSFET are given in the fig

- **TRANSFER CHARACTERISTICS:-**

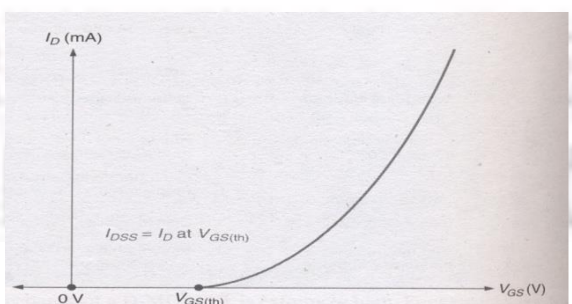
- The current Idss at Vgs≤ 0 is very small beinf of the order of a few nano amps.
- As Vgs is made +ve , the current Id increases slowly at forst, and then much more rapidly with an increase in Vgs.
- The standard transconductance formula will not work for the E MOSFET.
- To determine the value of ID at a given value of VGs we must use the following relation

$$Id = K[V_{gs} - V_{gs(Th)}]^2$$

Where K is constant for the MOSFET . found as

$$K = \frac{Id(on)}{[vgs(on) - Vgs(Th)]2}$$

From the data specification sheets, the 2N7000 has the following ratings.
Id(on)= 75mA(minimum).
And Vgs(th)=0.8(minimum)



E-MOSFET transconductance curve.

APPLICATION OF MOSFET

One of the primary contributions to electronics made by MOSFETs can be found in the area of digital (computer electronics). The signals in digital circuits are made up of rapidly switching dc levels. This signal is called as a rectangular wave ,made up of two dc levels (or logic levels). These logic levels are

0V and +5V. A group of circuits with similar circuitry and operating characteristics is referred to as a logic family. All the circuits in a given logic family respond to the same logic levels, have similar speed and power-handling capabilities , and can be directly connected together. One such logic family is complementary MOS (or CMOS) logic. This logic family is made up entirely of MOSFETs.

Small Signal Model, Analysis of CS, CD, CG JFET Amplifiers. Basic Concepts of MOSFET Amplifiers.

INTRODUCTION

Field Effect Transistor (FET) amplifiers provide an excellent voltage gain and high input impedance. Because of high input impedance and other characteristics of JFETs they are preferred over BJTs for certain types of applications.

There are 3 basic FET circuit configurations:

iv)Common Source ii)Common Drain iii)Common Gain

Similar to BJT CE,CC and CB circuits, only difference is in BJT large output collector current is controlled by small input base current whereas FET controls output current by means of small input voltage. In both the cases output current is controlled variable.

FET amplifier circuits use voltage controlled nature of the JFET. In Pinch off region, I_D depends only on V_{GS}.

Common Source (CS) Amplifier

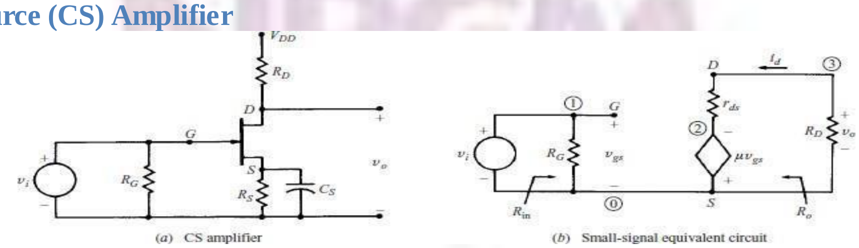


Fig. 7.1 (a) CS Amplifier (b) Small-signal equivalent circuit

A simple Common Source amplifier is shown in Fig. 7.1(a) and associated small signal equivalent circuit using voltage-source model of FET is shown in Fig. 7.1(b)

Voltage Gain

Source resistance (R_S) is used to set the Q-Point but is bypassed by C_S for mid-frequency operation. From the small signal equivalent circuit ,the output voltage

$$V_O = -R_D\mu V_{gs}(R_D + r_d)$$

Where $V_{gs} = V_i$, the input voltage,

Hence, the voltage gain,

$$A_V = V_O / V_i = -R_D\mu(R_D + r_d)$$

Input Impedance

From Fig. 7.1(b) Input Impedance is

$Z_i = R_G$

For voltage divider bias as in CE Amplifiers of BJT

$$R_G = R_1 \parallel R_2$$

Output Impedance

Output impedance is the impedance measured at the output terminals with the input voltage $V_I = 0$

From the Fig. 7.1(b) when the input voltage $V_i = 0$, $V_{gs} = 0$ and hence

$$\mu V_{gs} = 0$$

The equivalent circuit for calculating output impedance is given in Fig. 7.2.

Output impedance $Z_o = r_d \parallel R_D$

Normally r_d will be far greater than R_D . Hence $Z_o \approx R_D$

Common Drain Amplifier

A simple common drain amplifier is shown in Fig. 7.2(a) and associated small signal equivalent circuit using the voltage source model of FET is shown in Fig. 7.2(b).Since voltage V_{gd} is more easily determined than V_{gs}, the voltage source in the output circuit is expressed in terms of V_{gs} and Thevenin's theorem.

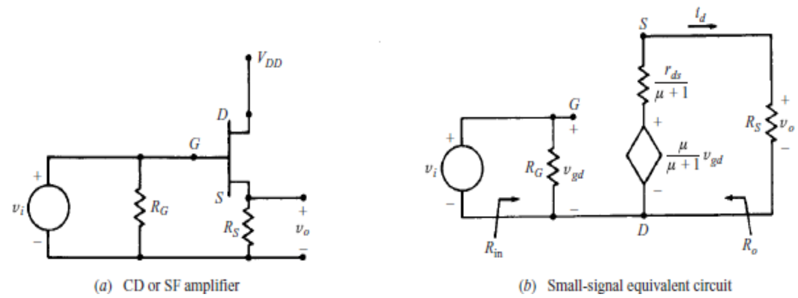


Fig. 7.2 (a)CD Amplifier (b)Small-signal equivalent circuit

Voltage Gain

The output voltage,

$$V_O = R_S\mu V_{gd} / (\mu + 1) R_S + r_d$$

Where $V_{gd} = V_i$ the input voltage.

Hence, the voltage gain,

$$A_v = V_O / V_i = R_S\mu / (\mu + 1) R_S + r_d$$

Input Impedance

Input Impedance $Z_i = R_G$

Output Impedance

From Fig. 7.2(b), Output impedance measured at the output terminals with input voltage $V_i = 0$ can be calculated from the following equivalent circuit.

As $V_i = 0$: $V_{gd} = 0$: $\mu v_{gd} / (\mu + 1) = 0$

Output Impedance

$$Z_O = r_d / (\mu + 1) \parallel R_S \qquad \text{When } \mu \gg 1$$

$$Z_O = (r_d / \mu) \parallel R_S = (1/g_m) \parallel R_S$$

MODULE-III

MULTISTAGE AND POWER AMPLIFIERS

Direct coupled and RC Coupled multi-stage amplifiers; Differential Amplifiers, Power amplifiers- Class A, Class B, Class C

In order to realize the function of amplification, the transformer may appear to be a potential device. However, in a transformer, though there is magnification of input voltage or current, the power required for the load has to be drawn from the source driving the input of the transformer. The output power is always less than the input power due to the losses in the core and windings. The situation in amplification is that the input source is not capable of supplying appreciable power. Hence the functional block meant for amplification should not draw any power from the input source but should deliver finite out power to the load.

Thus the functional block required should have input power

$$P_i = V_i I_i = 0$$

And give the output

$$P_0 = V_0 I_0 = \text{finite}$$

Such a functional block is called an ideal amplifier, which is shown in Fig.1 below.

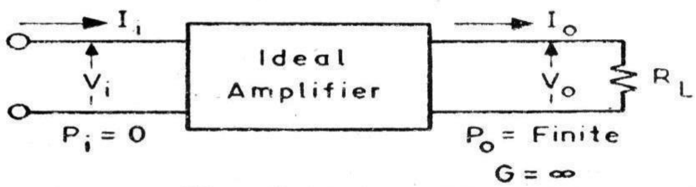


Fig. 1 Ideal amplifier

Power gain is $G = P_0/P_i$

The power gain of an ideal amplifier being infinite may sound like witchcraft in that something can be produced from nothing. The real fact is that the ideal amplifier requires dc input power. It converts dc power to ac power without any demand on the signal source to supply the power for the load.

CLASSIFICATION OF AMPLIFIERS:

Amplifiers are classified in many ways based on different criteria as given below.

I In terms of frequency range:

1. DC amplifiers. (0 Hz to 20 Hz)
2. Audio amplifiers (20 Hz to 20 KHz)
3. Radio frequency amplifiers (Few KHz to hundreds of KHz)
4. Microwave amplifiers (In the range of GHz)
5. Video amplifiers (Hundreds of GHz)

II **In terms of signal strength:**

4. Small signal amplifiers.
5. Large signal mplifiers

III. In terms of coupling:

1. Direct coupling.
2. Resistance – capacitance (RC) coupling.
3. Transformer coupling.

IV. In terms of parameter:

1. Voltage amplifiers.
2. Current amplifiers.
3. Power amplifiers.

V. In terms of biasing condition:

1. Class A amplifier
2. Class B amplifier
3. Class AB amplifier
4. Class C amplifier.

VI. In terms of tuning:

1. Single tuned amplifier
2. Double tuned amplifier
3. Stagger tuned amplifier.

DECIBEL NOTATION:

The power gain of an amplifier is expressed as the ratio of the output power to the input power. When we have more than one stage of amplification i.e. when the output of one stage becomes the input to the next stage, the overall gain has to be obtained by multiplying the gains of the individual stages. When large numbers are involved, this calculation becomes cumbersome. Also, when we have passive coupling networks between amplifier stages, there will be attenuation of the signal that is gain less than unity. To find the overall gain of a typical multistage amplifier such as the one given below.

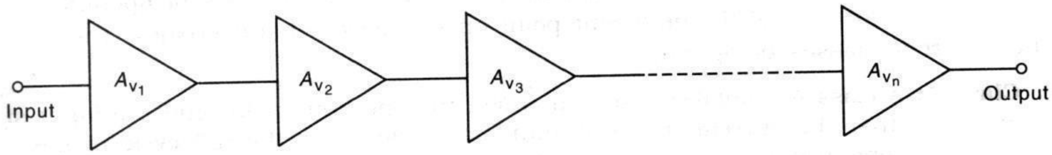


Fig. Cascaded amplifiers

We have to multiply the various gains and attenuations. Moreover, when we wish to plot the gain of an amplifier versus frequency, using large numbers for plotting is not convenient. Hence it has been the practice to use a new unit called the decibel (usually abbreviated as dB) for measuring the power gain of a four terminal network. The power gain in decibels is given by

$$G = 10 \log_{10} P_0 / P_i \text{ dB}$$

This new notation is also significant in the field of acoustics as the response of the human ear to sound intensity is found to be following this logarithmic pattern. The overall gain in decibel notation can be obtained for the amplifier gain of the figure1 by simply adding the decibel gains of the individual networks. If any network attenuates the signal, the gain will be less than the unity and the decibel gain will be negative. Thus the overall gain for the amplifier chain shown above is given by

$$\text{Overall gain} = 10 - 6 + 30 - 10 + 20 = 44 \text{ dB}$$

The absolute power level of the output of an amplifier is sometimes specified in dBm, i.e. decibels with reference to a standard power power level, which is usually, 1 Mw dissipated in a 600 load. Therefore, if an amplifier has 100 Mw, its power level in dBm is equal to 10 log 100/1 = 20 dBm.

MULTISTAGE AMPLIFIERS:

In real time applications, a single amplifier can't provide enough output. Hence, two or more amplifier stages are cascaded (connected one after another) to provide greater output Such an arrangement is known as multistage amplifier Though the basic purpose of this arrangement is increase the overall gain, many new problems as a consequence of this, are to be taken care. For e.g. problems such as the interaction between stages due to impedance mismatch, cumulative hum & noise etc.

DISTORTION IN AMPLIFIERS:

In any amplifier, ideally the output should be a faithful reproduction of the input. This is called fidelity. Of course there could be changes in the amplitude levels. However in practice this never happens. The output waveform tends to be different from the input. This is called as the distortion. The distortion may arise either from the inherent non – linearity in the transistor characteristics or from the influence of the associated circuit.

The distortions are classified as:

1. Non – linear or amplitude distortion
2. Frequency distortion
3. Phase distortion
4. Inter modulation distortion

NON – LINEAR DISTORTION:

This is produced when the operation is over the non-linear part of the transfer characteristics of the transistor. (A plot between output v/s input is called as the transfer characteristics). Since the amplifier amplifies different parts of the input differently. For example, there can be compression of the positive half cycle and expansion of the negative half cycle. Sometimes, the waveform can become clipped also. (Flattening at the tips). Such a deviation from linear amplification produces frequencies in the output, which are not originally present in the output. Harmonics (multiples) of the input signal frequency are present in the output. The percentage harmonic distortion for the n^{th}

Harmonic is given by

$$D_n = \frac{A_n \text{ (amplitude of the n the harmonic)}}{A_1 \text{(amplitude of the fundamental)}} \quad 100\%$$

And the total harmonic distortion by

$$D_T = \sqrt{D_2^2 + D_3^2 + ------ D_n^2}$$

Where D_2, D_3 □ □ □ □ are harmonic components.

A distortion factor meter measures the total distortion. The spectrum or wave analyzer can be used to measure the amplitude of each harmonic.

FREQUENCY DISTORTION:

A practical signal is usually complex (containing many frequencies). Frequency distortion occurs when the different frequency components in the input signal are amplified differently. This is due to the various frequency dependent reactances (capacitive & inductive) present in the circuit or the active devices (BJT or FET).

PHASE DISTRIBUTION:

This occurs due to different frequency components of the input signal suffering different phase shifts. The phase shifts are also due to reactive effects and the active devices. This causes problems in TV picture reception. To avoid this amplifier phase shift should be proportional to the frequency.

INTERMODULATION DISTORTION:

The harmonics introduced in the amplifier can combine with each other or with the original frequencies to produce new frequencies to produce new frequencies that are not harmonics of the fundamental. This is called inter modulation distortion. This distortion results in unpleasant hearing.

FREQUENCY RESPONSE OF AN AMPLIFIER:

Frequency response of an amplifier is a plot between gain & frequency. If the gain is constant (same) for all frequencies of the input signal, then this plot would be a flat line. But this never happens in practice.

As explained earlier, there are different reactive effects present in the amplifier circuit and the active devices used. Infact there are external capacitors used for blocking, capacitors etc. Also, in tuned amplifiers, resonant LC circuits are connected in the collector circuits of the amplifier to get narrow band amplification around the resonant frequencies.

Fig below shows a frequency response of a typical amplifier.

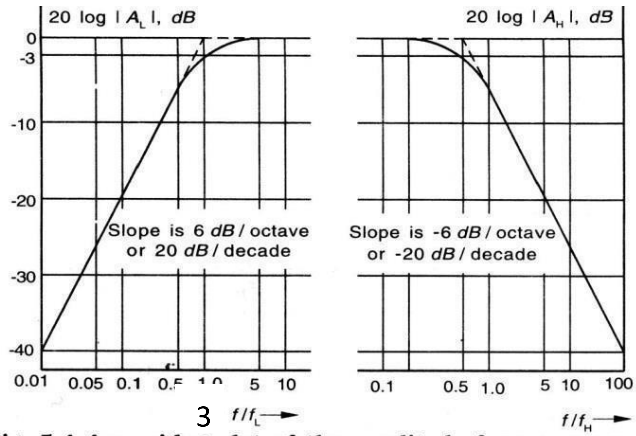


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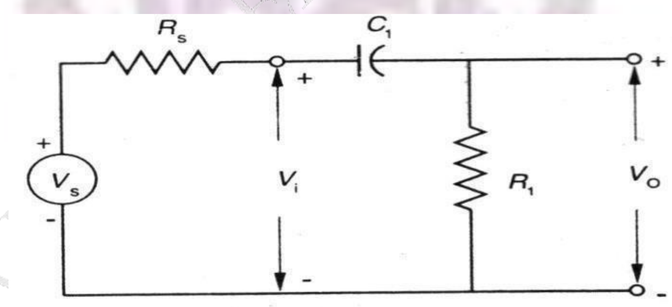
Fig. 5.4 A semi-log plot of the amplitude frequency-response (Bode) characteristic of an *RC* coupled amplifier

Where A_{mid} = mid band voltage gain (in dB)

f_L = Lower cut – off frequency. (in Hz)

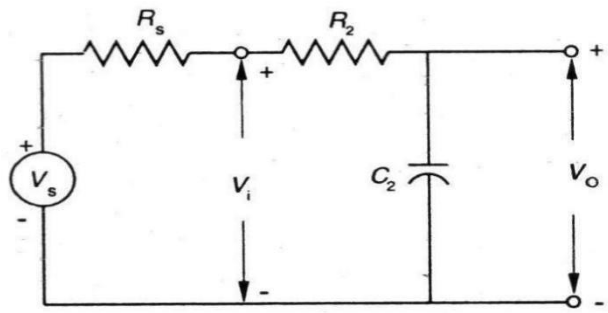
f_H = Upper cut - off frequency (in Hz)

Usually the frequency response of an amplifier is divided into three regions. (i) The mid band region or flat region, over which the gain is constant (ii) The lower frequency region. Here the amplifier behaves like a high pass filter, which is shown below.



(a) High-pass circuit

At high frequencies, the reactance of C_1 will be small & hence it acts as a short without any attenuation (reduction in signal voltage) (iii) In the high frequency region above mid band, the circuit often behaves like the low pass filter as shown below.



(b) Low-pass circuit

As the frequency is increased, the reactance of C_2 decreases. Hence more voltage is dropped across Rs and less is available at the output. Thus the voltage gain of the amplifier decreases at high frequencies.

LOW FREQUENCY RESPONSE:

In the frequency below the mid band, the High pass filter as shown above can approximate the amplifier. This is equal to 3 dB in log scale. For higher frequencies $f >> f_L$, A_L tends to unity. Hence, the magnitude of A_{VL} falls of to 70.7 % of the mid band value at $f = f_{L,}$ Such a frequency is called the lower cut-off or lower 3 dB frequency.

HIGH FREQUENCY RESPONSE:

In the high frequency region, above the mid band , the amplifier stage can be approximated by the low pass circuit.

FREQUENCY RESPONSE PLOTS:

The gain & phase plots versus frequency can be approximately sketched by using straight-line segments called asymptotes. Such plots are called Bode plots. Being in log scale, these plots are very convenient for evaluation of cascaded amplifiers.

BANDWIDTH:

The range of frequencies from f_L to f_H is called the bandwidth of the amplifier. The product of mid band gain and the 3dB Bandwidth of an amplifier is called the Gain-bandwidth product. It is figure of merit or performance measure for the amplifier.

RC COUPLED AMPLIFIER:

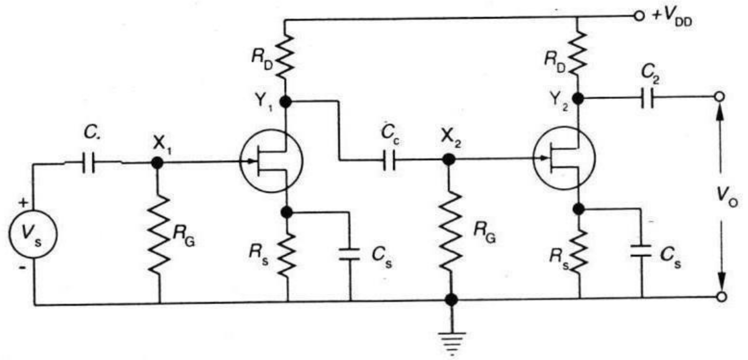


Fig 2 **Two-stage *RC* coupled amplifier with FETs**

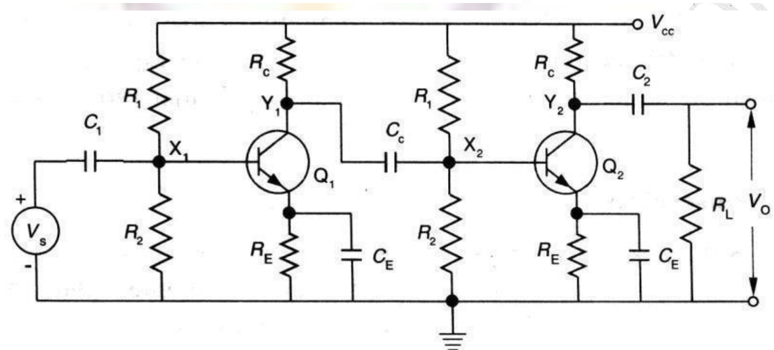


Fig 1 **Two-stage *RC* coupled amplifier with BJTs**

Fig. (1) above shows a two stage RC coupled CE amplifier using BJTs where as fig.(2) shows the FET version. The resistors R_C & R_B (= R_1R_2 / (R_1 + R_2) and capacitors C_C form the coupling network. Because of this, the arrangement is called as RC coupled amplifier. The bypass capacitors C_E (= C_S) are used to prevent loss of amplification due to –ve feedback. The junction capacitance C_j should be taken into account when high frequency operation is considered.

When an ac signal is applied to the input of the I stage, it is amplified by the active device (BJT or FET) and appears across the collector resistor R_C / drain resistor $R_{D.}$ this output signal is connected to the input of the second stage through a coupling capacitor C_C. The second stage doesn't further amplification of the signal. In this way, the cascaded stages give a large output & the overall gain is equal to the product of this individual stage gains.

ANALYSIS OF TWO STAGE RC COUPLED AMPLIFIER:

This analysis is done using h parameter model. Assuming all capacitors are arbitrarily large and act as ac short circuits across $R_{E.}$ The dc power supply is also replaced by a short circuit. Their h parameter approximate models replace the transistors.

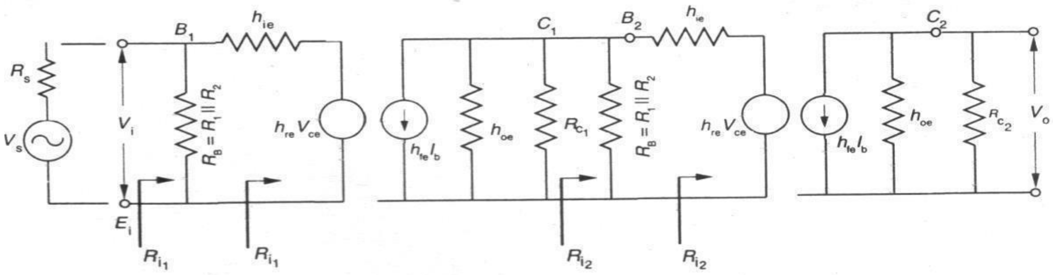


Fig. 5.6 *h*-parameter equivalent circuit for *RC* coupled amplifier

The parallel combination of resistors R_1 and R_2 is replaced by a single stage resistor R_B.

$$R_B = R_1 \| R_2 = R_1R_2 / (R_1 + R_2)$$

For finding the overall gain of the two stage amplifier, we must know the gains of the individual stages.

Current gain (A_{i2}):

$$A_i = - h_{fe} / (1 + h_{oe} R_L)$$

Neglecting h_{oe} as it is very small, $A_i = -h_{fe}$

Input resistance (R_{i2}):

We know that $R_i = h_{ie} + h_{re} A_i R_L$

Hence, $R_i = h_{ie}$ and $R_{i2} = h_{ie}$

Voltage gain (A_{v2}):

We know that $A_v = A_i R_L / R_i$

$$A_{v2} = - h_{fe} R_{C2} / R_{i2}$$

Current gain (A_{i1}):

$$A_{i1} = -h_{fe}$$

Input resistance (R_{i1}):

$$R_{i1} = h_{ie}$$

Voltage gain (Av1):

$$A_V = A_i R_L / R_{i1}$$

Here $R_L = R_{C1} \parallel R_B \parallel R_{i2}$

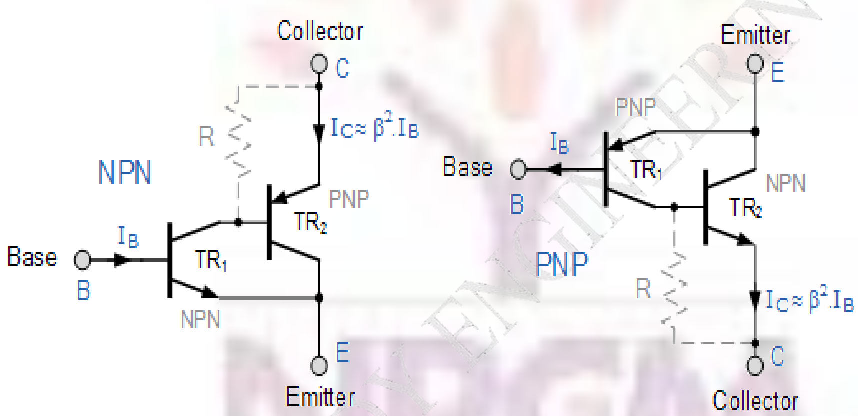
$$A_{V1} = - h_{fe} (R_{C1} \parallel R_B \parallel R_{i2}) / R_{i1}$$

Overall gain (A_v):

$$A_V = A_{V1} \times A_{V2}$$

A **Darlington Transistor** configuration, also known as a "Darlington pair" or "super-alpha circuit", consist of two NPN or PNP transistors connected together so that the emitter current of the first transistor TR_1 becomes the base current of the second transistor TR_2. Then transistor TR1 is connected as an emitter follower and TR2 as a common emitter amplifier as shown below. Also note that in this Darlington pair configuration, the collector current of the slave or control transistor, TR1 is "in-phase" with that of the master switching transistor TR2.

Basic Darlington Transistor Configuration



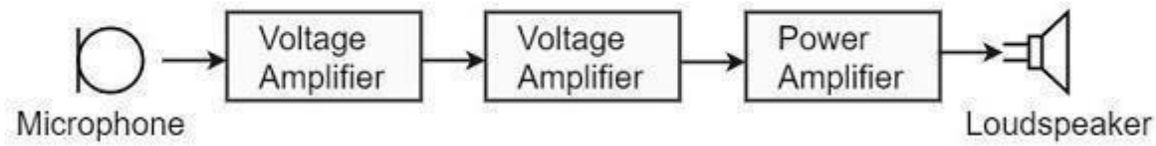
Using the NPN Darlington pair as the example, the collectors of two transistors are connected together, and the emitter of TR_1 drives the base of TR_2. This configuration achieves β multiplication because for a Base current i_b, the collector current is $\beta * i_b$ where the current gain is greater than one, or unity and this is defined as:

But the base current, I_{B2} is equal to transistor TR1 emitter current, I_{E1} as the emitter of TR1 is connected to the base of TR2.

This means that the overall current gain, β is given by the gain of the first transistor multiplied by the gain of the second transistor as the current gains of the two transistors multiply. In other words, a pair of bipolar transistors combined together to make a single Darlington transistor pair can be regarded as a single transistor with a very high value of β and consequently a high input resistance.

POWER AMPLIFIERS

After the audio signal is converted into electrical signal, it has several voltage amplifications done, after which the power amplification of the amplified signal is done just before the loud speaker stage. This is clearly shown in the below figure.



While the voltage amplifier raises the voltage level of the signal, the power amplifier raises the power level of the signal. Besides raising the power level, it can also be said that a power amplifier is a device which converts DC power to AC power and whose action is controlled by the input signal.

The DC power is distributed according to the relation,

DC power input = AC power output + losses

PowerTransistor

For such Power amplification, a normal transistor would not do. A transistor that is manufactured to suit the purpose of power amplification is called as a **Power transistor**.

A Power transistor differs from the other transistors, in the following factors.

- It is larger in size, in order to handle large powers.
- The collector region of the transistor is made large and a heat sink is placed at the collector-base junction in order to minimize heat generated.
- The emitter and base regions of a power transistor are heavily doped.
- Due to the low input resistance, it requires low input power.

Hence there is a lot of difference in voltage amplification and power amplification. So, let us now try to get into the details to understand the differences between a voltage amplifier and a power amplifier.

Differencebetween VoltageandPowerAmplifiers

Let us try to differentiate between voltage and power amplifier.

Voltage Amplifier

The function of a voltage amplifier is to raise the voltage level of the signal. A voltage amplifier is designed to achieve maximum voltage amplification.

The voltage gain of an amplifier is given by

$$Av=\beta(RcRin)Av=\beta(RcRin)$$

The characteristics of a voltage amplifier are as follows −

- The base of the transistor should be thin and hence the value of β should be greater than 100.
- The resistance of the input resistor R_{in} should be low when compared to collector load R_C.
- The collector load R_C should be relatively high. To permit high collector load, the voltage amplifiers are always operated at low collector current.
- The voltage amplifiers are used for small signal voltages.

Power Amplifier

The function of a power amplifier is to raise the power level of input signal. It is required to deliver a large amount of power and has to handle large current.

The characteristics of a power amplifier are as follows −

- The base of transistor is made thicken to handle large currents. The value of β being (β > 100) high.
- The size of the transistor is made larger, in order to dissipate more heat, which is produced during transistor operation.
- Transformer coupling is used for impedance matching.
- Collector resistance is made low.

The Power amplifiers amplify the power level of the signal. This amplification is done in the last stage in audio applications. The applications related to radio frequencies employ radio power amplifiers. But the **operating point** of a transistor, plays a very important role in determining the efficiency of the amplifier. The **main classification** is done based on this mode of operation.

The classification is done based on their frequencies and also based on their mode of operation.

ClassificationBasedonFrequencies:

Power amplifiers are divided into two categories, based on the frequencies they handle. They are as follows.

- **Audio Power Amplifiers** − The audio power amplifiers raise the power level of signals that have audio frequency range (20 Hz to 20 KHz). They are also known as **Small signal power amplifiers**.
- **Radio Power Amplifiers** − Radio Power Amplifiers or tuned power amplifiers raise the power level of signals that have radio frequency range (3 KHz to 300 GHz). They are also known as **large signal power amplifiers**.

ClassificationBasedonModeofOperation

On the basis of the mode of operation, i.e., the portion of the input cycle during which collector current flows, the power amplifiers may be classified as follows.

- **Class A Power amplifier** − When the collector current flows at all times during the full cycle of signal, the power amplifier is known as **class A power amplifier**.
- **Class B Power amplifier** − When the collector current flows only during the positive half cycle of the input signal, the power amplifier is known as **class B power amplifier**.
- **Class C Power amplifier** − When the collector current flows for less than half cycle of the input signal, the power amplifier is known as **class C power amplifier**.

There forms another amplifier called Class AB amplifier, if we combine the class A and class B amplifiers so as to utilize the advantages of both.

Before going into the details of these amplifiers, let us have a look at the important terms that have to be considered to determine the efficiency of an amplifier.

TermsConsideringPerformance

The primary objective of a power amplifier is to obtain maximum output power. In order to achieve this, the important factors to be considered are collector efficiency, power dissipation capability and distortion. Let us go through them in detail.

Collector Efficiency

This explains how well an amplifier converts DC power to AC power. When the DC supply is given by the battery but no AC signal input is given, the collector output at such a condition is observed as **collector efficiency**.

The collector efficiency is defined as

η=averagea.cpoweroutputaveraged.cpowerinputtotransistorη=averagea.cpoweroutputaveraged.cpowerinputtotransistor

For example, if the battery supplies 15W and AC output power is 3W. Then the transistor efficiency will be 20%.

The main aim of a power amplifier is to obtain maximum collector efficiency. Hence the higher the value of collector efficiency, the efficient the amplifier will be.

Power Dissipation Capacity

Every transistor gets heated up during its operation. As a power transistor handles large currents, it gets more heated up. This heat increases the temperature of the transistor, which alters the operating point of the transistor.

So, in order to maintain the operating point stability, the temperature of the transistor has to be kept in permissible limits. For this, the heat produced has to be dissipated. Such a capacity is called as Power dissipation capability.

Power dissipation capability can be defined as the ability of a power transistor to dissipate the heat developed in it. Metal cases called heat sinks are used in order to dissipate the heat produced in power transistors.

Distortion

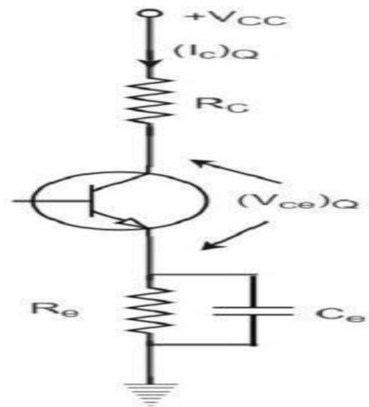
A transistor is a non-linear device. When compared with the input, there occur few variations in the output. In voltage amplifiers, this problem is not pre-dominant as small currents are used. But in power amplifiers, as large currents are in use, the problem of distortion certainly arises.

Distortion is defined as the change of output wave shape from the input wave shape of the amplifier. An amplifier that has lesser distortion, produces a better output and hence considered efficient.

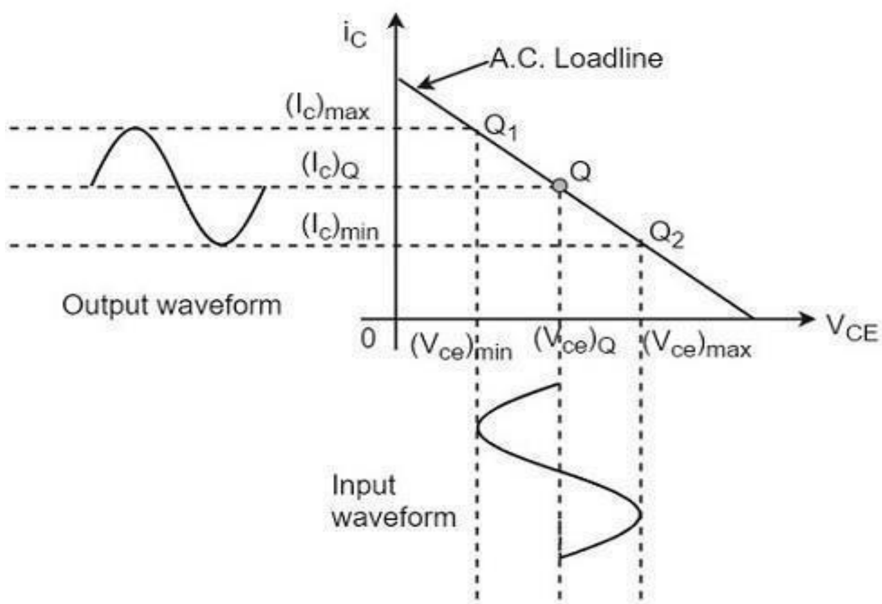
CLASS A POWER AMPLIFIER:

We have already come across the details of transistor biasing, which is very important for the operation of a transistor as an amplifier. Hence to achieve faithful amplification, the biasing of the transistor has to be done such that the amplifier operates over the linear region.

A Class A power amplifier is one in which the output current flows for the entire cycle of the AC input supply. Hence the complete signal present at the input is amplified at the output. The following figure shows the circuit diagram for Class A Power amplifier.



From the above figure, it can be observed that the transformer is present at the collector as a load. The use of transformer permits the impedance matching, resulting in the transference of maximum power to the load e.g. loud speaker.The operating point of this amplifier is present in the linear region. It is so selected that the current flows for the entire ac input cycle. The below figure explains the selection of operating point.



The output characteristics with operating point Q is shown in the figure above. Here $(I_c)_Q$ and $(V_{ce})_Q$ represent no signal collector current and voltage between collector and emitter respectively. When signal is applied, the Q-point shifts to Q_1 and Q_2. The output current increases to $(I_c)_{max}$ and decreases to $(I_c)_{min}$. Similarly, the collector-emitter voltage increases to $(V_{ce})_{max}$ and decreases to $(V_{ce})_{min}$.

Power drawn from collector battery V_{cc} is given by

Pin=voltage×current=VCC(IC)QPin=voltage×current=VCC(IC)Q

This power is used in the following two parts −

- Power dissipated in the collector load as heat is given by

  PRC=(current)2×resistance=(IC)2QRCPRC=(current)2×resistance=(IC)Q2RC

- Power given to transistor is given by

Ptr=Pin−PRC=VCC−(IC)2QRCPtr=Pin−PRC=VCC−(IC)Q2RC

When signal is applied, the power given to transistor is used in the following two parts −

- A.C. Power developed across load resistors RC which constitutes the a.c. power output.

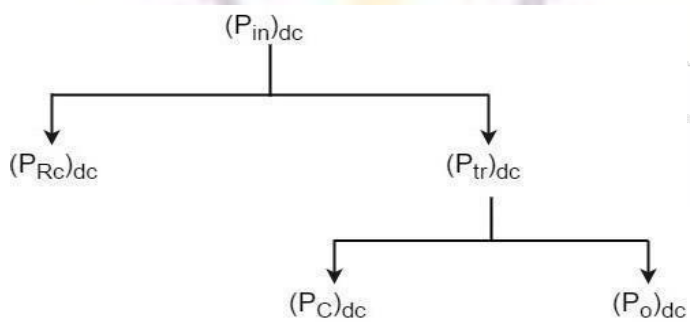
(PO)ac=I2RC=V2RC=(Vm2–

√)21RC=V2m2RC(PO)ac=I2RC=V2RC=(Vm2)21RC=Vm22RC

Where **I** is the R.M.S. value of a.c. output current through load, **V** is the R.M.S. value of a.c. voltage, and **V_m** is the maximum value of V.

- The D.C. power dissipated by the transistor (collector region) in the form of heat, i.e., $(P_C)_{dc}$

We have represented the whole power flow in the following diagram.



This class A power amplifier can amplify small signals with least distortion and the output will be an exact replica of the input with increased strength.

Let us now try to draw some expressions to represent efficiencies.

Overall Efficiency

The overall efficiency of the amplifier circuit is given by

(η)overall=a.cpowerdeliveredtotheloadtotalpowerdeliveredbyd.csupply(η)overall=a.cpowerdelivered totheloadtotalpowerdeliveredbyd.csupply

=(PO)ac(Pin)dc=(PO)ac(Pin)dc

Collector Efficiency

The collector efficiency of the transistor is defined as

(η)collector=averagea.cpoweroutputaveraged.cpowerinputtotransistor(η)collector=averagea.cpowero utputaveraged.cpowerinputtotransistor

=(PO)ac(Ptr)dc=(PO)ac(Ptr)dc

Expression for overall efficiency

(PO)ac=Vrms×Irms(PO)ac=Vrms×Irms

=12–√[(Vce)max−(Vce)min2]×12–

√[(IC)max−(IC)min2]=12[(Vce)max−(Vce)min2]×12[(IC)max−(IC)min2]

=[(Vce)max−(Vce)min]×[(IC)max−(IC)min]8=[(Vce)max−(Vce)min]×[(IC)max−(IC)min]8

Therefore

$$(\eta)overall=[(Vce)max-(Vce)min]\times[(IC)max-(IC)min]8\times VCC(IC)Q(\eta)overall=[(Vce)max-(Vce)min]\times[(IC)max-(IC)min]8\times VCC(IC)Q$$

Advantages of Class A Amplifiers

The advantages of Class A power amplifier are as follows −

- The current flows for complete input cycle
- It can amplify small signals
- The output is same as input
- No distortion is present

Disadvantages of Class A Amplifiers

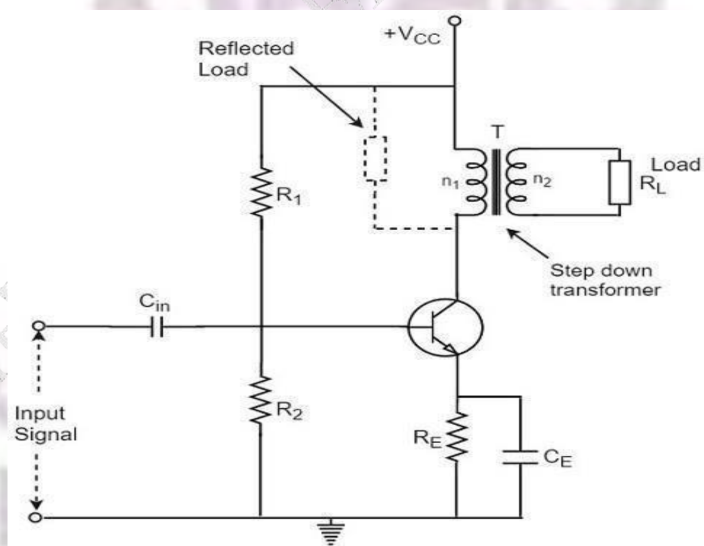
The advantages of Class A power amplifier are as follows −

- Low power output
- Low collector efficiency

TRANSFORMER COUPLED CLASS-A POWER AMPLIFIER

The class A power amplifier as discussed in the previous chapter, is the circuit in which the output current flows for the entire cycle of the AC input supply. We also have learnt about the disadvantages it has such as low output power and efficiency. In order to minimize those effects, the transformer coupled class A power amplifier has been introduced.

The **construction of class A power amplifier** can be understood with the help of below figure. This is similar to the normal amplifier circuit but connected with a transformer in the collector load.

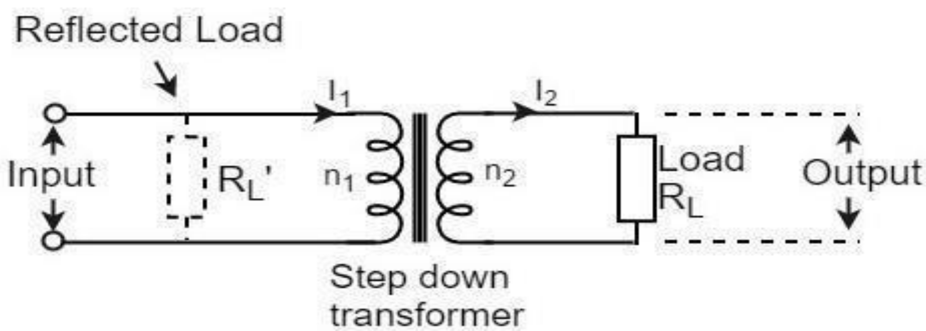


Here R_1 and R_2 provide potential divider arrangement. The resistor Re provides stabilization, C_e is the bypass capacitor and R_e to prevent a.c. voltage. The transformer used here is a step-down transformer. The high impedance primary of the transformer is connected to the high impedance collector circuit. The low impedance secondary is connected to the load (generally loud speaker).

Transformer Action

The transformer used in the collector circuit is for impedance matching. R_L is the load connected in the secondary of a transformer. R_L’ is the reflected load in the primary of the transformer.

The number of turns in the primary are n_1 and the secondary are n_2. Let $V_1$and V_2 be the primary and secondary voltages and I_1 and I_2 be the primary and secondary currents respectively. The below figure shows the transformer clearly.



We know that

V1V2=n1n2andI1I2=n1n2V1V2=n1n2andI1I2=n1n2

Or

V1=n1n2V2andI1=n1n2I2V1=n1n2V2andI1=n1n2I2

Hence

V1I1=(n1n2)2V2I2V1I1=(n1n2)2V2I2

But $V_1/I_1 = R_L$’ = effective input resistance

And $V_2/I_2 = R_L$ = effective output resistance

Therefore,

R′L=(n1n2)2RL=n2RLRL′=(n1n2)2RL=n2RL

Where

n=numberofturnsinprimarynumberofturnsinsecondary=n1n2n=numberofturnsinprimarynumberofturnsinsecondary=n1n2

A power amplifier may be matched by taking proper turn ratio in step down transformer.

Circuit Operation

If the peak value of the collector current due to signal is equal to zero signal collector current, then the maximum a.c. power output is obtained. So, in order to achieve complete amplification, the operating point should lie at the center of the load line.

The operating point obviously varies when the signal is applied. The collector voltage varies in opposite phase to the collector current. The variation of collector voltage appears across the primary of the transformer.

Circuit Analysis

The power loss in the primary is assumed to be negligible, as its resistance is very small.

The input power under dc condition will be

(Pin)dc=(Ptr)dc=VCC×(IC)Q(Pin)dc=(Ptr)dc=VCC×(IC)Q

Under maximum capacity of class A amplifier, voltage swings from $(V_{ce})_{max}$ to zero and current from $(I_c)_{max}$ to zero.

Hence

Vrms=12–√[(Vce)max−(Vce)min2]=12–√[(Vce)max2]=2VCC22–√=VCC2–√Vrms=12[(Vce)max−(Vce)min2]=12[(Vce)max2]=2VCC22=VCC2

Irms=12–√[(IC)max−(IC)min2]=12–√[(IC)max2]=2(IC)Q22–√=(IC)Q2–√Irms=12[(IC)max−(IC)min2]=12[(IC)max2]=2(IC)Q22=(IC)Q2

Therefore,

(PO)ac=Vrms×Irms=VCC2–√×(IC)Q2–√=VCC×(IC)Q2(PO)ac=Vrms×Irms=VCC2×(IC)Q2=VCC×(IC)Q2

Therefore,

Collector Efficiency = (PO)ac(Ptr)dc(PO)ac(Ptr)dc

Or,

(η)collector=VCC×(IC)Q2×VCC×(IC)Q=12(η)collector=VCC×(IC)Q2×VCC×(IC)Q=12

=12×100=50%=12×100=50%

The efficiency of a class A power amplifier is nearly than 30% whereas it has got improved to 50% by using the transformer coupled class A power amplifier.

Advantages

The advantages of transformer coupled class A power amplifier are as follows.

- No loss of signal power in the base or collector resistors.
- Excellent impedance matching is achieved.
- Gain is high.
- DC isolation is provided.

Disadvantages

The disadvantages of transformer coupled class A power amplifier are as follows.

- Low frequency signals are less amplified comparatively.
- Hum noise is introduced by transformers.
- Transformers are bulky and costly.
- Poor frequency response.

Applications

The applications of transformer coupled class A power amplifier are as follows.

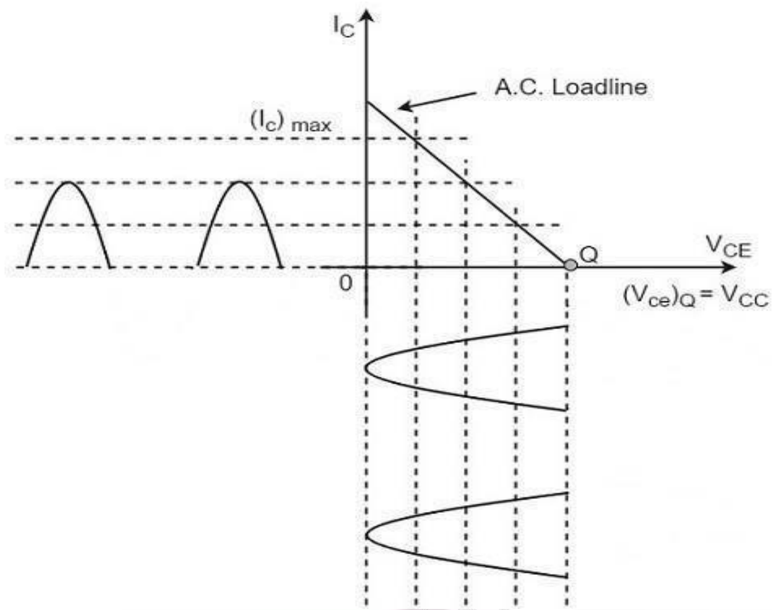
- This circuit is where impedance matching is the main criterion.
- These are used as driver amplifiers and sometimes as output amplifiers.

CLASS –B POWER AMPLIFIER:

Class B Operation

The biasing of the transistor in class B operation is in such a way that at zero signal condition, there will be no collector current. The **operating point** is selected to be at collector cut off voltage. So, when the signal is applied, **only the positive half cycle** is amplified at the output.

The figure below shows the input and output waveforms during class B operation.



When the signal is applied, the circuit is forward biased for the positive half cycle of the input and hence the collector current flows. But during the negative half cycle of the input, the circuit is reverse biased and the collector current will be absent. Hence **only the positive half cycle** is amplified at the output.

As the negative half cycle is completely absent, the signal distortion will be high. Also, when the applied signal increases, the power dissipation will be more. But when compared to class A power amplifier, the output efficiency is increased.

Well, in order to minimize the disadvantages and achieve low distortion, high efficiency and high output power, the push-pull configuration is used in this class B amplifier.

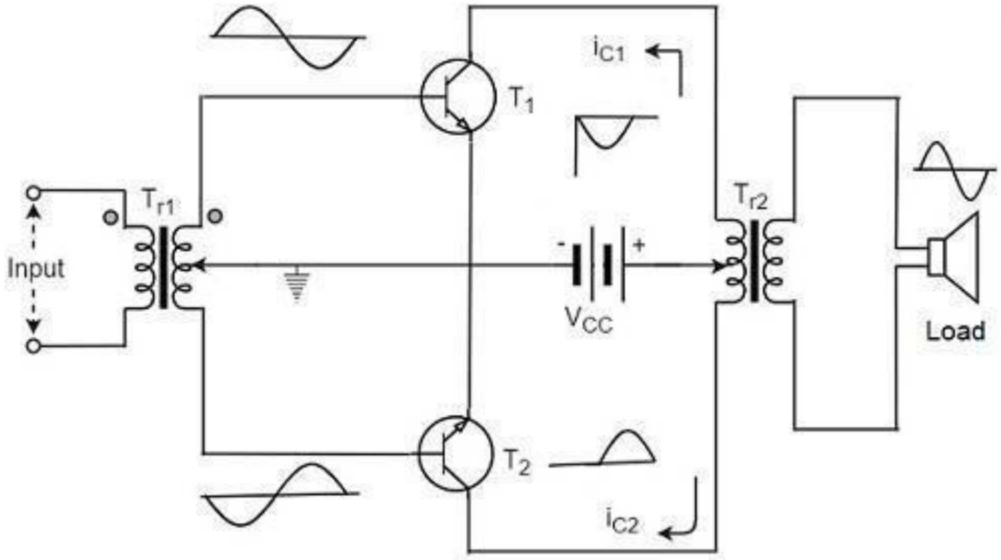
ClassBPush-PullAmplifier

Though the efficiency of class B power amplifier is higher than class A, as only one half cycle of the input is used, the distortion is high. Also, the input power is not completely utilized. In order to compensate these problems, the push-pull configuration is introduced in class B amplifier.

Construction

The circuit of a push-pull class B power amplifier consists of two identical transistors T_1 and T_2 whose bases are connected to the secondary of the center-tapped input transformer T_{r1}. The emitters are shorted and the collectors are given the V_{CC} supply through the primary of the output transformer T_{r2}.

The circuit arrangement of class B push-pull amplifier, is same as that of class A push-pull amplifier except that the transistors are biased at cut off, instead of using the biasing resistors. The figure below gives the detailing of the construction of a push-pull class B power amplifier.

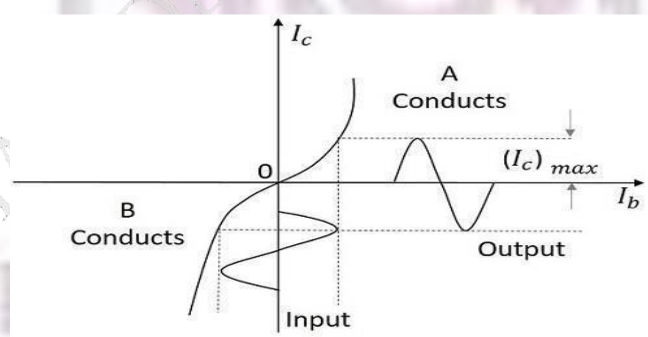


The circuit operation of class B push pull amplifier is detailed below.

Operation

The circuit of class B push-pull amplifier shown in the above figure clears that both the transformers are center-tapped. When no signal is applied at the input, the transistors T_1 and T_2 are in cut off condition and hence no collector currents flow. As no current is drawn from V_{CC}, no power is wasted.

When input signal is given, it is applied to the input transformer T_{r1} which splits the signal into two signals that are 180° out of phase with each other. These two signals are given to the two identical transistors T_1 and T_2. For the positive half cycle, the base of the transistor T_1 becomes positive and collector current flows. At the same time, the transistor T_2 has negative half cycle, which throws the transistor T_2 into cutoff condition and hence no collector current flows. The waveform is produced as shown in the following figure.



For the next half cycle, the transistor T_1 gets into cut off condition and the transistor T_2 gets into conduction, to contribute the output. Hence for both the cycles, each transistor conducts alternately. The output transformer T_{r3} serves to join the two currents producing an almost undistorted output waveform.

PowerEfficiencyofClassB Push-PullAmplifier

The current in each transistor is the average value of half sine loop.

For half sine loop, I_{dc} is given by

Therefore,Idc=(IC)maxπIdc=(IC)maxπ

(pin)dc=2×[(IC)maxπ×VCC](pin)dc=2×[(IC)maxπ×VCC]

Here factor 2 is introduced as there are two transistors in push-pull amplifier.

R.M.S. value of collector current = (IC)max/2–√(IC)max/2
R.M.S. value of output voltage = VCC/2–√VCC/2
Under ideal conditions of maximum power

Therefore,

(PO)ac=(IC)max2–√×VCC2–√=(IC)max×VCC2(PO)ac=(IC)max2×VCC2=(IC)max×VCC2
Now overall maximum efficiency

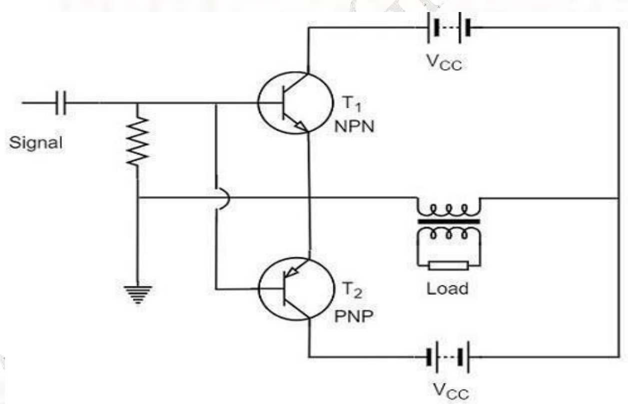
ηoverall=(PO)ac(Pin)dcηoverall=(PO)ac(Pin)dc
=(IC)max×VCC2×π2(IC)max×VCC=(IC)max×VCC2×π2(IC)max×VCC
=π4=0.785=78.5%=π4=0.785=78.5%

The collector efficiency would be the same.

Hence the class B push-pull amplifier improves the efficiency than the class A push-pull amplifier.

ComplementarySymmetry Push-PullClassBAmplifier

The push pull amplifier which was just discussed improves efficiency but the usage of center-tapped transformers makes the circuit bulky, heavy and costly. To make the circuit simple and to improve the efficiency, the transistors used can be complemented, as shown in the following circuit diagram.



The above circuit employs a NPN transistor and a PNP transistor connected in push pull configuration. When the input signal is applied, during the positive half cycle of the input signal, the NPN transistor conducts and the PNP transistor cuts off. During the negative half cycle, the NPN transistor cuts off and the PNP transistor conducts. In this way, the NPN transistor amplifies during positive half cycle of the input, while PNP transistor amplifies during negative half cycle of the input. As the transistors are both complement to each other, yet act symmetrically while being connected in push pull configuration of class B, this circuit is termed as **Complementary symmetry push pull class B amplifier**.

Advantages

The advantages of Complementary symmetry push pull class B amplifier are as follows.

- As there is no need of center tapped transformers, the weight and cost are reduced.

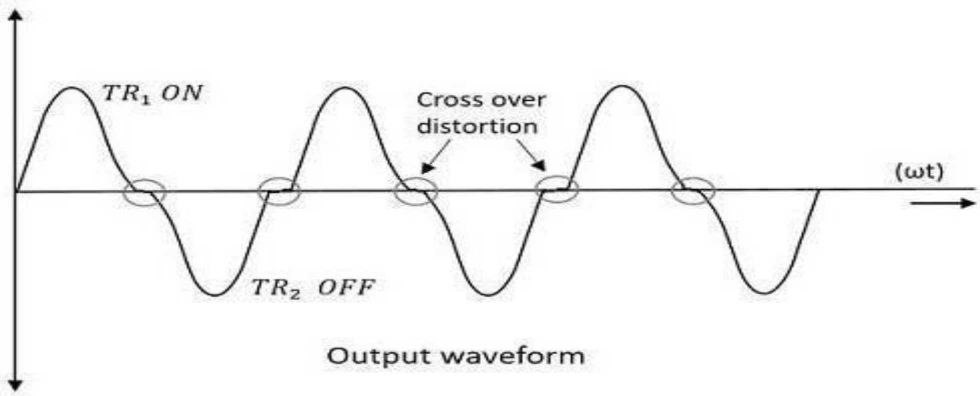
Equal and opposite input signal voltages are not required.Disadvantages

The disadvantages of Complementary symmetry push pull class B amplifier are as follows.

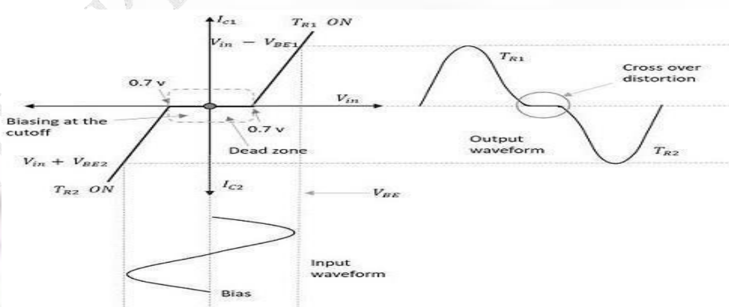
- It is difficult to get a pair of transistors (NPN and PNP) that have similar characteristics.
- We require both positive and negative supply voltages.

Cross-overDistortion

In the push-pull configuration, the two identical transistors get into conduction, one after the other and the output produced will be the combination of both. When the signal changes or crosses over from one transistor to the other at the zero voltage point, it produces an amount of distortion to the output wave shape. For a transistor in order to conduct, the base emitter junction should cross 0.7v, the cut off voltage. The time taken for a transistor to get ON from OFF or to get OFF from ON state is called the **transition period**. At the zero voltage point, the transition period of switching over the transistors from one to the other, has its effect which leads to the instances where both the transistors are OFF at a time. Such instances can be called as **Flat spot** or **Dead band** on the output wave shape.



The above figure clearly shows the cross over distortion which is prominent in the output waveform. This is the main disadvantage. This cross over distortion effect also reduces the overall peak to peak value of the output waveform which in turn reduces the maximum power output. This can be more clearly understood through the non-linear characteristic of the waveform as shown below.



It is understood that this cross-over distortion is less pronounced for large input signals, where as it causes severe disturbance for small input signals. This cross over distortion can be eliminated if the conduction of the amplifier is more than one half cycle, so that both the transistors won't be OFF at the same time. This idea leads to the invention of class AB amplifier, which is the combination of both class A and class B amplifiers, as discussed below.

ClassAB PowerAmplifier

As the name implies, class AB is a combination of class A and class B type of amplifiers. As class A has the problem of low efficiency and class B has distortion problem, this class AB is emerged to eliminate these two problems, by utilizing the advantages of both the classes.

The cross over distortion is the problem that occurs when both the transistors are OFF at the same instant, during the transition period. In order to eliminate this, the condition has to be chosen for more than one half cycle. Hence, the other transistor gets into conduction, before the operating transistor switches to cut off state. This is achieved only by using class AB configuration, as shown in the following circuit diagram.

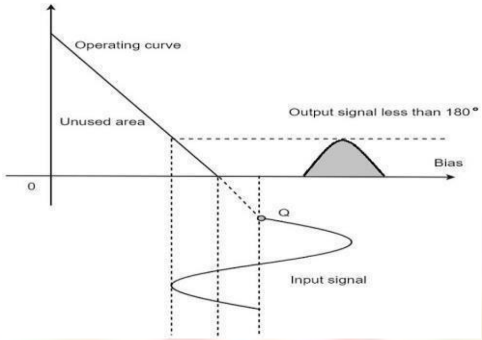
Therefore, in class AB amplifier design, each of the push-pull transistors is conducting for slightly more than the half cycle of conduction in class B, but much less than the full cycle of conduction of class A. The conduction angle of class AB amplifier is somewhere between 180^o to 360^o depending upon the operating point selected. This is understood with the help of below figure.

The small bias voltage given using diodes D_1 and D_2, as shown in the above figure, helps the operating point to be above the cutoff point. Hence the output waveform of class AB results as seen in the above figure. The crossover distortion created by class B is overcome by this class AB, as well the inefficiencies of class A and B don’t affect the circuit.

So, the class AB is a good compromise between class A and class B in terms of efficiency and linearity having the efficiency reaching about 50% to 60%. The class A, B and AB amplifiers are called as **linear amplifiers** because the output signal amplitude and phase are linearly related to the input signal amplitude and phase.

ClassCPowerAmplifier

When the collector current flows for less than half cycle of the input signal, the power amplifier is known as **class C power amplifier**. The efficiency of class C amplifier is high while linearity is poor. The conduction angle for class C is less than 180°. It is generally around 90°, which means the transistor remains idle for more than half of the input signal. So, the output current will be delivered for less time compared to the application of input signal. The following figure shows the operating point and output of a class C amplifier.



This kind of biasing gives a much improved efficiency of around 80% to the amplifier, but introduces heavy distortion in the output signal. Using the class C amplifier, the pulses produced at its output can be converted to complete sine wave of a particular frequency by using LC circuits in its collector circuit.

MODULE-IV
FEEDBACK AMPLIFIERS AND OSCILLATORS

Feedback Amplifiers : Concepts of feedback– Classification of feedback amplifiers– General characteristics of Negative feedback amplifiers – Effect of Feedback on Amplifier characteristics –Voltage series, Voltage shunt, Current series and Current shunt Feedback configurations – Simple problems.

Oscillators: Condition for Oscillations, RC type Oscillators-RC phase shift and Wien- bridge Oscillators, LC type Oscillators–Generalized analysis of LC Oscillators, Hartley and Colpitts Oscillators.

INTRODUCTION TO FEEDBACK AMPLIFIERS

Feedback is a common phenomenon in nature. It plays an important role in electronics & control systems. Feedback is a process whereby a portion of the output signal of the amplifier is feedback to the input of the amplifier. The feedback signal can be either a voltage or a current, being applied in series or shunt respectively with the input signal.

The path over which the feedback is applied is the feedback loop. There are two types of feedback used in electronic circuits. (i) If the feedback voltage or current is in phase with the input signal and adds to its magnitude, the feedback is called positive or regenerative feedback.(ii) If the feedback voltage or current is opposite in phase to the input signal and opposes it , the feedback is called negative or regenerative feedback.

CLASSIFICATION OF AMPLIFIERS:

Before analyzing the concept of feedback, it is useful to classify amplifiers based on the magnitudes of the input & output impedances of an amplifier relative to the sources & load impedances respectively as (i) voltage (ii) current (iii) Tran conductance (iv) Tran resistance amplifiers.

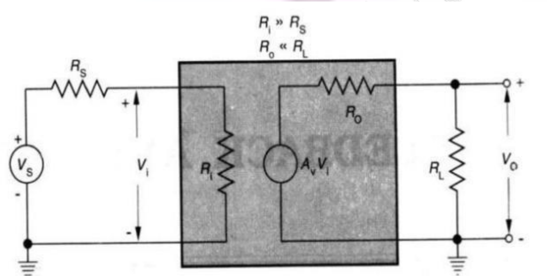


Fig. 4 Thevenin's equivalent circuit of a voltage amplifier

VOLTAGE AMPLIFIER:

The above figure shows a Thevenin's equivalent circuit of an amplifier. If the input resistance of the amplifier Ri is large compared with the source resistance Rs, then Vi = Vs. If the external load RL is large compared with the output resistance R0 of the amplifier, then V0 = AV VS .This type

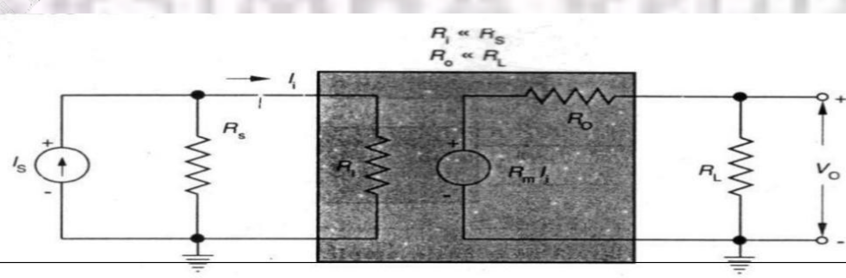


Fig. 7 Equivalent circuit of a transresistance amplifier

of amplifier provides a voltage output proportional to the input voltage & the proportionality factor doesn't depend on the magnitudes of the source and load resistances. Hence, this amplifier is known as voltage amplifier. An ideal voltage amplifier must have infinite resistance Ri and zero output resistance.

CURRENT AMPLIFIER:

Above figure shows a Norton's equivalent circuit of a current amplifier. If the input resistance of the amplifier Ri is very low compared to the source resistance RS, then Ii = IS. If the output resistance of the amplifier R0 is very large compared to external load RL, then IL = AiIi = Ai IS. This amplifier provides an output current proportional to the signal current and the proportionally is dependent of the source and load resistance. Hence, this amplifier is called a current amplifier. An ideal current amplifier must have zero input resistance & infinite output resistance.

TRANSCONDUCTANCE AMPLIFIER:

The above figure shows the equivalent circuit of a transconductance amplifier. In this circuit, the output current I0 is proportional to the signal voltage VS and the proportionality factor is independent of the magnitudes of source and load resistances. An ideal transconductance amplifier must have an infinite resistance Ri & infinite output resistance R0.

TRANSRESISTANCE AMPLIFIER:

Figure above shows the equivalent circuit of a transconductance amplifier. Here, the output voltage V0 is proportional to the signal current IS and the proportionality factor is independent of magnitudes of source and loads resistances. If RS >>Ri , then Ii = IS , Output voltage V0 = RmIS

An ideal transconductance amplifier must have zero input resistance and zero output resistance.

THE FEEDBACK CONCEPT:

In each of the above discussed amplifiers, we can sample the output voltage or current by means of a suitable sampling network & this sampled portion is feedback to the input through a feedback network as shown below.

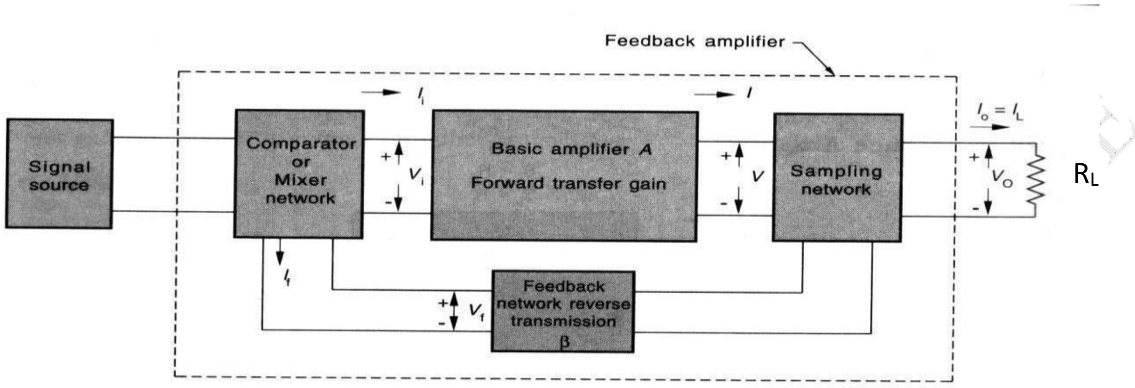


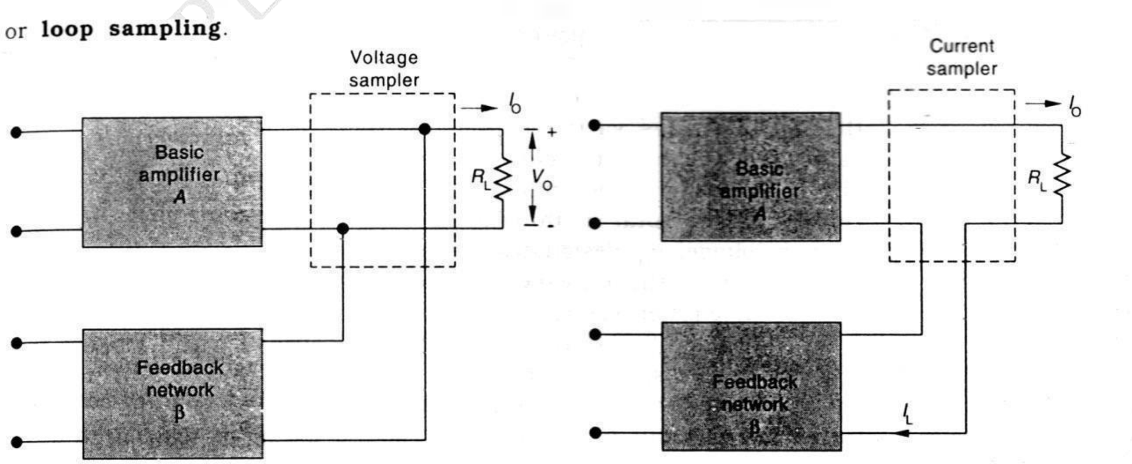
Fig. 1 Block diagram of a basic amplifier with feedback connection

All the input of the amplifier, the feedback signal is combined with the source signal through a unit called mixer. The signal source shown in the above figure can be either a voltage source VS or a current source. The feedback connection has three networks.

1. Sampling network
2. Feedback network
3. Mixer network

SAMPLING NETWORK:

There are two ways to sample the output, depending on the required feedback parameter. The output voltage is sampled by connecting the feedback network in shunt with the output. This is called as voltage sampling.



(a) Voltage or node sampling Fig. 2 (b) Current or loop sampling

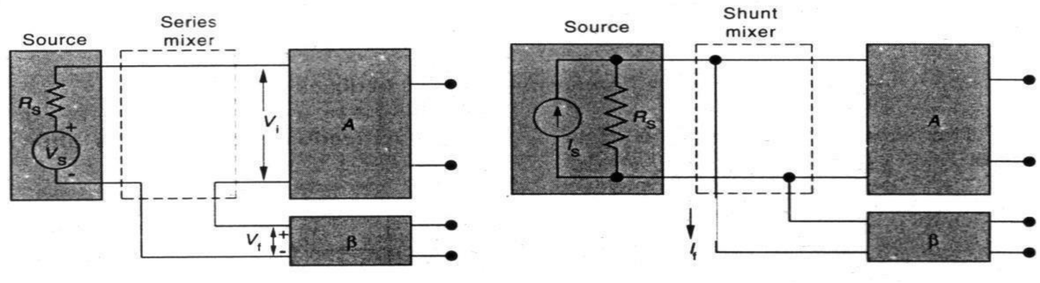
FEEDBACK NETWORK:

This is usually a passive two-port network consisting of resistors, capacitors and inductors. In case of a voltage shunt feedback, it provides a fraction of the output voltage as feedback signal Vf to the input of the mixer.

MIXER:

There are two ways of mixing the feedback signal with the input signal with the input signal as shown in figure . below.

(iii) Mixer Network



(a) Series mixing (b) Shunt mixing

Fig. 3 'eedback connections of the input of a basic amplifier

When the feedback voltage is applied in series with the input voltage through the feedback network as shown in figure 6.7 (a) above, it is called series mixing. Otherwise, when the feedback voltage is applied in parallel to the input of the amplifier as shown in figure (b) above, it is called shunt feedback.

GAIN OR TRANSFER RATIO:

The ratio of the output signal to the input signal of the basic amplifier is represented by the symbol A , with proper suffix representing the different quantities.

TYPES OF FEEDBACK:

Feedback amplifiers can be classified as positive or negative feedback depending on how the feedback signal gets added to the incoming signal. If the feedback signal is of the same sign as the incoming signal, they get added & this is called as positive feedback. On the other hand, if the feedback signal is in phase inverse with the incoming signal, they get subtracted from each other; it will be called as negative feedback amplifier. Positive feedback is employed in oscillators whereas negative feedback is used in amplifiers.

FEATURE OF NEGATIVE FEEDBACK AMPLIFIERS:

- Overall gain is reduced
- Bandwidth is improved
- Distortion is reduced
- Stability is improved
- Noise is reduced

ANALYSIS OF FEEDBACK AMPLIFIER:

The analysis of the feedback amplifier can be carried out by replacing each active element (BJT, FET) by its small signal model and by writing Kirchoff’s loop or nodal equations. Consider the schematic representation of the feedback amplifier as shown below.

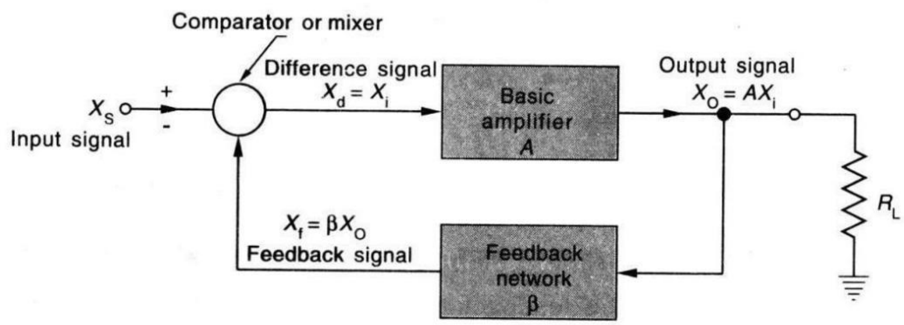
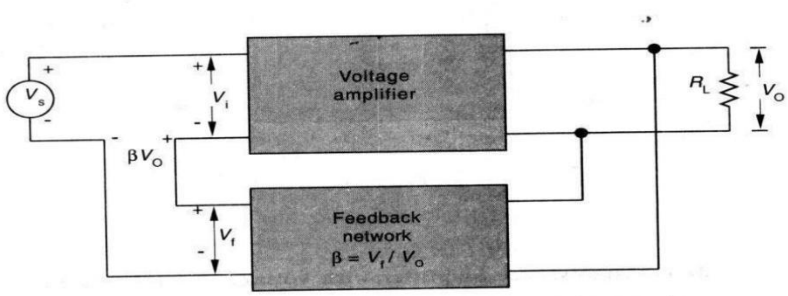
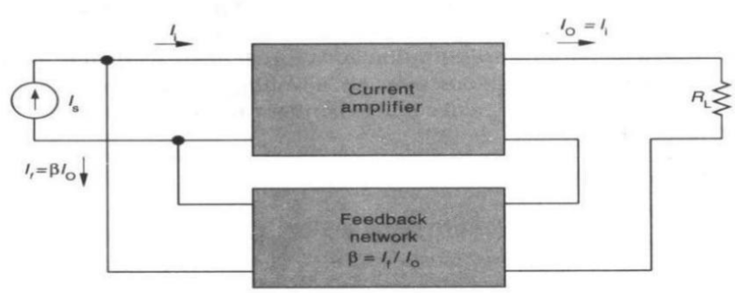


Fig. 4 Schematic representation of a single-loop feedback amplifier

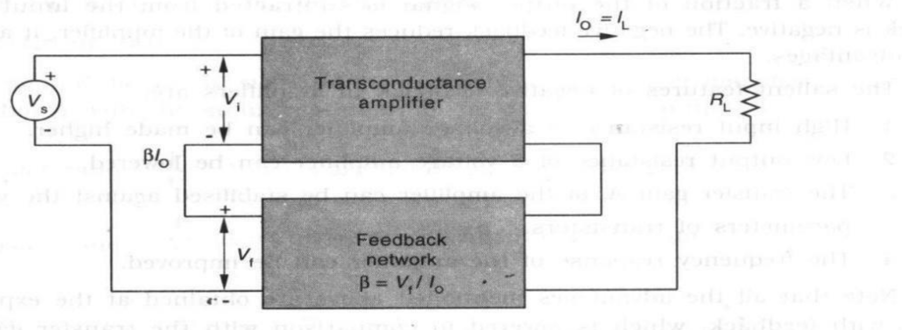


(a) Voltage amplifier with voltage-series feedback

Fig. 5 Types of amplifiers with negative feedback



(c) Current amplifier with current-shunt feedback



(b) Transconductance amplifier with current-series feedback

The four basic types of feedback are:

- Voltage –Series feedback
- Current – Series feedback
- Current – Shunt feedback
- Voltage – Shunt feedback

GAIN WITH FEEDBACK:

Consider the schematic representation of negative feedback amplifier as shown in fig.6.8.The source resistance RS to be part of the amplifier & transfer gain A (AV,Ai ,Gm ,Rm) includes the effect of the loading of the network upon the amplifier.The input signal XS, the output signal X0, the feedback signal Xf and the difference signal Xd , each represents either a voltage or a current and also the ratios A and as summarized below.

The gain, A = X0 / XS (1)

The output of the mixer,

Xd = Xs + (-Xf) = Xi (2)

The feedback ratio , □ = Xf / X0 (3)

The overall gain (including the feedback)

Af = X0 / XS (4)

From equation (2), XS = Xi + Xf Af = X0 / (Xi + Xf)

Dividing both numerator and denominator by Xi and simplifying, we get Af = A / (1 + A) (5)

Equation (5) indicates that the overall gain Af is less the open loop gain. The denominator term (1 + A) in equation (5) is called the loop gain. The forward path consists only of the basic amplifier, whereas the feedback is in the return path.

GAIN STABILITY:

Gain of an amplifier depends on the factors such as temperature, operating point aging etc. It can be shown that the negative feedback tends to stabilize the gain. The ratio of fractional change in amplification with feedback to the fractional change in without feedback is called the sensitivity of the gain

REDUCTION IN FREQUENCY DISTORTION:

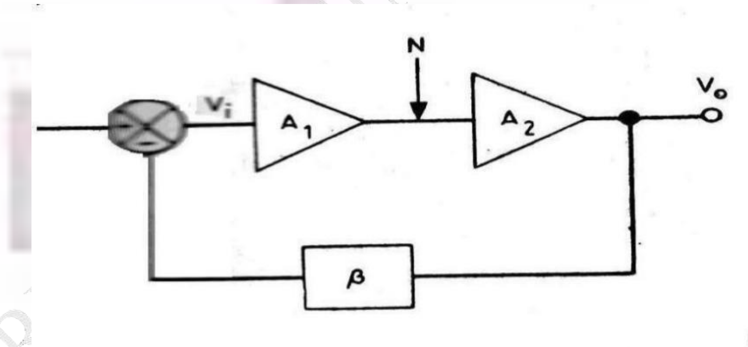
If the feedback network is purely resistive, the overall gain is then not a function of frequency even though the basic amplifier gain is frequency dependent. Under such conditions a substantial reduction in frequency & phase distortion is obtained.

NONLINEAR DISTORTION:

Negative feedback tends to reduce the amount of noise and non-linear distortion. Suppose that a large amplitude signal is applied to an amplifier, so that the operation of the device extends slightly beyond its range of linear operation and as a consequence the output signal is distorted. Negative feedback is now introduced and the input signal is increased by the same amount by which the gain is reduced, so that the output signal amplitude remains the same. Assume that the second harmonic component, in the absence of feedback is B2. Because of feedback, a component B2f actually appears in the output. To find the relationship that exists between B2f& B2, it is noted that the output will contain the term –AβB2f , which arises from the component –βB2f that is feedback to the input. Thus the output contains two terms: B2, generated in the transistor and –AβB2f , which represents the effect of the feedback. Thus, it is seen that, the negative feedback tends to reduce the second harmonic distortion by the factor (1+βA).

NOISE:

Noise or hum components introduced into an amplifier inside the feedback loop are reduced by the feedback loop. Suppose there are two stages of amplifier with gains A1 & A 2 and noise or hum pick-up is introduced after the amplifier with gain A1 as shown in the fig. below



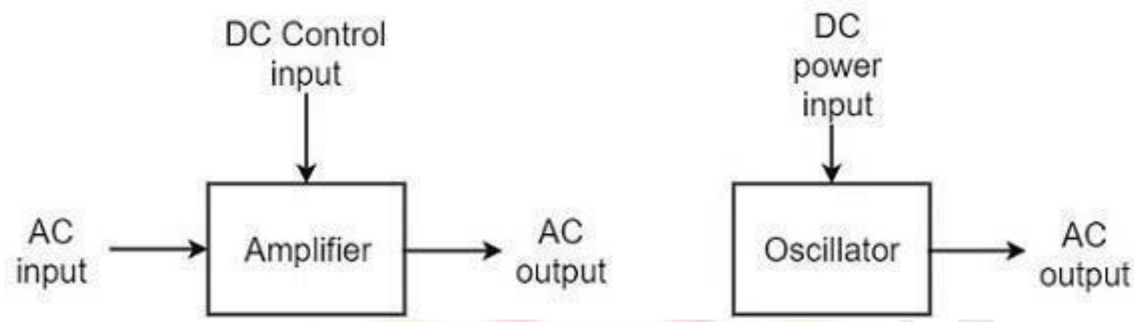
The overall gain of the two stage amplifier is reduced by the factor 1 + A1A2β. In addition the noise output is reduced by the additional factor A1 which is the gain that precedes the introduction of noise. In a single stage amplifier, noise will be reduced by the factor 1/(1 + Aβ) just like distortion. But if signal-to-noise ratio has to improve, we have to increase the signal level at the input by the factor (1 + Aβ) to bring back the signal level to the same value as obtained without feedback. If we can assume that noise does not further increase when we increase the signal input, we can conclude that noise is reduced by the factor 1/(1+Aβ) due to feedback while the signal level is maintained constant.

OSCILLATORS:

An **oscillator** generates output without any ac input signal. An electronic oscillator is a circuit which converts dc energy into ac at a very high frequency. An amplifier with a positive feedback can be understood as an oscillator.

Amplifier vs. Oscillator

An **amplifier** increases the signal strength of the input signal applied, whereas an **oscillator** generates a signal without that input signal, but it requires dc for its operation. This is the main difference between an amplifier and an oscillator. Take a look at the following illustration. It clearly shows how an amplifier takes energy from d.c. power source and converts it into a.c. energy at signal frequency. An oscillator produces an oscillating a.c. signal on its own.



The frequency, waveform, and magnitude of a.c. power generated by an amplifier, is controlled by the a.c. signal voltage applied at the input, whereas those for an oscillator are controlled by the components in the circuit itself, which means no external controlling voltage is required.

Alternator vs. Oscillator

An **alternator** is a mechanical device that produces sinusoidal waves without any input. This a.c. generating machine is used to generate frequencies up to 1000Hz. The output frequency depends on the number of poles and the speed of rotation of the armature.

The following points highlight the differences between an alternator and an oscillator −

- An alternator converts mechanical energy to a.c. energy, whereas the oscillator converts d.c. energy into a.c. energy.
- An oscillator can produce higher frequencies of several MHz whereas an alternator cannot.
- An alternator has rotating parts, whereas an electronic oscillator doesn't.
- It is easy to change the frequency of oscillations in an oscillator than in an alternator.

Oscillators can also be considered as opposite to rectifiers that convert a.c. to d.c. as these convert d.c. to a.c. You can get a detailed description on rectifiers in our Electronic Circuits tutorial.

ClassificationofOscillators

Electronic oscillators are classified mainly into the following two categories −

- **Sinusoidal Oscillators** − The oscillators that produce an output having a sine waveform are called **sinusoidal** or **harmonic oscillators**. Such oscillators can provide output at frequencies ranging from 20 Hz to 1 GHz.

- **Non-sinusoidal Oscillators** − The oscillators that produce an output having a square, rectangular or saw-tooth waveform are called **non-sinusoidal** or **relaxation oscillators**. Such oscillators can provide output at frequencies ranging from 0 Hz to 20 MHz.

- **SinusoidalOscillators**

Sinusoidal oscillators can be classified in the following categories −

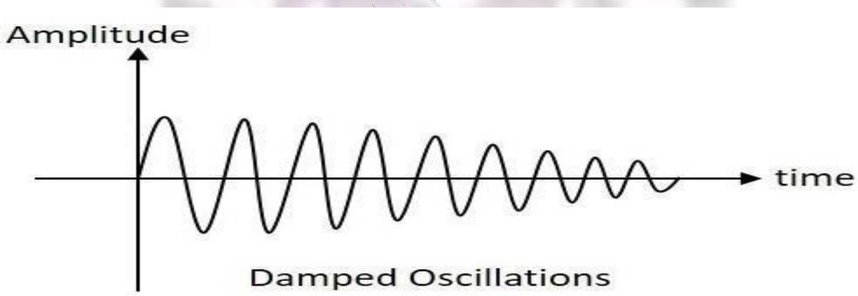
- **Tuned Circuit Oscillators** − These oscillators use a tuned-circuit consisting of inductors (L) and capacitors (C) and are used to generate high-frequency signals. Thus they are also known as radio frequency R.F. oscillators. Such oscillators are Hartley, Colpitts, Clapp-oscillators etc.
- **RC Oscillators** − There oscillators use resistors and capacitors and are used to generate low or audio-frequency signals. Thus they are also known as audio-frequency (A.F.) oscillators. Such oscillators are Phase –shift and Wein-bridge oscillators.
- **Crystal Oscillators** − These oscillators use quartz crystals and are used to generate highly stabilized output signal with frequencies up to 10 MHz. The Piezo oscillator is an example of a crystal oscillator.
- **Negative-resistance Oscillator** − These oscillators use negative-resistance characteristic of the devices such as tunnel devices. A tuned diode oscillator is an example of a negative-resistance oscillator.

NatureofSinusoidalOscillations

The nature of oscillations in a sinusoidal wave are generally of two types. They are damped and undamped oscillations.

Damped Oscillations

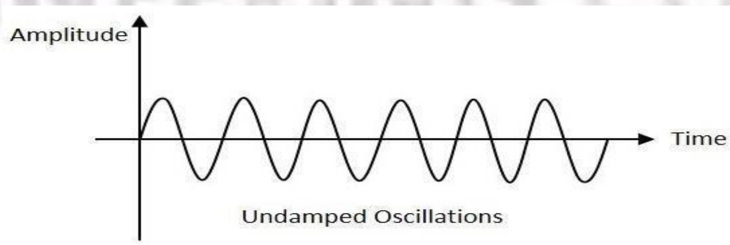
The electrical oscillations whose amplitude goes on decreasing with time are called as **Damped Oscillations**. The frequency of the damped oscillations may remain constant depending upon the circuit parameters.



Damped oscillations are generally produced by the oscillatory circuits that produce power losses and doesn't compensate if required.

Undamped Oscillations

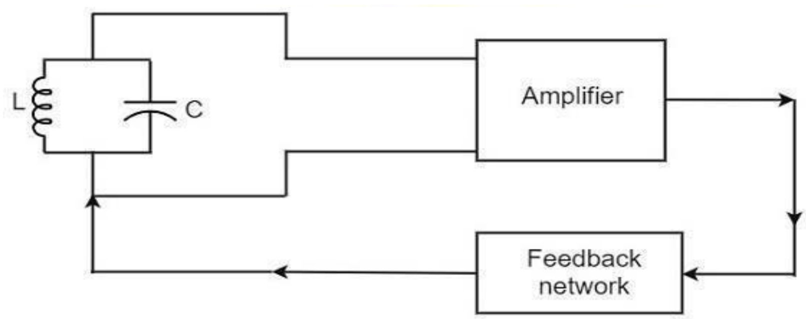
The electrical oscillations whose amplitude remains constant with time are called as **Undamped Oscillations**. The frequency of the Undamped oscillations remains constant.



Undamped oscillations are generally produced by the oscillatory circuits that produce no power losses and follow compensation techniques if any power losses occur. An Oscillator circuit is a complete set of all the parts of circuit which helps to produce the oscillations. These oscillations should sustain and should be Undamped as just discussed before. Let us try to analyze a practical Oscillator circuit to have a better understanding on how an Oscillator circuit works.

PracticalOscillatorCircuit

A Practical Oscillator circuit consists of a tank circuit, a transistor amplifier, and a feedback circuit. The following circuit diagram shows the arrangement of a practical oscillator.



Let us now discuss the parts of this practical oscillator circuit.

- **Tank Circuit** − The tank circuit consists of an inductance L connected in parallel with capacitor **C**. The values of these two components determine the frequency of the oscillator circuit and hence this is called as **Frequency determining circuit**.
- **Transistor Amplifier** − The output of the tank circuit is connected to the amplifier circuit so that the oscillations produced by the tank circuit are amplified here. Hence the output of these oscillations are increased by the amplifier.
- **Feedback Circuit** − The function of feedback circuit is to transfer a part of the output energy to LC circuit in proper phase. This feedback is positive in oscillators while negative in amplifiers.

FrequencyStabilityofan Oscillator

The frequency stability of an oscillator is a measure of its ability to maintain a constant frequency, over a long time interval. When operated over a longer period of time, the oscillator frequency may have a drift from the previously set value either by increasing or by decreasing.

The change in oscillator frequency may arise due to the following factors −

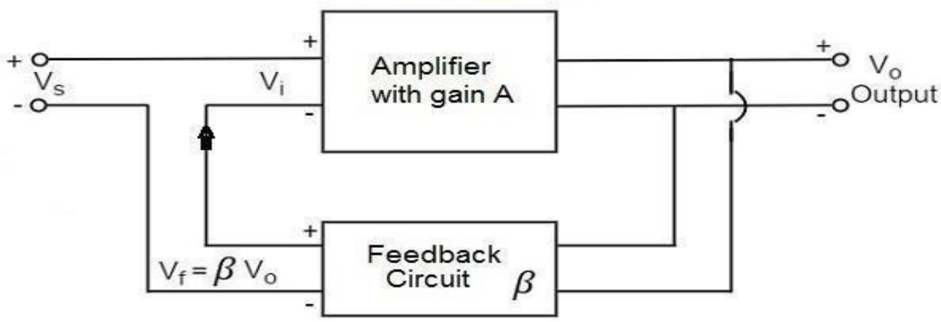
- Operating point of the active device such as BJT or FET used should lie in the linear region of the amplifier. Its deviation will affect the oscillator frequency.
- The temperature dependency of the performance of circuit components affect the oscillator frequency.
- The changes in d.c. supply voltage applied to the active device, shift the oscillator frequency. This can be avoided if a regulated power supply is used.
- A change in output load may cause a change in the Q-factor of the tank circuit, thereby causing a change in oscillator output frequency.
- The presence of inter element capacitances and stray capacitances affect the oscillator output frequency and thus frequency stability.

TheBarkhausen Criterion

With the knowledge we have till now, we understood that a practical oscillator circuit consists of a tank circuit, a transistor amplifier circuit and a feedback circuit. so, let us now try to brush up the concept of feedback amplifiers, to derive the gain of the feedback amplifiers.

Principle of Feedback Amplifier

A feedback amplifier generally consists of two parts. They are the **amplifier** and the **feedback circuit**. The feedback circuit usually consists of resistors. The concept of feedback amplifier can be understood from the following figure below.



From the above figure, the gain of the amplifier is represented as A. The gain of the amplifier is the ratio of output voltage Vo to the input voltage V_i. The feedback network extracts a voltage $V_f = \beta V_o$ from the output V_o of the amplifier.

This voltage is added for positive feedback and subtracted for negative feedback, from the signal voltage V_s.

So, for a positive feedback,

$$V_i = V_s + V_f = V_s + \beta V_o$$

The quantity $\beta = V_f/V_o$ is called as feedback ratio or feedback fraction.

The output V_o must be equal to the input voltage $(V_s + \beta V_o)$ multiplied by the gain A of the amplifier.

Hence,

$$(Vs+\beta Vo)A=Vo(Vs+\beta Vo)A=Vo$$ **Or**

$$AVs+A\beta Vo=VoAVs+A\beta Vo=Vo$$ **Or**

$$AVs=Vo(1-A\beta)AVs=Vo(1-A\beta)$$

Therefore , $VoVs=A1-A\beta VoVs=A1-A\beta$

Let A_f be the overall gain (gain with the feedback) of the amplifier. This is defined as the ratio of output voltage V_o to the applied signal voltage V_s, i.e.,

Af=OutputVoltageInputSignal Voltage=VoVsAf=OutputVoltageInputSignalVoltage=VoVs

from the above two equations, we can understand that, the equation of gain of the feedback amplifier with positive feedback is given by

$$Af=A1-A\beta Af=A1-A\beta$$

Where **Aβ** is the **feedback factor** or the **loop gain**.

If $A\beta = 1$, $A_f = \infty$. Thus the gain becomes infinity, i.e., there is output without any input. In another words, the amplifier works as an Oscillator.

The condition $A\beta = 1$ is called as **Barkhausen Criterion of oscillations**. This is a very important factor to be always kept in mind, in the concept of Oscillators.

Tuned circuit oscillators are the circuits that produce oscillations with the help of tuning circuits. The tuning circuits onsists of an inductance L and a capacitor C. These are also known as **LC oscillators, resonant circuit oscillators** or **tank circuit oscillators**.

The tuned circuit oscillators are used to produce an output with frequencies ranging from 1 MHz to 500 MHz Hence these are also known as **R.F. Oscillators**. A BJT or a FET is used as an amplifier with tuned circuit oscillators. With an amplifier and an LC tank circuit, we can feedback a signal with right amplitude and phase to maintain oscillations.

TypesofTunedCircuitOscillators

Most of the oscillators used in radio transmitters and receivers are of LC oscillators type. Depending upon the way the feedback is used in the circuit, the LC oscillators are divided as the following types.

- **Tuned-collector or Armstrong Oscillator** − It uses inductive feedback from the collector of a transistor to the base. The LC circuit is in the collector circuit of the transistor.
- **Tuned base Oscillator** − It uses inductive feedback. But the LC circuit is in the base circuit.
- **Hartley Oscillator** − It uses inductive feedback.
- **Colpitts Oscillator** − It uses capacitive feedback.
- **Clapp Oscillator** − It uses capacitive feedback.

Hartley Oscillator:

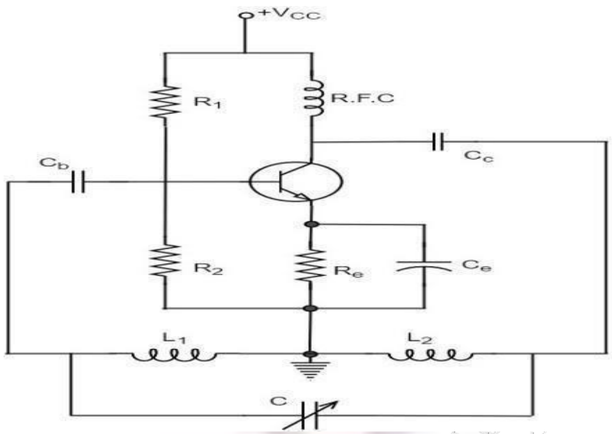
A very popular **local oscillator** circuit that is mostly used in **radio receivers** is the **Hartley Oscillator** circuit. The constructional details and operation of a Hartley oscillator are as discussed below.

Construction

In the circuit diagram of a Hartley oscillator shown below, the resistors R_1, $R_2$and R_e provide necessary bias condition for the circuit. The capacitor C_e provides a.c. ground thereby providing any signal degeneration. This also provides temperature stabilization. The capacitors C_c and C_b are employed to block d.c. and to provide an a.c. path. The radio frequency choke (R.F.C) offers very high impedance to high frequency currents which means it shorts for d.c. and opens for a.c. Hence it provides d.c. load for collector and keeps a.c. currents out of d.c. supply source

Tank Circuit

The frequency determining network is a parallel resonant circuit which consists of the inductors L_1 and L_2 along with a variable capacitor C. The junction of $L_1$and L_2 are earthed. The coil L_1 has its one end connected to base via C_c and the other to emitter via C_e. So, L_2 is in the output circuit. Both the coils L_1 and L_2 are inductively coupled and together form an **Auto-transformer**. The following circuit diagram shows the arrangement of a Hartley oscillator. The tank circuit is **shunt fed** in this circuit. It can also be a **series-fed**.



Operation

When the collector supply is given, a transient current is produced in the oscillatory or tank circuit. The oscillatory current in the tank circuit produces a.c. voltage across L_1. The **auto-transformer** made by the inductive coupling of L_1 and L_2 helps in determining the frequency and establishes the feedback. As the CE configured transistor provides 180^o phase shift, another 180^o phase shift is provided by the transformer, which makes 360^o phase shift between the input and output voltages. This makes the feedback positive which is essential for the condition of oscillations. When the **loop gain |βA| of the amplifier is greater than one**, oscillations are sustained in the circuit.

Frequency

The equation for **frequency of Hartley oscillator** is given as

$$f=12\pi LTC----\sqrt{}f=12\pi LTC$$

$$LT=L1+L2+2MLT=L1+L2+2M$$

Here, L_T is the total cumulatively coupled inductance; L_1 and L_2 represent inductances of 1st and 2nd coils; and **M** represents mutual inductance. **Mutual inductance** is calculated when two windings are considered.

Advantages

The advantages of Hartley oscillator are

- Instead of using a large transformer, a single coil can be used as an auto-transformer.
- Frequency can be varied by employing either a variable capacitor or a variable inductor.
- Less number of components are sufficient.
- The amplitude of the output remains constant over a fixed frequency range.

Disadvantages

The disadvantages of Hartley oscillator are

- It cannot be a low frequency oscillator.
- Harmonic distortions are present.

Applications

The applications of Hartley oscillator are

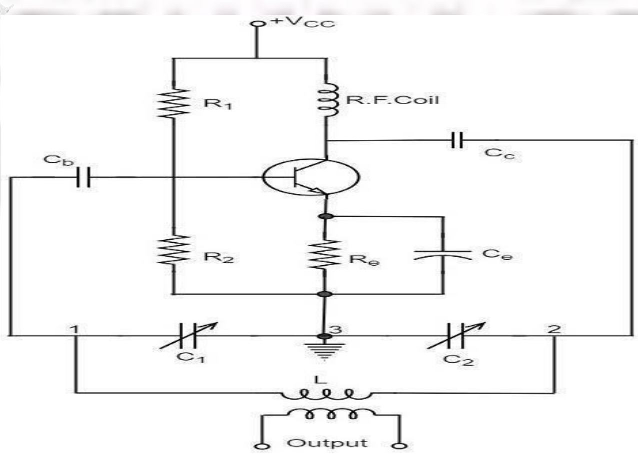
- It is used to produce a sine wave of desired frequency.
- Mostly used as a local oscillator in radio receivers.
- It is also used as R.F. Oscillator.

Colpitts Oscillator:

A Colpitts oscillator looks just like the Hartley oscillator but the inductors and capacitors are replaced with each other in the tank circuit. The constructional details and operation of a colpitts oscillator are as discussed below.

Construction

Let us first take a look at the circuit diagram of a Colpitts oscillator.



The resistors R_1, R_2 and R_e provide necessary bias condition for the circuit. The capacitor C_e provides a.c. ground thereby providing any signal degeneration. This also provides temperature stabilization. The capacitors C_c and C_b are employed to block d.c. and to provide an a.c. path. The radio frequency choke (R.F.C) offers very high impedance to high frequency currents which means it shorts for d.c. and opens for a.c. Hence it provides d.c. load for collector and keeps a.c. currents out of d.c. supply source.

Tank Circuit

The frequency determining network is a parallel resonant circuit which consists of variable capacitors C_1 and C_2 along with an inductor L. The junction of $C_1$and C_2 are earthed. The capacitor C_1 has its one end connected to base via C_c and the other to emitter via C_e. the voltage developed across C_1 provides the regenerative feedback required for the sustained oscillations.

Operation

When the collector supply is given, a transient current is produced in the oscillatory or tank circuit. The oscillatory current in the tank circuit produces a.c. voltage across C_1 which are applied to the base emitter junction and appear in the amplified form in the collector circuit and supply losses to the tank circuit. If terminal 1 is at positive potential with respect to terminal 3 at any instant, then terminal 2 will be at negative potential with respect to 3 at that instant because terminal 3 is grounded. Therefore, points 1 and 2 are out of phase by 180^o. As the CE configured transistor provides 180^o phase shift, it makes 360^ophase shift between the input and output voltages. Hence, feedback is properly phased to produce continuous Undamped oscillations. When the **loop gain |βA| of the amplifier is greater than one, oscillations are sustained** in the circuit.

Frequency

The equation for **frequency of Colpitts oscillator** is given as

$$f=12\pi LCT----\sqrt{}f=12\pi LCT$$

C_T is the total capacitance of C_1 and C_2 connected in series.

$$1CT=1C1+1C21CT=1C1+1C2$$
$$CT=C1\times C2C1+C2CT=C1\times C2C1+C2$$

Advantages

The advantages of Colpitts oscillator are as follows −

- Colpitts oscillator can generate sinusoidal signals of very high frequencies.
- It can withstand high and low temperatures.
- The frequency stability is high.
- Frequency can be varied by using both the variable capacitors.
- Less number of components are sufficient.
- The amplitude of the output remains constant over a fixed frequency range.

The Colpitts oscillator is designed to eliminate the disadvantages of Hartley oscillator and is known to have no specific disadvantages. Hence there are many applications of a colpitts oscillator.

Applications

The applications of Colpitts oscillator are as follows −

- Colpitts oscillator can be used as High frequency sine wave generator.
- This can be used as a temperature sensor with some associated circuitry.
- Mostly used as a local oscillator in radio receivers.
- It is also used as R.F. Oscillator.
- It is also used in Mobile applications.
- It has got many other commercial applications.

RC Phase shift oscillator:

One of the important features of an oscillator is that the feedback energy applied should be in correct phase to the tank circuit. The oscillator circuits discussed so far has employed inductor (L) and capacitor (C) combination, in the tank circuit or frequency determining circuit. We have observed that the LC combination in oscillators provide 180° phase shift and transistor in CE configuration provide 180° phase shift to make a total of 360° phase shift so that it would make a zero difference in phase.

Drawbacks of LC circuits

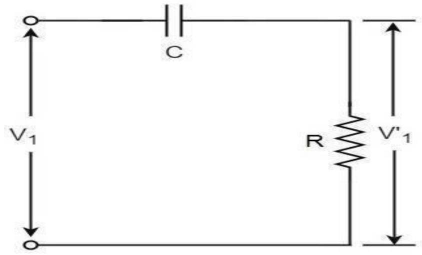
Though they have few applications, the **LC** circuits have few **drawbacks** such as

- Frequency instability
- Waveform is poor
- Cannot be used for low frequencies
- Inductors are bulky and expensive

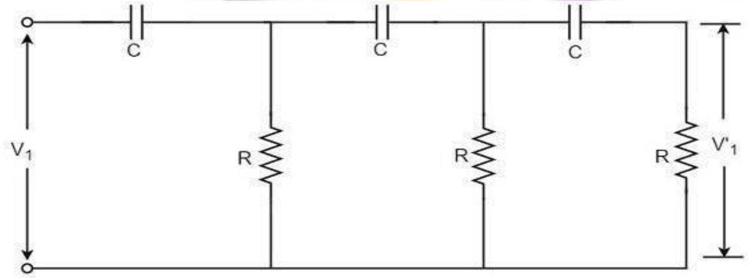
We have another type of oscillator circuits, which are made by replacing the inductors with resistors. By doing so, the frequency stability is improved and a good quality waveform is obtained. These oscillators can also produce lower frequencies. As well, the circuit becomes neither bulky nor expensive. All the drawbacks of **LC** oscillator circuits are thus eliminated in **RC** oscillator circuits. Hence the need for RC oscillator circuits arise. These are also called as **Phase–shift Oscillators**.

PrincipleofPhase-shiftoscillators

We know that the output voltage of an RC circuit for a sine wave input leads the input voltage. The phase angle by which it leads is determined by the value of RC components used in the circuit. The following circuit diagram shows a single section of an RC network.



The output voltage V_1' across the resistor R leads the input voltage applied input V_1 by some phase angle ϕ^o. If R were reduced to zero, V_1' will lead the V_1 by 90^o i.e., $\phi^o = 90^o$. 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^o. The following circuit diagram shows the three sections of the RC network.



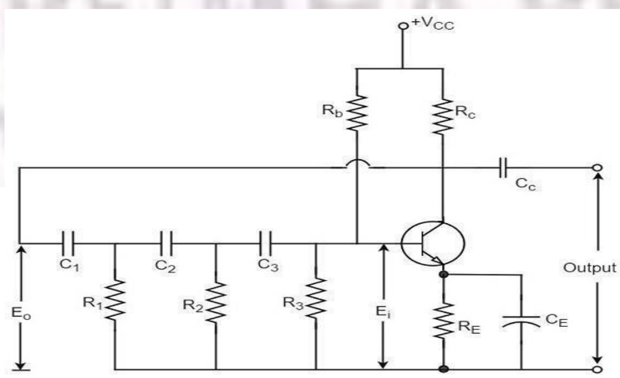
Each section produces a phase shift of 60^o. Consequently, a total phase shift of 180^o is produced, i.e., voltage V_2 leads the voltage V_1 by 180^o.

Phase-shiftOscillatorCircuit

The oscillator circuit that produces a sine wave using a phase-shift network is called as a Phase-shift oscillator circuit.

Construction

The phase-shift oscillator circuit consists of a single transistor amplifier section and a RC phase-shift network. The phase shift network in this circuit, consists of three RC sections. At the resonant frequency f_o, the phase shift in each RC section is 60^o so that the total phase shift produced by RC network is 180^o. The following circuit diagram shows the arrangement of an RC phase-shift oscillator.



The frequency of oscillations is given by

fo=12πRC6–√fo=12πRC6

Where

R1=R2=R3=RR1=R2=R3=R
C1=C2=C3=CC1=C2=C3=C

Operation

The circuit when switched ON oscillates at the resonant frequency f_o. The output E_o of the amplifier is fed back to RC feedback network. This network produces a phase shift of 180° and a voltage E_i appears at its output. This voltage is applied to the transistor amplifier.

The feedback applied will be

m=Ei/Eom=Ei/Eo

The feedback is in correct phase, whereas the transistor amplifier, which is in CE configuration, produces a 180° phase shift. The phase shift produced by network and the transistor add to form a phase shift around the entire loop which is 360°.

Advantages

The advantages of RC phase shift oscillator are as follows −

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

Disadvantages

The disadvantages of RC phase shift oscillator are as follows −

- Starting the oscillations is difficult as the feedback is small.
- The output produced is small.

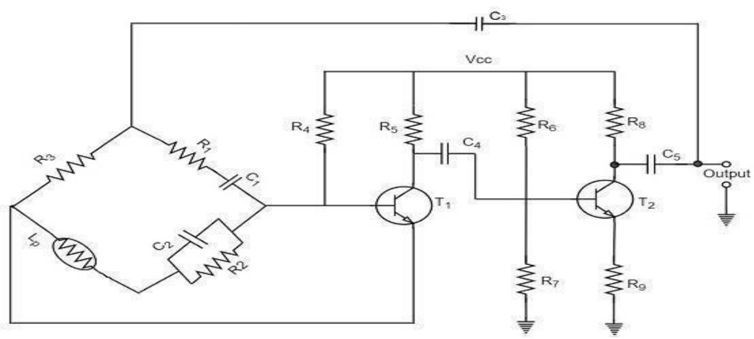
Wien bridge oscillator

Another type of popular audio frequency oscillator is the Wien bridge oscillator circuit. This is mostly used because of its important features. This circuit is free from the **circuit fluctuations** and the **ambient temperature**.

The main advantage of this oscillator is that the frequency can be varied in the range of 10Hz to about 1MHz whereas in RC oscillators, the frequency is not varied.

Construction

The circuit construction of Wien bridge oscillator can be explained as below. It is a two-stage amplifier with RC bridge circuit. The bridge circuit has the arms R_1C_1, R_3, R_2C_2 and the tungsten lamp L_p. Resistance R_3 and the lamp L_p are used to stabilize the amplitude of the output. The following circuit diagram shows the arrangement of a Wien bridge oscillator.



The transistor T_1 serves as an oscillator and an amplifier while the other transistor T_2 serves as an inverter. The inverter operation provides a phase shift of 180^o. This circuit provides positive feedback through R_1C_1, C_2R_2 to the transistor T_1 and negative feedback through the voltage divider to the input of transistor T_2. The frequency of oscillations is determined by the series element R_1C_1 and parallel element R_2C_2 of the bridge.

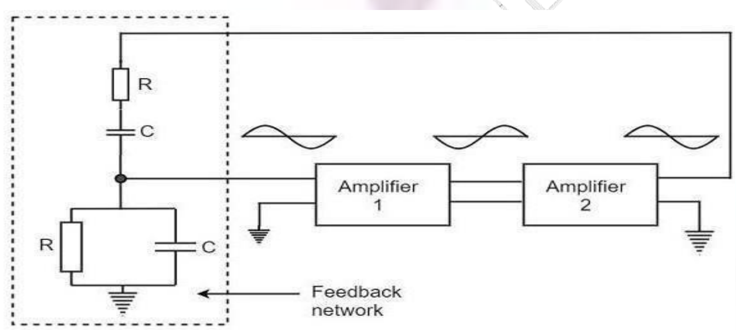
f=12πR1C1R2C2—————————√f=12πR1C1R2C2

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

Then,

f=12πRCf=12πRC

Now, we can simplify the above circuit as follows −



The oscillator consists of two stages of RC coupled amplifier and a feedback network. The voltage across the parallel combination of R and C is fed to the input of amplifier 1. The net phase shift through the two amplifiers is zero. The usual idea of connecting the output of amplifier 2 to amplifier 1 to provide signal regeneration for oscillator is not applicable here as the amplifier 1 will amplify signals over a wide range of frequencies and hence direct coupling would result in poor frequency stability. By adding Wien bridge feedback network, the oscillator becomes sensitive to a particular frequency and hence frequency stability is achieved.

Operation

When the circuit is switched ON, the bridge circuit produces oscillations of the frequency stated above. The two transistors produce a total phase shift of 360^o so that proper positive feedback is ensured. The negative feedback in the circuit ensures constant output. This is achieved by temperature sensitive tungsten lamp L_p. Its resistance increases with current. If the amplitude of the output increases, more current is produced and more negative feedback is achieved. Due to this, the output would return to the original value. Whereas, if the output tends to decrease, reverse action would take place.

Advantages

The advantages of Wien bridge oscillator are as follows −

- The circuit provides good frequency stability.
- It provides constant output.
- The operation of circuit is quite easy.
- The overall gain is high because of two transistors.
- The frequency of oscillations can be changed easily.
- The amplitude stability of the output voltage can be maintained more accurately, by replacing R_2 with a thermistor.

Disadvantages

The disadvantages of Wien bridge oscillator are as follows −

- The circuit cannot generate very high frequencies.
- Two transistors and number of components are required for the circuit construction.

MODULE-V

OPERATIONAL AMPLIFIERS

Ideal op-amp, Output offset voltage, input bias current, input offset current, slew rate, gain bandwidth product, Inverting and non-inverting amplifier, Differentiator, integrator, Square-wave and triangular-wave generators.

Introduction to Operational amplifiers:

An **electronic circuit** is a group of electronic components connected for a specific purpose.

A simple electronic circuit can be designed easily because it requires few discrete electronic components and connections. However, designing a complex electronic circuit is difficult, as it requires more number of discrete electronic components and their connections. It is also time taking to build such complex circuits and their reliability is also less. These difficulties can be overcome with Integrated Circuits.

IntegratedCircuit(IC)

If multiple electronic components are interconnected on a single chip of semiconductor material, then that chip is called as an **Integrated Circuit (IC)**. It consists of both active and passive components.

This chapter discusses the advantages and types of ICs.

AdvantagesofIntegratedCircuits

Integrated circuits offer many advantages. They are discussed below −

- **Compact size** − For a given functionality, you can obtain a circuit of smaller size using ICs, compared to that built using a discrete circuit.
- **Lesser weight** − A circuit built with ICs weighs lesser when compared to the weight of a discrete circuit that is used for implementing the same function of IC. using ICs, compared to that built using a discrete circuit.
- **Low power consumption** − ICs consume lower power than a traditional circuit,because of their smaller size and construction.
- **Reduced cost** − ICs are available at much reduced cost than discrete circuits because of their fabrication technologies and usage of lesser material than discrete circuits.
- **Increased reliability** − Since they employ lesser connections, ICs offer increased reliability compared to digital circuits.
- **Improved operating speeds** − ICs operate at improved speeds because of their switching speeds and lesser power consumption.

TypesofIntegratedCircuits

Integrated circuits are of two types − **Analog Integrated Circuits and Digital Integrated Circuits**.

Analog Integrated Circuits

Integrated circuits that operate over an entire range of continuous values of the signal amplitude are called as **Analog Integrated Circuits.** These are further classified into the two types as discussed here −

- **Linear Integrated Circuits** − An analog IC is said to be Linear, if there exists a linear relation between its voltage and current. IC 741, an 8-pin Dual In-line Package (DIP)op-amp, is an example of Linear IC.
- **Radio Frequency Integrated Circuits** − An analog IC is said to be Non-Linear, if there exists a non-linear relation between its voltage and current. A Non-Linear IC is also called as Radio Frequency IC.

Digital Integrated Circuits

If the integrated circuits operate only at a few pre-defined levels instead of operating for an entire range of continuous values of the signal amplitude, then those are called as **Digital Integrated Circuits**.

Operational Amplifier, also called as an Op-Amp, is an integrated circuit, which can be used to perform various linear, non-linear, and mathematical operations. An op-amp is a **direct coupled high gain amplifier**. You can operate op-amp both with AC and DC signals. This chapter discusses the characteristics and types of op-amps.

ConstructionofOperationalAmplifier

An op-amp consists of differential amplifier(s), a level translator and an output stage. A differential amplifier is present at the input stage of an op-amp and hence an op-amp consists of **two input terminals**. One of those terminals is called as the **inverting terminal** and the other one is called as the **non-inverting terminal**. The terminals are named based on the phase relationship between their respective inputs and outputs.

Characteristics of Operational Amplifier

The important characteristics or parameters of an operational amplifier are as follows −

- Open loop voltage gain
- Output offset voltage
- Common Mode Rejection Ratio
- Slew Rate

This section discusses these characteristics in detail as given below −

Open loop voltage gain

The open loop voltage gain of an op-amp is its differential gain without any feedback path.

Mathematically, the open loop voltage gain of an op-amp is represented as −

$$Av=v0v1-v2Av=v0v1-v2$$

Output offset voltage

The voltage present at the output of an op-amp when its differential input voltage is zero is called as **output offset voltage.**

Common Mode Rejection Ratio

Common Mode Rejection Ratio (**CMRR**) of an op-amp is defined as the ratio of the closed loop differential gain, AdAd and the common mode gain, AcAc.
Mathematically, CMRR can be represented as −

$$CMRR=AdAcCMRR=AdAc$$

Note that the common mode gain, AcAc of an op-amp is the ratio of the common mode output voltage and the common mode input voltage.

Slew Rate

Slew rate of an op-amp is defined as the maximum rate of change of the output voltage due to a step input voltage.

Mathematically, slew rate (SR) can be represented as −

SR=MaximumofdV0dtSR=MaximumofdV0dt

Where, V0V0 is the output voltage. In general, slew rate is measured in either V/μSecV/μSec or V/mSecV/mSec.

TypesofOperationalAmplifiers

An op-amp is represented with a triangle symbol having two inputs and one output.

Op-amps are of two types: **Ideal Op-Amp** and **Practical Op-Amp**.

They are discussed in detail as given below −

Ideal Op-Amp

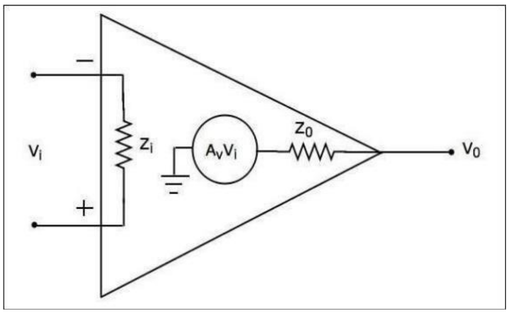
An ideal op-amp exists only in theory, and does not exist practically. The **equivalent circuit** of an ideal op-amp is shown in the figure given below −

An **ideal op-amp** exhibits the following characteristics −

- Input impedance Zi=∞ΩZi=∞Ω
- Output impedance Z0=0ΩZ0=0Ω
- Open loop voltage gaine Av=∞Av=∞
- If (the differential) input voltage Vi=0VVi=0V, then the output voltage will be V0=0VV0=0V
- Bandwidth is **infinity**. It means, an ideal op-amp will amplify the signals of any frequency without any attenuation.
- Common Mode Rejection Ratio **(CMRR)** is **infinity**.
- Slew Rate **(SR)** is **infinity**. It means, the ideal op-amp will produce a change in the output instantly in response to an input step voltage.

Practical Op-Amp

Practically, op-amps are not ideal and deviate from their ideal characteristics because of some imperfections during manufacturing. The **equivalent circuit** of a practical op-amp is shown in the following figure −



A **practical op-amp** exhibits the following characteristics −

- Input impedance, ZiZi in the order of **Mega ohms**.
- Output impedance, Z0Z0 in the order of **few ohms.**.
- Open loop voltage gain, AvAv will be **high**.

When you choose a practical op-amp, you should check whether it satisfies the following conditions −

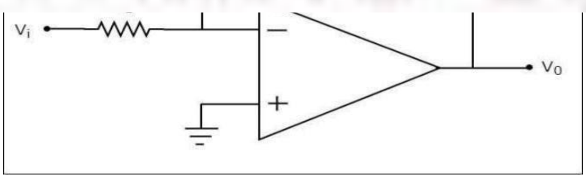
- Input impedance, ZiZi should be as high as possible.
- Output impedance, Z0Z0 should be as low as possible.
- Open loop voltage gain, AvAv should be as high as possible.
- Output offset voltage should be as low as possible.
- The operating Bandwidth should be as high as possible.
- CMRR should be as high as possible.
- Slew rate should be as high as possible.

A circuit is said to be **linear**, if there exists a linear relationship between its input and the output. Similarly, a circuit is said to be **non-linear**, if there exists a non-linear relationship between its input and output. Op-amps can be used in both linear and non-linear applications. The following are the basic applications of op-amp −

- Inverting Amplifier
- Non-inverting Amplifier
- Voltage follower

InvertingAmplifier

An inverting amplifier takes the input through its inverting terminal through a resistor R1R1, and produces its amplified version as the output. This amplifier not only amplifies the input but also inverts it (changes its sign).



Note that for an op-amp, the voltage at the inverting input terminal is equal to the voltage at its non-inverting input terminal. Physically, there is no short between those two terminals but **virtually**, they are in **short** with each other. In the circuit shown above, the non-inverting input terminal is connected to ground. That means zero volts is applied at the non-inverting input terminal of the op-amp. According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp will be zero volts.

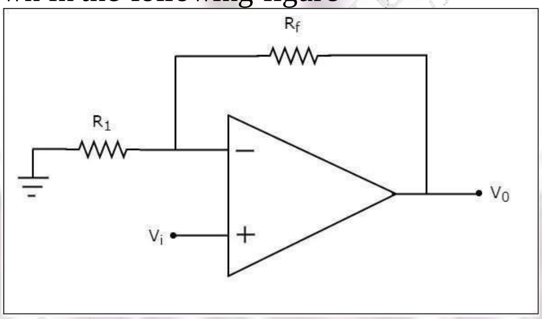
The **nodal equation** at this terminal's node is as shown below −

0−ViR1+0−V0Rf=00−ViR1+0−V0Rf=0
=>−ViR1=V0Rf=>−ViR1=V0Rf
=>V0=(−RfR1)Vt=>V0=(−RfR1)Vt
=>V0Vi=−RfR1=>V0Vi=−RfR1

The ratio of the output voltage V0V0 and the input voltage ViVi is the voltage-gain or gain of the amplifier. Therefore, the **gain of inverting amplifier** is equal to −RfR1−RfR1.
Note that the gain of the inverting amplifier is having a **negative sign**. It indicates that there exists a 180^0 phase difference between the input and the output.

Non-Inverting Amplifier

A non-inverting amplifier takes the input through its non-inverting terminal, and produces its amplified version as the output. As the name suggests, this amplifier just amplifies the input, without inverting or changing the sign of the output. The **circuit diagram** of a non-inverting amplifier is shown in the following figure −



In the above circuit, the input voltage ViVi is directly applied to the non-inverting input terminal of op-amp. So, the voltage at the non-inverting input terminal of the op-amp will be ViVi. By using **voltage division principle**, we can calculate the voltage at the inverting input terminal of the op-amp as shown below −

=>V1=V0(R1R1+Rf)=>V1=V0(R1R1+Rf)

According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp is same as that of the voltage at its non-inverting input terminal.

=>V1=Vi=>V1=Vi
=>V0(R1R1+Rf)=Vi=>V0(R1R1+Rf)=Vi
=>V0Vi=R1+RfR1=>V0Vi=R1+RfR1
=>V0Vi=1+RfR1=>V0Vi=1+RfR1

Now, the ratio of output voltage V0V0 and input voltage ViVi or the voltage-gain or **gain of the non-inverting amplifier** is equal to 1+RfR11+RfR1. Note that the gain of the non-inverting amplifier is having a **positive sign**. It indicates that there is no phase difference between the input and the output.

Integrator and Differentiator:

The electronic circuits which perform the mathematical operations such as differentiation and integration are called as differentiator and integrator, respectively. This chapter discusses in detail about op-amp based **differentiator** and integrator. Please note that these also come under linear applications of op-amp.

Differentiator

A **differentiator** is an electronic circuit that produces an output equal to the first derivative of its input. This section discusses about the op-amp based differentiator in detail.

An op-amp based differentiator produces an output, which is equal to the differential of input voltage that is applied to its inverting terminal. The **circuit diagram** of an op-amp based differentiator is shown in the following figure −

In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

According to the **virtual short concept**, the voltage at the inverting input terminal of opamp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts.

The nodal equation at the inverting input terminal's node is −

Cd(0−Vi)dt+0−V0R=0Cd(0−Vi)dt+0−V0R=0

=>−CdVidt=V0R=>−CdVidt=V0R

=>V0=−RCdVidt=>V0=−RCdVidt

If RC=1secRC=1sec, then the output voltage V0V0 will be −

V0=−dVidtV0=−dVidt

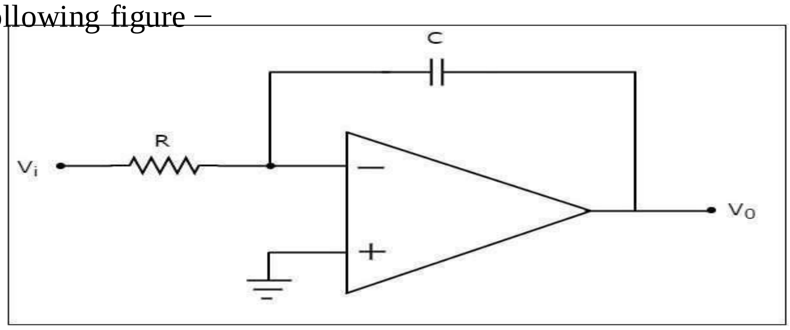
Thus, the op-amp based differentiator circuit shown above will produce an output, which is the differential of input voltage ViVi, when the magnitudes of impedances of resistor and capacitor are reciprocal to each other.

Note that the output voltage V0V0 is having a **negative sign**, which indicates that there exists a 180^0 phase difference between the input and the output.

Integrator

An **integrator** is an electronic circuit that produces an output that is the integration of the applied input. This section discusses about the op-amp based integrator.

An op-amp based integrator produces an output, which is an integral of the input voltage applied to its inverting terminal. The **circuit diagram** of an op-amp based integrator is shown in the following figure −



In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal. According to **virtual short concept**, the voltage at the inverting input terminal of op-amp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts.

The **nodal equation** at the inverting input terminal is −

0−ViR+Cd(0−V0)dt=00−ViR+Cd(0−V0)dt=0

=>−ViR=CdV0dt=>−ViR=CdV0dt

=>dV0dt=−ViRC=>dV0dt=−ViRC

=>dV0=(−ViRC)dt=>dV0=(−ViRC)dt

Integrating both sides of the equation shown above, we get −

∫dV0=∫(−ViRC)dt∫dV0=∫(−ViRC)dt

=>V0=−1RC∫Vtdt=>V0=−1RC∫Vtdt

If RC=1secRC=1sec, then the output voltage, V0V0 will be −

V0=−∫VidtV0=−∫Vidt

So, the op-amp based integrator circuit discussed above will produce an output, which is the integral of input voltage ViVi, when the magnitude of impedances of resistor and capacitor are reciprocal to each other.

Note − The output voltage, V0V0 is having a **negative sign**, which indicates that there exists 180^0 phase difference between the input and the output.

Waveform Generators:

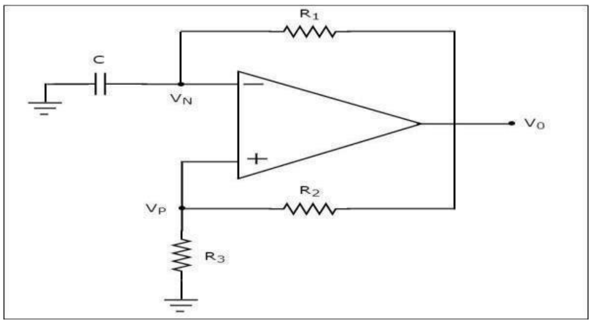
A **waveform generator** is an electronic circuit, which generates a standard wave. There are two types of op-amp based waveform generators −

- Square wave generator
- Triangular wave generator

SquareWaveGenerator:

A **square wave generator** is an electronic circuit which generates square wave. This section discusses about op-amp based square wave generators.

The **circuit diagram** of a op-amp based square wave generator is shown in the following figure

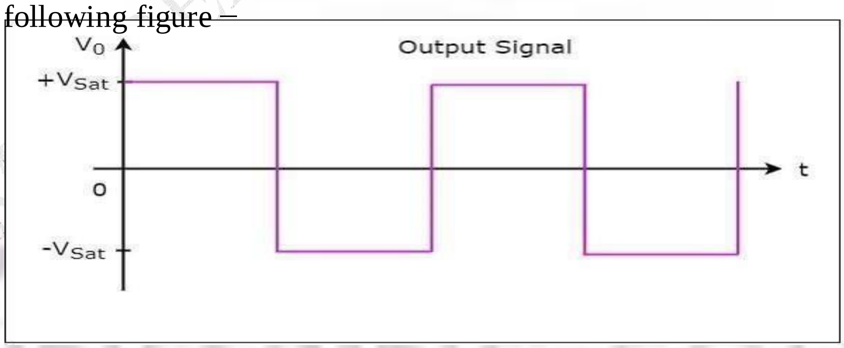


Observe that in the circuit diagram shown above, the resistor R1R1 is connected between the inverting input terminal of the op-amp and its output of op-amp. So, the resistor R1R1 is used in the **negative feedback**. Similarly, the resistor R2R2 is connected between the noninverting input terminal of the op-amp and its output. So, the resistor R2R2 is used in the **positive feedback** path. A capacitor C is connected between the inverting input terminal of the op-amp and ground. So, the **voltage across capacitor C** will be the input voltage at this inverting terminal of op-amp. Similarly, a resistor R3R3 is connected between the non-inverting input terminal of the op-amp and ground. So, the **voltage across resistor** R3R3 will be the input voltage at this non-inverting terminal of the op-amp.

The **operation** of a square wave generator is explained below −

- Assume, there is **no charge** stored in the capacitor initially. Then, the voltage present at the inverting terminal of the op-amp is zero volts. But, there is some offset voltage at non-inverting terminal of op-amp. Due to this, the value present at the output of above circuit will be +Vsat+Vsat.
- Now, the capacitor C starts **charging** through a resistor R1R1. The value present at the output of the above circuit will change to −Vsat−Vsat, when the voltage across the capacitor C reaches just greater than the voltage (positive value) across resistor R3R3.
- The capacitor C starts **discharging** through a resistor R1R1, when the output of above circuit is −Vsat−Vsat. The value present at the output of above circuit will change to +Vsat+Vsat,when the voltage across capacitor C reaches just less than (more negative) the voltage (negative value) across resistor R3R3.

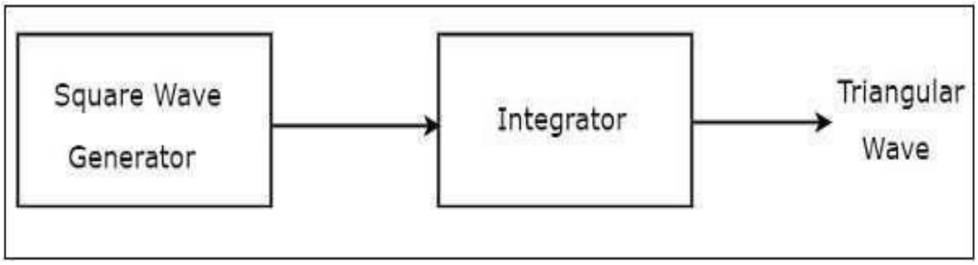
Thus, the circuit shown in the above diagram will produce a **square wave** at the output as shown in the following figure −



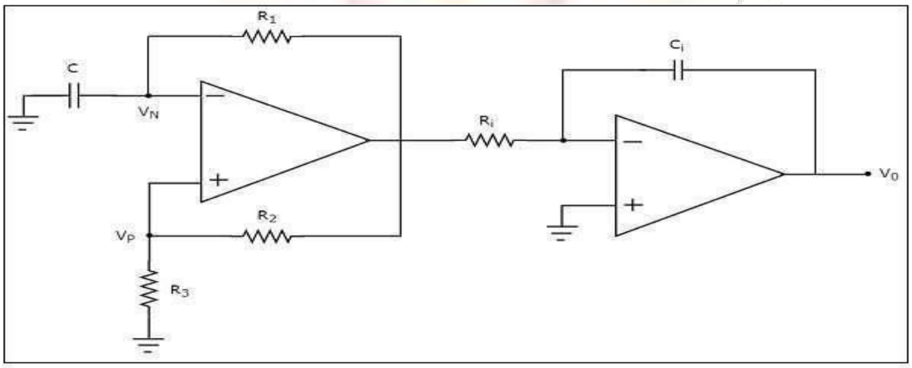
From the above figure we can observe that the output of square wave generator will have one of the two values: +Vsat+Vsat and −Vsat−Vsat. So, the output remains at one value for some duration and then transitions to another value and remains there for some duration. In this way, it continues.

Triangular Wave Generator:

A triangular wave generator is an electronic circuit, which generates a triangular wave. The **block diagram** of a triangular wave generator is shown in the following figure −



The block diagram of a triangular wave generator contains mainly two blocks: a square wave generator and an integrator. These two blocks are **cascaded**. That means, the output of square wave generator is applied as an input of integrator. Note that the integration of a square wave is nothing but a triangular wave. The **circuit diagram** of an op-amp based triangular wave generator is shown in the following figure −



We have already seen the circuit diagrams of a square wave generator and an integrator. Observe that we got the above **circuit diagram** of an op-amp based triangular wave generator by replacing the blocks with the respective circuit diagrams in the block diagram of a triangular wave generator.