Unit-2

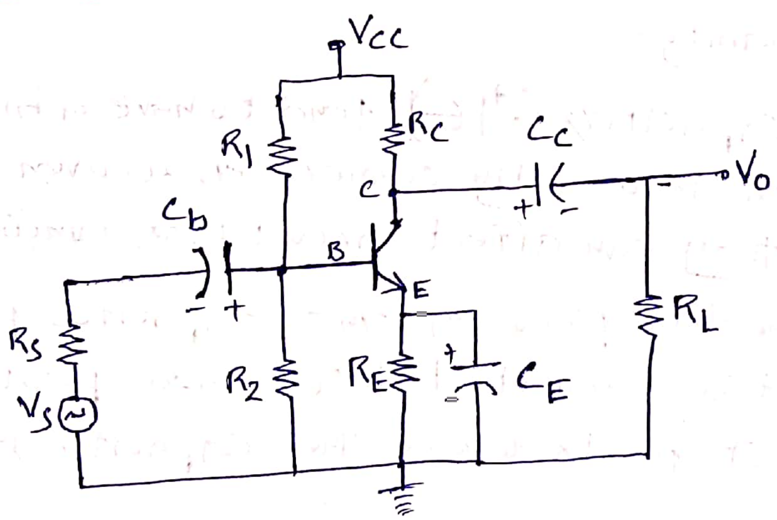
UNIT-1: FREQUENCY RESPONSE

Small Signal High Frequency Transistor Amplifier Models

Introduction:-

V-I characteristics of BJT are non-linear. The analysis of non-linear device is complex. To simplify the analysis of BJT, its operation is restricted to the linear V-I characteristics around the Q-point i.e; in the Active region. This approximation is possible only with small input signals. The term small signal amplifier refers to the use of signal that takes up a relatively small percentage of an amplifier's operational range. With small input signals the transistor can be replaced with small signal linear model. This model is also called "small signal Equivalent circuit".

Common Emitter (CE) Amplifier circuit:-



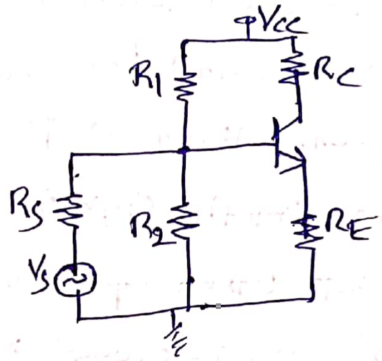
From the above circuit:-

i) Resistances R_1, R_2, R_C, R_E Forms the Voltage divider bias circuit for CE amplifier. It sets the proper operating point for CE amplifier and provides faithful amplification of input signal.

Blocking Capacitor (or)

ii) Input capacitor, C_b :- It couples the input signal to the base of the transistor. It blocks any DC component present in the signal and allows (passes) only ac signal for amplification.

If 'C_b' is not connected in the circuit then source is directly connected to circuit as shown in the figure below.



The bias voltage is altered to

$$V_{R_2} = \frac{V_{CC} \cdot (R_S \| R_2)}{R_1 + (R_S \| R_2)}$$

instead of $V_{R_2} = \dfrac{V_{CC} R_2}{R_1 + R_2}$.

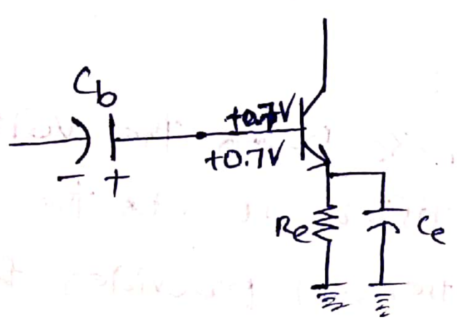
Then the circuit bias conditions will be altered and the operating point is unstable.

∴ Blocking capacitor, 'C_b' is required to keep operating point stable

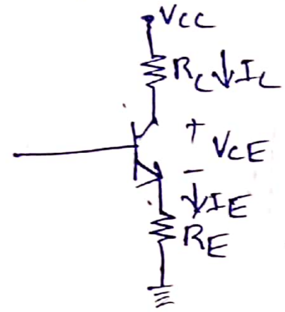
Capacitor polarity :-

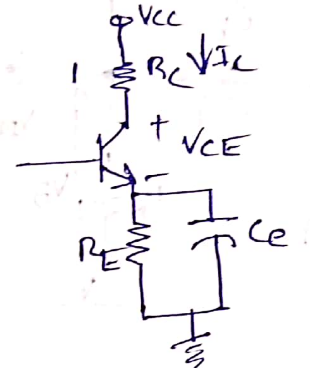
Electrolytic capacitors (+|(-) tend to have a high leakage current when incorrectly connected, so even if they do not explode, they can affect circuit bias conditions.

i.e, to overcome this problem the capacitor positive terminal must be connected to the more positive of the two circuit points where the capacitor is installed.



iii) Emitter Bypass Capacitor (C_E):- It is placed parallel with R_E to provide a low reactance path to the amplified a.c signal. If it is not placed, the amplified a.c signal passing through R_E will cause a voltage drop across it. This will reduce the output voltage, reducing the gain of amplifier.





$V_{CC} = I_C R_C + V_{CE} + I_E R_E$

$I_C R_C = V_{CC} - V_{CE} - I_E R_E$

As $I_E R_E \uparrow$ $I_C R_C \downarrow$

$\therefore$ Voltage gain decreases.

$V_{CC} = I_C R_C + V_{CE} + I_E [R_E \| X_{CE}]$

$I_C R_C = V_{CC} - V_{CE} - I_E \left[\frac{R_E}{1 + j\omega R_E C_E}\right]$

As $I_E [R_E \| X_{CE}] \downarrow$ $I_C R_C \uparrow$

$\therefore$ Voltage gain Increases.

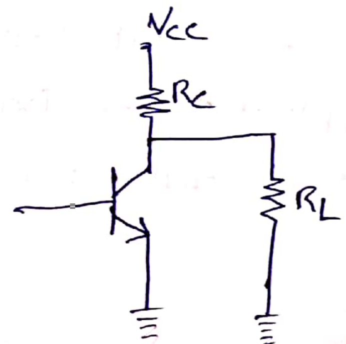
iv) Coupling capacitor (C_C):-

This capacitor couples the output of the amplifier to the load or to the next stage of the amplifier. It blocks d.c and passes only a.c part of amplified signal.

If it is connected then 'R_L' is directly coupled to the circuit output and the collector supply voltage is reduced from V_{CC} to $\frac{V_{CC} R_L}{R_C + R_L}$ and collector resistance becomes $(R_C \| R_L)$.

This affects the circuit d.c load line and Q-point.

If capacitor 'C_C' is kept then it passes a.c output waveform to the load without affecting the circuit bias conditions.



Common Collector (CC) Amplifier Circuit:-

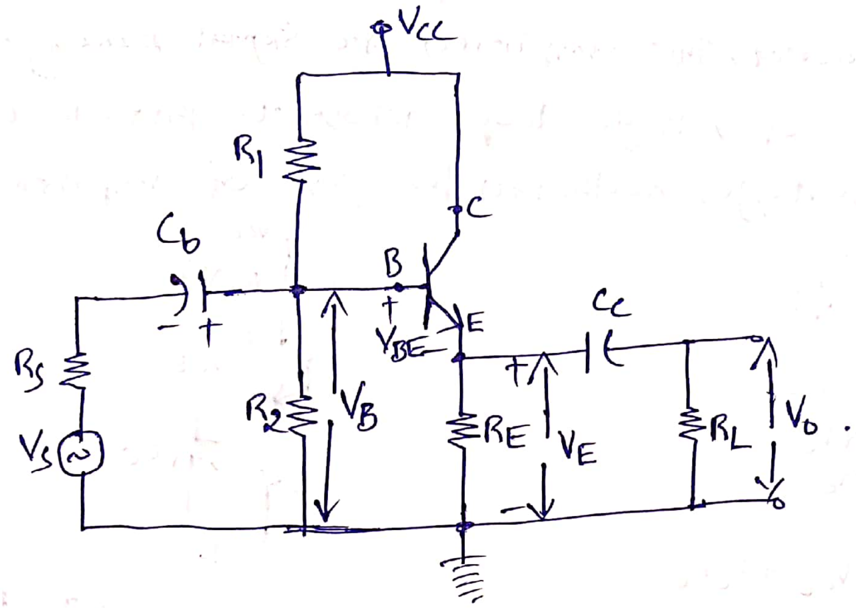


Figure above represents common collector circuit.
The d.c biasing is provided by R_1, R_2 & R_E.

From the figure applying KVL at Base we get:

$$-V_B + V_{BE} + V_E = 0$$

$$V_B = V_{BE} + V_E$$

$$V_E = V_B - V_{BE}$$

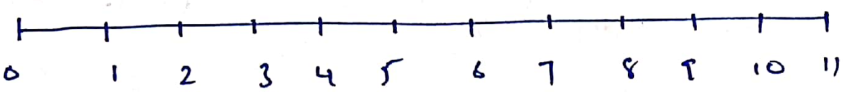
$\boxed{V_E = V_B}$ since V_{BE} is fairly constant.

Variation in input V_B occurs at Base and Emitter voltage V_E' will vary same as base voltage, V_B'.

In CC circuit Emitter terminal follows the signal voltage applied to the Base. Hence CC circuit is also called as "Emitter Follower".

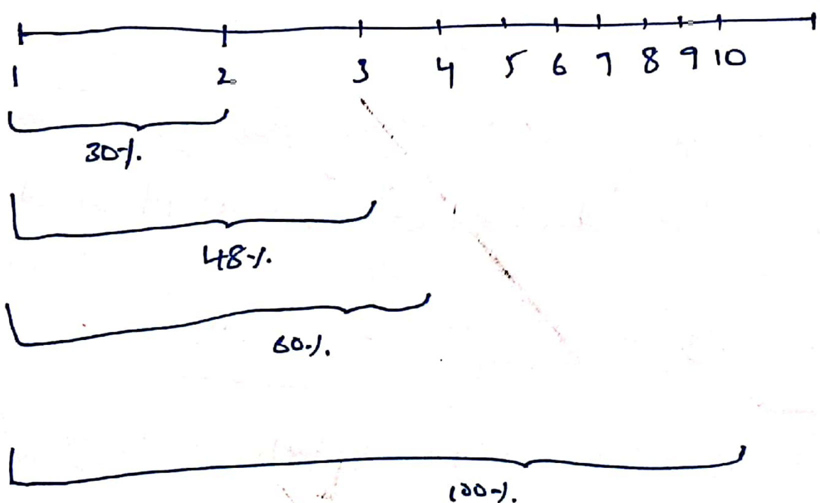
Logarithms:

Ordinary graph paper has a linear scale on both axes and has equal space between the numbers.



Linear Scale:

Use of "Logarithmic scale" compresses distances and significantly expand the range of variation of a particular variable on graph.



Most graph papers available are of "semilog". The term "semi" (meaning one-half) indicates that only one of the two scales is a log scale.

log of 2 to base 10 is 0.3 = 30%.

$\log_{10} 3 = 48$

$\log_{10} 4 = 60\%$

$\log_{10} 10 = 100\%$

Decibels:

The gain of amplifier is expressed as number, yet it is of great practical importance to assign it a unit. The unit assigned is "bel" or 'decibel (dB)'.

A logarithmic unit, named "bel" after Alexander Graham Bell was proposed by telephone industry is assigned to conveniently compare two powers on a logarithmic scale.

$$\boxed{\text{Number of bels} = \log_{10} \frac{P_{out}}{P_{in}}}$$

$$= \log_{10} 100 = 2 \text{ bels.}$$

The bel proved to be too large for most work, so one tenth of a bel the "decibel (dB)", was adopted.

$$\text{In decibels} = 10 \log_{10} 100 = 20 \text{ dB.}$$

$$\boxed{\text{Number of dB} = 10 \times \text{Number of bels} = 10 \cdot \log_{10} \frac{P_{out}}{P_{in}}}$$

For voltage gain $= 10 \times \log_{10} \dfrac{V_{out}^2 / R_L}{V_{in}^2 / R_{in}}$

$$= 10 \times \log_{10} \left(\frac{V_{out}}{V_{in}} \right)^2 = 20 \cdot \log_{10} A_V.$$

For current gain $= 10 \cdot \log_{10} \dfrac{I_{out}^2 R_L}{I_{in}^2 R_{in}}$

$$= 10 \cdot \log_{10} \left(\frac{I_{out}}{I_{in}} \right)^2 = 20 \cdot \log_{10} A_I.$$

Frequency Response of an Amplifier :- [General Frequency considerations]

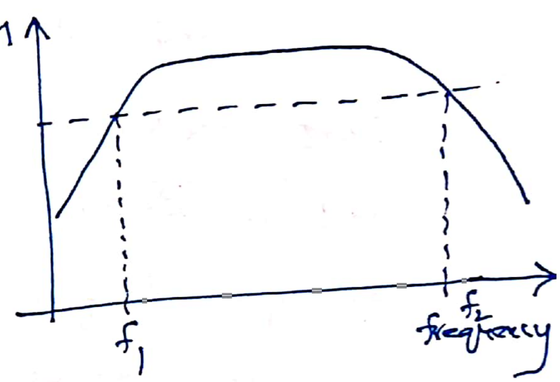
The Voltage gain of an amplifier varies with signal frequency due to the effect of variations in circuit capacitive reactance with signal frequency on the output voltage. The curve drawn between the voltage gain and signal frequency of an amplifier is known as "Frequency Response".

If input voltage is kept constant for an amplifier but if its frequency is varied, it is observed that the amplifier gain

i) remains practically constant over a sizeable range of mid frequencies.

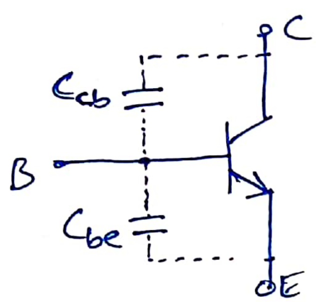
ii) falls off at low as well as at high frequencies.

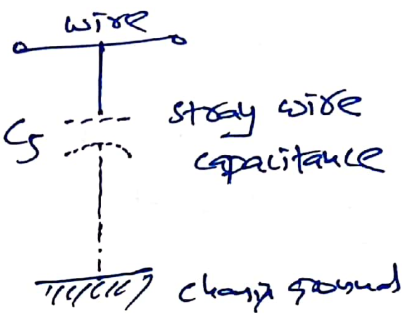
The gain over this middle range is termed the "mid-frequency gain". Gain falls by 3dB at low & high freq. are designated as 'f_1' and 'f_2' respectively. This range is considered as useful range of operating frequency for the amplifier and the frequency difference $(f_2 - f_1)$ is termed the "Amplifier Bandwidth".



At low frequencies, the voltage gain falls because the coupling and bypass capacitors no longer act like short circuits. Instead their capacitive reactances are large enough to drop some of the ac signal voltage. The result is a loss of voltage gain as we approach zero hertz (0 Hz).

At high frequencies, all transistors have capacitances b/w their terminals, known as internal capacitances, these capacitances provide bypass path for ac signal. with the increase in frequency, capacitive reactances become low enough ($X_c \propto 1/f$) to prevent normal transistor action. The result is a loss of voltage gain.





Stray wiring capacitance is another reason for a loss of voltage gain. at high frequencies. Any connecting wire in a transistor circuit acts like one plate of a capacitor, and the chassis ground acts like the other plate.
At higher frequencies, its low capacitive reactance prevents the ac current from reaching the load resistor and voltage gain drops off.

$$\left(\frac{1}{\sqrt{1+\left(\frac{f_2}{f^x}\right)^2}}\right)^n = 1/\sqrt{2}$$

$$\frac{1}{\left(1+\left(\frac{f_2}{f^x}\right)^2\right)^{n/2}} = \left(\frac{1}{2^{1/2}}\right)$$

$$2^{1/n} = 1+\left(\frac{f_2}{f^x}\right)^2$$

$$\sqrt{2^{1/n}-1} = \frac{f_2}{f^x}$$

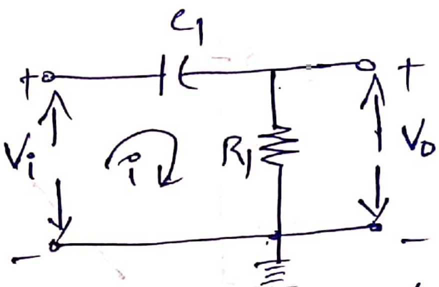
$$f^x = \frac{f_2}{\sqrt{2^{1/n}-1}}$$

Low-frequency Analysis:

Frequency characteristics are divided into three regions:
There is a range called the mid band frequencies, in which amplification is reasonably constant and equal to A_0 and delay is also quite constant.

In second (Low frequency) region, below the mid band, an amplifier stage behaves like simple high-pass circuit of time constant $T_1 = R_1C_1$.

From the circuit:



High pass circuit (differentiator)

$$V_i = iX_{C_1} + iR_1 \qquad V_o = iR_1$$

$$= i\left[X_{C_1} + R_1\right] \qquad i = \frac{V_o}{R_1}$$

$$= i\left[\frac{1}{j\omega C_1} + R_1\right]$$

$$V_i = \frac{V_o}{R_1}\left[\frac{1}{j\omega C_1} + R_1\right]$$

$$\frac{V_o}{V_i} = \frac{R_1}{R_1 + \frac{1}{j\omega C_1}} = \frac{1}{1 + \frac{1}{j\omega R_1C_1}} = \frac{1}{1 - j\times\frac{1}{2\pi f R_1C_1}} = \frac{1}{1 - j\frac{f_L}{f}}$$

where $f_L = \frac{1}{2\pi R_1C_1}$

Voltage gain at low frequencies is the ratio of output voltage to input voltage.

$$A_L = \frac{V_o}{V_i} = \frac{1}{1 - j\frac{f_L}{f}}$$

Magnitude, $\boxed{|A_L| = \frac{1}{\sqrt{1 + \left(\frac{f_L}{f}\right)^2}}}$; phase $\theta_L = -\tan^{-1}\left[\frac{-f_L/f}{1}\right]$

$$\theta_L = \tan^{-1}\left[f_L/f\right].$$

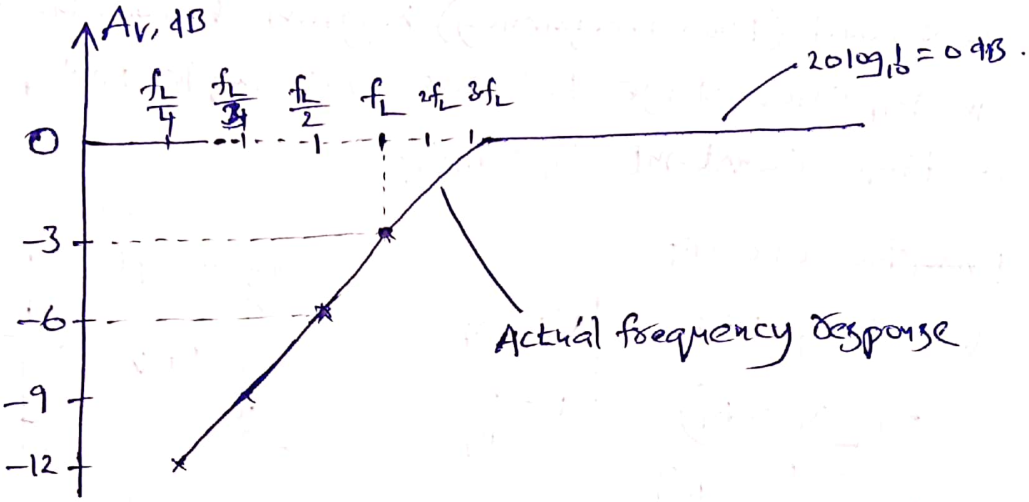
i) In midband region $f \gg f_L$; $A_L \to 1$; $A_{L,dB} = 20\log_{10} A_L = 0$ dB.

ii) At frequency $f = f_L$; $A_L = \frac{1}{\sqrt{2}} = 0.707$; $A_{L,dB} = 20\log_{10} 0.707 = -3$ dB.

Hence f_L' is the frequency at which gain has fallen to 0.707 times its mid band value A_o'.

Droop in signal level corresponds to a decibel reduction of 3 dB.

$\therefore$ f_L' is referred to as the "Lower 3-dB frequency" (or) Lower cut-off frequency.



From the equation $|A_L| = \dfrac{1}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}}$

The gain in dB is $A_{L,dB} = 20\log_{10}\dfrac{1}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}} = 20\log_{10}\left[1+\left(\frac{f_L}{f}\right)^2\right]^{-1/2}$

$$= -10\log_{10}\left[1+\left(\frac{f_L}{f}\right)^2\right]$$

For frequencies $f \ll f_L$; $\left(\frac{f_L}{f}\right)^2 \gg 1$ then $A_{L,dB} = -10\log_{10}\left[\frac{f_L}{f}\right]^2$

finally, $\boxed{A_{L,dB} = -20\log_{10}\frac{f_L}{f}}$

At $f = f_L \Rightarrow \frac{f_L}{f} = 1$; $A_{L,dB} = 0$ dB

At $f = \frac{f_L}{2} \Rightarrow \frac{f_L}{f} = 2$; $A_{L,dB} = -6$ dB

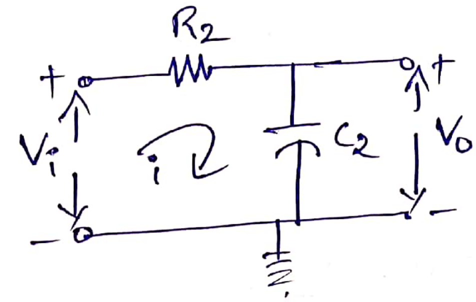
At $f = \frac{f_L}{4} \Rightarrow \frac{f_L}{f} = 4$; $A_{L,dB} = -12$ dB

At $f = \frac{f_L}{10} \Rightarrow \frac{f_L}{f} = 10$; $A_{L,dB} = -20$ dB

High Frequency Analysis :

In the third (high-frequency) region, above the midband, the amplifier stage behaves like simple low-pass circuit (Integrator) with a time constant $T_2 = R_2 C_2$.

From the circuit:



$$V_i = iR_2 + iX_{C_2}$$
$$= i\left[R_2 + \frac{1}{j\omega C_2}\right]$$
$$= \frac{V_o}{X_{C_2}}\left[R_2 + \frac{1}{j\omega C_2}\right]$$

$$V_o = iX_{C_2}$$
$$i = \frac{V_o}{X_{C_2}}$$

$$V_i = \frac{V_o}{\frac{1}{j\omega C_2}}\left[R_2 + \frac{1}{j\omega C_2}\right] = V_o\, j\omega C_2\left[R_2 + \frac{1}{j\omega C_2}\right] = V_o\left[1 + j\omega R_2 C_2\right]$$

$$\therefore \frac{V_o}{V_i} = \frac{1}{1 + j2\pi f R_2 C_2} \Rightarrow \boxed{A_H = \frac{1}{1 + j\frac{f}{f_H}}} \; ; \; f_H = \frac{1}{2\pi R_2 C_2}$$

Magnitude, $|A_H| = \dfrac{1}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}}$; phase $\theta = -\tan^{-1}\left[f/f_H\right]$.

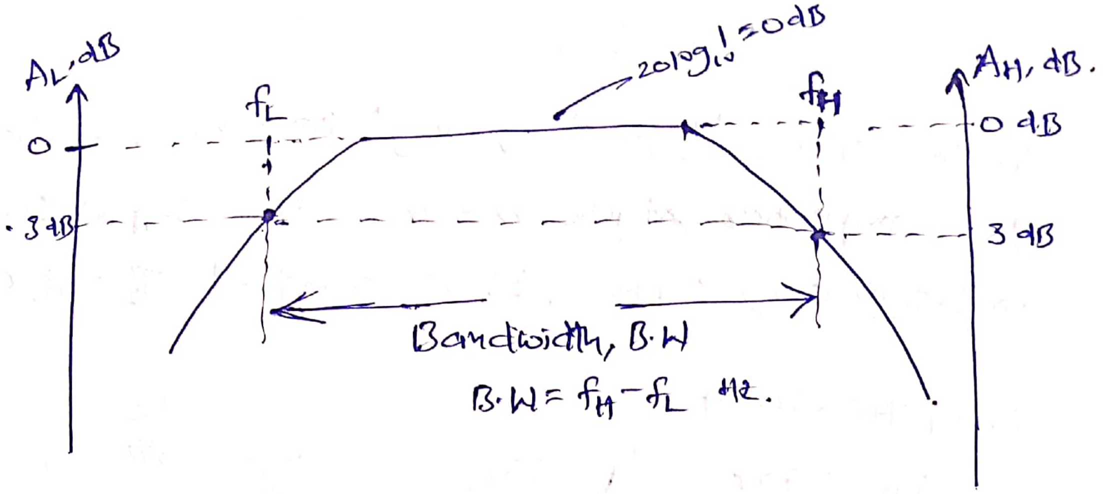
i) At $f << f_H$; $|A_H| = 1$; $A_{H,dB} = 20\log_{10} A_H = 20\log_{10} 1 = 0$ dB

ii) At $f = f_H$; $|A_H| = \frac{1}{\sqrt{2}} = 0.707$; $A_{H,dB} = 20\log_{10} 0.707 = -3$ dB.

Hence 'f_H' is the frequency at which gain has fallen to 0.707 times its midband value A_o.

Drop in signal level corresponds to a decibel reduction of 3 dB.

$\therefore$ 'f_H' is referred to as the "Higher 3-dB frequency" (or) Higher cut-off frequency.



Bandwidth:-

The frequency range from f_L to f_H is called the Bandwidth of the amplifier stage.

i.e; A signal with all fourier components of appreciable amplitude lie within the range f_L to f_H, will pass through the stage without excessive distortion.

(P) Find the magnitude gain corresponding to a voltage gain of 100dB.

Sol: $A_V = 100$ dB.

$A_{V,dB} = 20 \log_{10} A_V \Rightarrow 100 = 20 \log_{10} A_V$

$5 = \log_{10} A_V \Rightarrow A_V = 10^5 = 10000.$

(P) The input power to a device is 10,000 W at a voltage of 1000 V. The output power is 500 W and the output impedance is 20 Ω.

a) find the power gain in decibels.

b) find the voltage gain in decibels.

$P_o = V_o^2/R_o$

$V_o = \sqrt{P_o R_o}$

Sol: a) $P_{,dB} = 10 \log_{10} \frac{P_o}{P_{in}} = 10 \log_{10} \frac{10000}{500} = -13.01$ dB.

b) $V_{,dB} = 20 \log_{10} V_o/V_{in} = 20 \log_{10} \frac{\sqrt{500 \times 20}}{1000} = -20$ dB.

(P) An Amplifier rated at 40W output is connected to a 10 Ω speaker.

a) calculate the input power required for full power output if the power gain is 25 dB.

b) Calculate the input voltage for rated output if the amplifier voltage gain is 40 dB.

Sol:
$P_o = 40W$; $R_o = 10\,\Omega$

a) $A_p = 25\,dB \Rightarrow 25 = 10\log_{10}\frac{P_o}{P_i}$

$25 = 10\log_{10}\frac{40}{P_i} \Rightarrow P_i = \frac{40}{10^{2.5}} = 126.5\,mW.$

b) ~~A_p~~ $A_V = 40\,dB \Rightarrow 40 = 20\log_{10}\frac{V_o}{V_i}$

$40 = 20\log_{10}\frac{20}{V_i} \Rightarrow 100 = \frac{20}{V_i} \Rightarrow V_i = 200\,mV.$

$P_o = \frac{V_o^2}{R_o}$

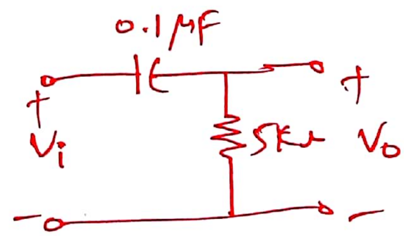
$V_o = \sqrt{P_o R_o} = \sqrt{40\times10}$

$= 20$

(P) For the network shown in fig.

a) Determine Break frequency

b) Find Gain at $A_{V(dB)} = -6\,dB$.



Sol: a) $f_L = \frac{1}{2\pi RC} = \frac{1}{2\pi\times5\times10^3\times0.1\times10^{-6}} = 318.5\,Hz.$

b) $A_{V,dB} = 20\log_{10}\frac{V_o}{V_i}$

$-6 = 20\log_{10}\frac{V_o}{V_i} \Rightarrow 10^{-6/20} = A_V \Rightarrow A_V = 0.501$

$\frac{V_o}{V_i} = 0.501 \Rightarrow V_o = 0.501\,V_i$ (or) approximately 50% of V_i.

UNIT-3

Multistage Amplifiers

Classification of Amplifiers :

The Transistor amplifiers may be classified in several ways such as on the basis of :

1) Transistor configuration used:
   - common Emitter (CE) amplifier
   - common Base (CB) amplifier
   - common collector (CC) amplifier
2) Active device used: BJT amplifiers and FET amplifiers
3) Output: Voltage amplifiers and power amplifiers
4) Input: Small Signal amplifiers and large Signal amplifiers
5) Frequency range of operation:
   - dc amplifiers (from 0 to 10Hz)
   - audio-frequency amplifiers (20Hz to 20KHz)
   - radio-frequency amplifiers (few KHz to hundred of MHz)
6) Bandwidth:
   - Narrowband amplifiers — RF amplifiers (or) tuned amplifiers.
   - Wideband amplifiers — Video amplifiers
7) Number of stages:
   - Single stage amplifiers
   - Multistage amplifiers
     - R-C coupled amplifiers
     - Transformer coupled amplifiers
     - L-C coupled amplifiers
     - Direct-coupled amplifiers

8) Mode of operation:-

This classification depends on the portion of input signal cycle during which collector current is expected to flow.

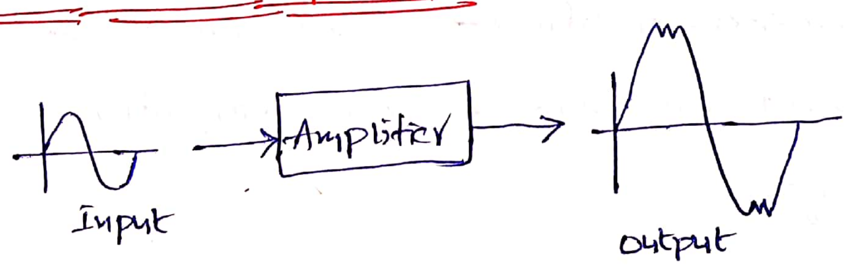
class A:- The operating point and input signal are such that the output collector current flows at all times. This operates over a linear portion of its characteristic.

Class B:- Amplification takes place for only one-half a cycle. The operating point is at an extreme end of its characteristic.

class AB:- The output collector current flows for more than half ~~and~~ but less than entire cycle of input ac signal.

class C:- The output collector current flows for less than half cycle of ac signal.

Distortion in Amplifiers:-



The output waveform of an amplifier is not an exact replica of the input signal waveform because of various types of distortions that may arise, either from nonlinearity in the characteristics of the transistor or from the influence of associated circuit.

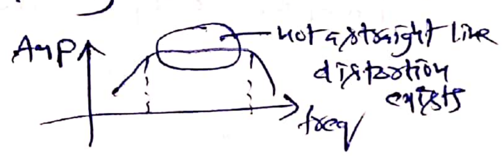
- Non-linear distortion
  - Amplitude distortion
- Linear distortion
  - Frequency distortion
  - phase-shift (or) delay distortion.

1) Amplitude distortion:-

The output collector current, I_c is not a sinusoidal signal. The upper half of the wave is elongated. Since this output current flows through a load resistance, the output Voltage also have nonlinear distortion. Such a distortion produces new frequency components in the output which are not present in input signal. These frequencies are harmonics of the input frequency.

2) Frequency distortion:-

This type of distortion exists when Signal components of different frequencies are amplified differently. This distortion is caused by internal device capacitances. In the plot of amplitude frequency-response characteristic, over a range of frequencies the plot is not a straight line then the circuit exhibit frequency distortion over this range.

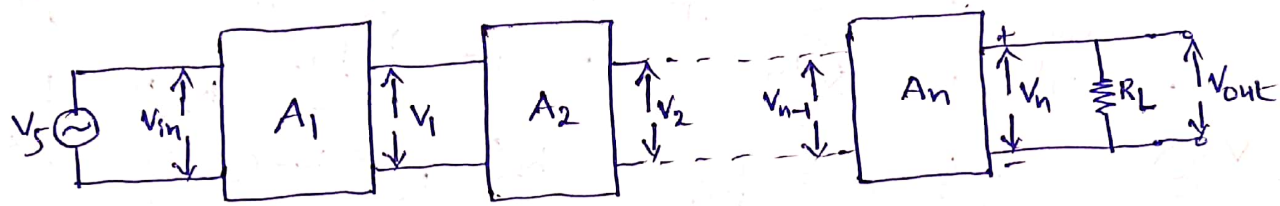


3) phase-shift distortion:-

phase shift distortion results from unequal phase shifts of signals of different frequencies. This is due to the fact that phase angle of complex gain A depends upon the frequency.

Multistage Amplifiers:-

A Transistor circuit containing more than one stage of amplification is known as a multistage amplifier.



A multistage amplifier is represented by a block diagram shown above. The output of first stage makes the input for the second stage, the output of second stage makes the input for third stage and so on.

overall Voltage Gain of amplifier is given as:

$$A_V = \frac{V_{out}}{V_s}$$

$$= \frac{V_1}{V_S} \times \frac{V_2}{V_1} \times \frac{V_3}{V_2} \times \cdots \frac{V_{n-1}}{V_{n-2}} \times \frac{V_n}{V_{n-1}}$$

$$\boxed{A_V = A_{V_1} \times A_{V_2} \times A_{V_3} \times \cdots \times A_{V_{n-1}} \times A_{V_n}}$$

where $A_{V_1}, A_{V_2}, \cdots A_{V_n}$ are Voltage gains of first, second and last stages.

$$20 \log_{10} A_V = 20\log_{10}\left[A_{V_1} \times A_{V_2} \times \cdots \times A_{V_n}\right]$$

$$= 20\log_{10} A_{V_1} + 20\log_{10} A_{V_2} + \cdots + 20\log_{10} A_{V_n}.$$

Gain in dB is $\boxed{A_{VdB} = A_{V_1}dB + A_{V_2}dB + \cdots + A_{V_n}dB.}$

In a multistage amplifier, the output of I^{st} stage is combined to the next stage through a coupling device. The process is known as Cascading. The coupling device is used to i) Transfer ac output of I^{st} to next stage

ii) Block the dc to pass from I^{st} stage to next stage to isolate dc conditions.

Effect of Cascading on Bandwidth:

As we know that, $A_{V_{low,(overall)}} = A_{V_{1low}} A_{V_{2low}} A_{V_{3low}} \cdots A_{V_{nlow}}$

Overall Voltage Gain

at low frequencies is:

As all stages are identical $A_{V_{1low}} = A_{V_{2low}} = A_{V_{3low}}$

$$A_{V_{low}(overall)} = (A_{V_{1low}})^n$$

$$\frac{A_{V_{low}}(overall)}{A_{V_{mid}}} = \left(\frac{A_{V_{low}}}{A_{V_{mid}}}\right)^n = \frac{1}{\left(1 - j\frac{f_L}{f_{Ln}}\right)^n}$$

Magnitude of voltage gain in $\frac{1}{\sqrt{2}}$ (-3 dB level) results in

$$\frac{1}{\sqrt{\left[1+(f_L/f_{Ln})^2\right]^n}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{\left[1+\left(\frac{f_L}{f_{Ln}}\right)^2\right]^n} = \sqrt{2}$$

$$\left[1+\left(\frac{f_L}{f_{Ln}}\right)^2\right]^n = 2$$

$$1+\left(\frac{f_L}{f_{Ln}}\right)^2 = 2^{1/n}$$

$$\left(\frac{f_L}{f_{Ln}}\right)^2 = 2^{1/n} - 1$$

$$\frac{f_L}{f_{Ln}} = \sqrt{2^{1/n} - 1}$$

$$\therefore f_{Ln} = \frac{f_L}{\sqrt{2^{1/n} - 1}}$$

$\therefore$ n^{th} stage low frequency cut-off increases.

At high frequencies:

$$A_{v_{high}}(\text{overall}) = A_{v_1 high}\, A_{v_2 high}\, A_{v_3 high} \cdots A_{v_n high}$$

As all stages are identical: $A_{v_1 high} = A_{v_2 high} = \cdots$

$$A_{v_{high}}(\text{overall}) = (A_{v_1 high})^n$$

$$\frac{A_{v_{high}}}{A_{v_{mid}}}(\text{overall}) = \left(\frac{A_{v_{high}}}{A_{v_{mid}}}\right)^n = \frac{1}{\left(1 + j\frac{f_{Hn}}{f_H}\right)^n}$$

Magnitude of voltage gain is $\frac{1}{\sqrt{2}}$ (-3 dB) result in

$$\frac{1}{\sqrt{\left[1+\left(f_{Hn}/f_H\right)^2\right]^n}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{\left[1+\left(f_{Hn}/f_H\right)^2\right]^n} = \sqrt{2}$$

$$\left[1+\left(\frac{f_{Hn}}{f_H}\right)^2\right]^n = 2$$

$$1+\left(\frac{f_{Hn}}{f_H}\right)^2 = 2^{1/n}$$

$$\left(\frac{f_{Hn}}{f_H}\right)^2 = 2^{1/n} - 1$$

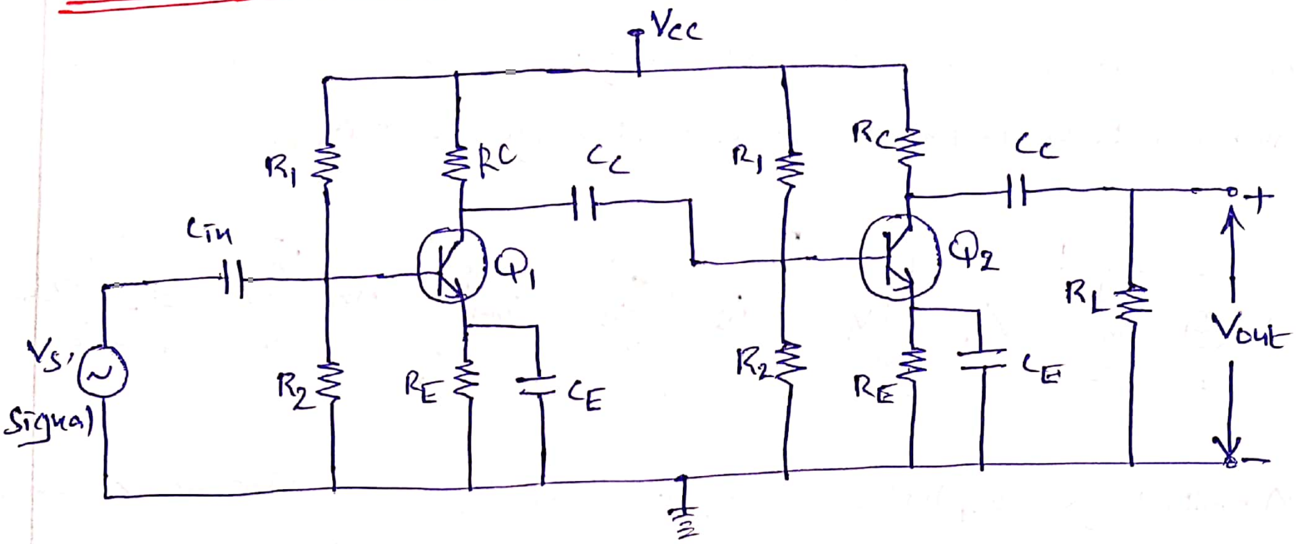
$$\frac{f_{Hn}}{f_H} = \sqrt{2^{1/n} - 1}$$

$$\boxed{f_{Hn} = f_H \sqrt{2^{1/n} - 1}}$$

$\therefore$ n^{th} stage high frequency cut-off decreases.

$\therefore$ Bandwidth of multistage amplifier is $\boxed{BW_n = BW_1 \sqrt{2^{1/n} - 1}}$ and it decreases

RC Coupled Amplifier:-



- A two stage RC coupled amplifiers using NPN transistors in CE configuration is shown in above figure.
- The Resistors R_1, R_2 and R_E form the biasing and stabilization network.
- In this arrangement, the signal developed across 'R_C' (collector Resistor) of first stage is coupled to the base of 2^{nd} stage through the coupling capacitor 'C_C'. such amplifiers are called Resistance-capacitance coupled (or) R-C coupled amplifiers.
- In the absence of C_{in} the signal source will be parallel with R_2 Resistance and bias voltage of base will be affected.
- The Emitter-bypass capacitor C_E, offers a low reactance path to the signal. If it is not present, then voltage drop across R_E will reduce the effective voltage and thus reduces the gain.
- The coupling capacitor "C_C" blocks dc voltage and transmits ac signal to the base of 2^{nd} stage. and dc biasing of next stage is not interfered. For this reason, the coupling capacitor "C_C" is also called the "blocking capacitor."

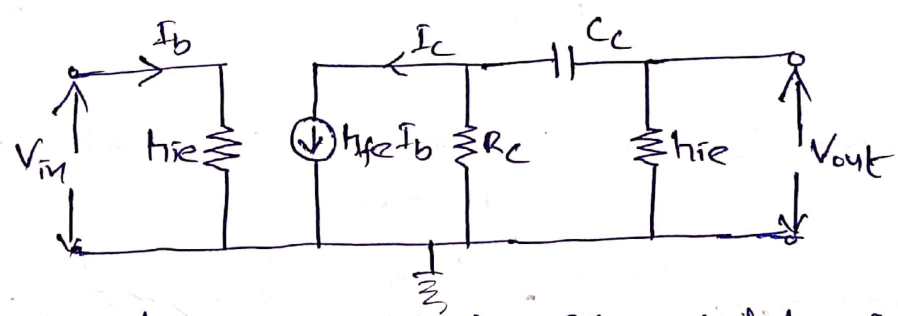
Operation:

When an ac signal is applied to the base of amplifier, it appears in amplified form across collector load 'R_C'. This amplified signal is transmitted to next stage through coupling capacitor 'C_C'. This is further amplified by the next stage and so on. Thus the cascade stages amplify the signal and thus the overall gain is considerably increased.

The phase of output is the same as that of input because the phase is reversed twice by two transistors as they are in CE configuration.

Analysis:

For drawing approximate model of the R-C coupled amplifier circuit shown in above figure the following assumptions are made.



Approximate model of an RC-coupled Amplifier

i) h_{re} is so small that $h_{re}V_{out}$ can be neglected

ii) $\frac{1}{h_{oe}}$ is so large and it is open circuited.

iii) The bias resistors R_1 & R_2 are very large in comparison to h_{ie}

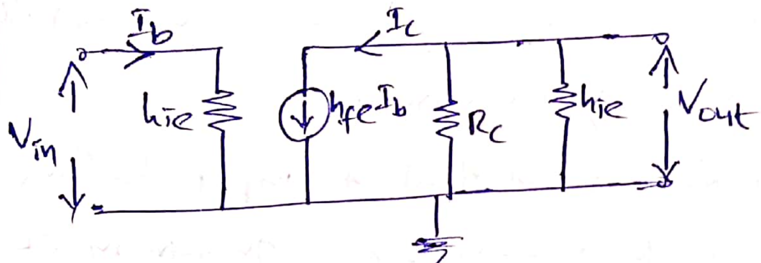
iv) The Reactance of Emitter-bypass capacitor C_E for any given input frequency is so small that $R_E \| C_E$ can be considered as short-circuit.

For the purpose of analysis the entire frequency range may be divided into the following three categories.

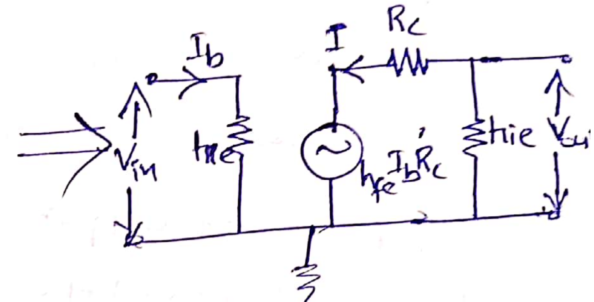
a) Mid-Frequency Range:-

At mid frequencies, the impedance offered by coupling capacitor C_c is so small that it is short circuited and can be neglected.

$$X_{C_C} = \frac{1}{j2\pi f C_c} = \frac{1}{\infty} = 0 \text{ (short)}$$



Equivalent circuit for Mid-frequency



Thevenin's Equivalent circuit

From Thevenin's Equivalent circuit:

current, $I = \dfrac{h_{fe} I_b R_c}{R_c + h_{ie}}$ $\Rightarrow$ current Gain, $\boxed{A_I = \dfrac{I}{I_b} = \dfrac{h_{fe} R_c}{R_c + h_{ie}}}$

output Voltage, $V_{out} = h_{ie} I = \dfrac{h_{ie} h_{fe} I_b R_c}{R_c + h_{ie}}$; Input Voltage, $V_i = h_{ie} I_b$

Voltage Gain, $A_V = \dfrac{V_{out}}{V_{in}} = \dfrac{\cancel{h_{ie}} h_{fe} \cancel{I_b} R_c / (R_c + h_{ie})}{\cancel{h_{ie}} \cancel{I_b}} \Rightarrow \boxed{A_V = \dfrac{h_{fe} R_c}{R_c + h_{ie}}}$

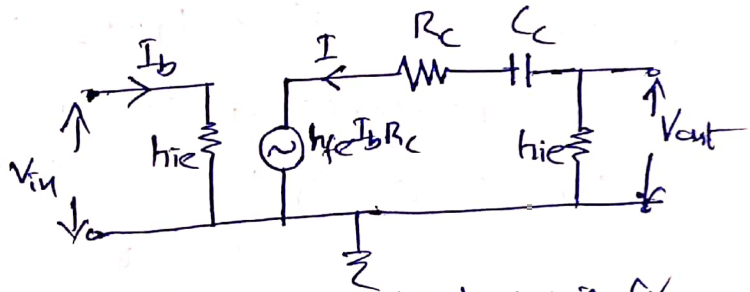
From the two equations A_I & A_V are equal.

b) Low-frequency Range:-

In low-frequency range,

$$X_{C_C} = \frac{1}{j2\pi f \cdot C_c} = \frac{1}{0} = \infty$$

$\therefore$ C_c largely affects current amplification $\therefore$ It is included in the circuit.



Thevenin's Equivalent circuit for low-frequency range

From Thevenin's Equivalent circuit;

$$\text{current, } I = \frac{h_{fe} I_b R_C}{h_{ie} + R_C + \frac{1}{j\omega C_C}} \Rightarrow \text{current gain, } \boxed{A_I = \frac{I}{I_b} = \frac{h_{fe} R_C}{h_{ie} + R_C - \frac{j}{\omega C_C}}}$$

output voltage, $V_{out} = h_{ie} I$

$$= \frac{h_{ie} h_{fe} I_b R_C}{h_{ie} + R_C + \frac{1}{j\omega C_C}} \quad ; \text{ Input voltage, } V_i = h_{ie} I_b$$

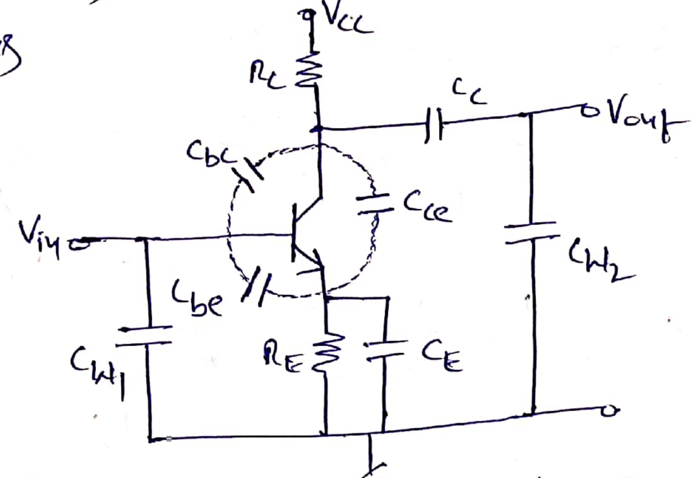
$$\text{Voltage gain, } A_V = \frac{V_{out}}{V_{in}} = \frac{\cancel{h_{ie}} h_{fe} \cancel{I_b} R_C}{h_{ie} + R_C - \frac{j}{\omega C_C}} \Big/ \cancel{h_{ie} I_b} \Rightarrow \boxed{A_V = \frac{h_{fe} R_C}{h_{ie} + R_C - \frac{j}{\omega C_C}}}$$

In the low-frequency range voltage gain decreases with decrease in frequency.

c) High-Frequency Range :-

- In high Frequency Range the Reactance offered by coupling capacitor C_C is $X_{C_C} = \frac{1}{j2\pi f C_C} = \frac{1}{\infty} = 0$ Very small and it is shorted.

- At high frequencies inter-electrode capacitances comes into existance and these capacitances are due to formation of depletion layers at the junctions and are shown by dotted lines.



RC coupled amplifier at high frequencies

- C_{bc} connects output with input and provide negative feedback in circuit then gain is reduced.
- C_{be} offers low impedance path at input side at high frequencies reducing input impedance and reducing input signal thus gain falls.

- C_{ce} capacitance produces a shunting effect at high frequencies on the output side.

C_{bc} is most important capacitance because feedback takes place from output circuit to input circuit through this capacitance and this is known as "Miller Effect".

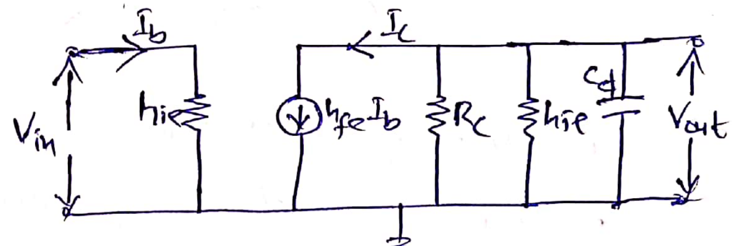
- Besides these inter-electrode capacitances there are wiring capacity C_{W_1} & C_{W_2} shown in the figure. These are the capacitances between the connecting wires of the circuit and ground.
- C_{bc} & C_{be} are replaced with single capacitor 'C_d' across the input resistance 'h_{ie}' of transistor.
- The value of C_d is small at input of first stage because it depends on the output impedance of first transistor, which is small.
- But in output circuit of I^{st} stage 'C_d' is increased by stray capacitance of wiring. The reactance $\left(\frac{1}{\omega C_d}\right)$ will have shunting effect on R_c & h_{ie}.

The equivalent circuits are:

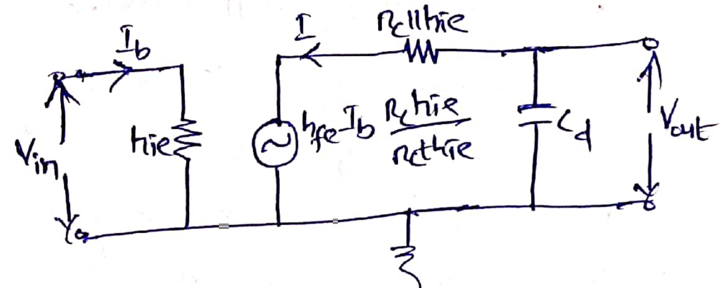
$$\text{Current, } I = \frac{h_{fe} I_b \dfrac{R_c h_{ie}}{R_c + h_{ie}}}{\dfrac{R_c h_{ie}}{R_c + h_{ie}} + \dfrac{1}{j\omega C_d}}$$

$$= \frac{h_{fe} I_b R_c h_{ie}}{R_c h_{ie} + \dfrac{R_c + h_{ie}}{j\omega C_d}}$$

$$\boxed{\text{Current Gain } A_I = \frac{I}{I_b} = \frac{h_{fe} R_c h_{ie}}{h_{ie} R_c + \dfrac{R_c + h_{ie}}{j\omega C_d}}}$$



Equivalent circuit for high frequency range



Thevenin's equivalent circuit

Output voltage, $V_{out} = I \times \frac{1}{j\omega C_d} = \frac{h_{fe} h_{ie} I_b R_c}{R_c h_{ie} + \frac{R_c + h_{ie}}{j\omega C_d}} \times \frac{1}{j\omega C_d}$

$$V_{out} = \frac{h_{fe} h_{ie} I_b R_c}{R_c h_{ie} j\omega C_d + R_c + h_{ie}}$$

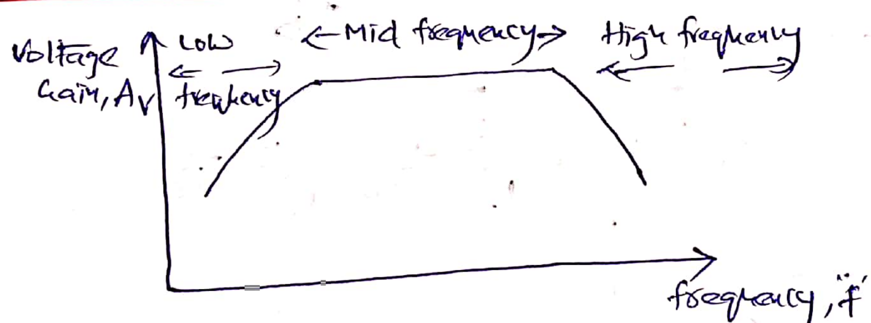
Input voltage, $V_{in} = h_{ie} I_b$.

Voltage Gain, $A_V = \frac{V_{out}}{V_{in}} = \frac{h_{fe} \cancel{h_{ie}} \cancel{I_b} R_c}{R_c h_{ie} j\omega C_d + R_c + h_{ie}} \Big/ \cancel{h_{ie} I_b}$

$$\boxed{A_V = \frac{h_{fe} R_c}{R_c h_{ie} j\omega C_d + R_c + h_{ie}}}$$

With increase in input frequency the magnitude of voltage gain falls.

Frequency Response curve :-



Advantages :-

- Excellent frequency response i.e, constant gain over the audio-frequency range (20-20kHz), the region for speech, music etc.
- Cheaper in cost
- Compact circuit (light resistors & capacitors)

Disadvantages :-

- Low voltage & power gains

Applications :-

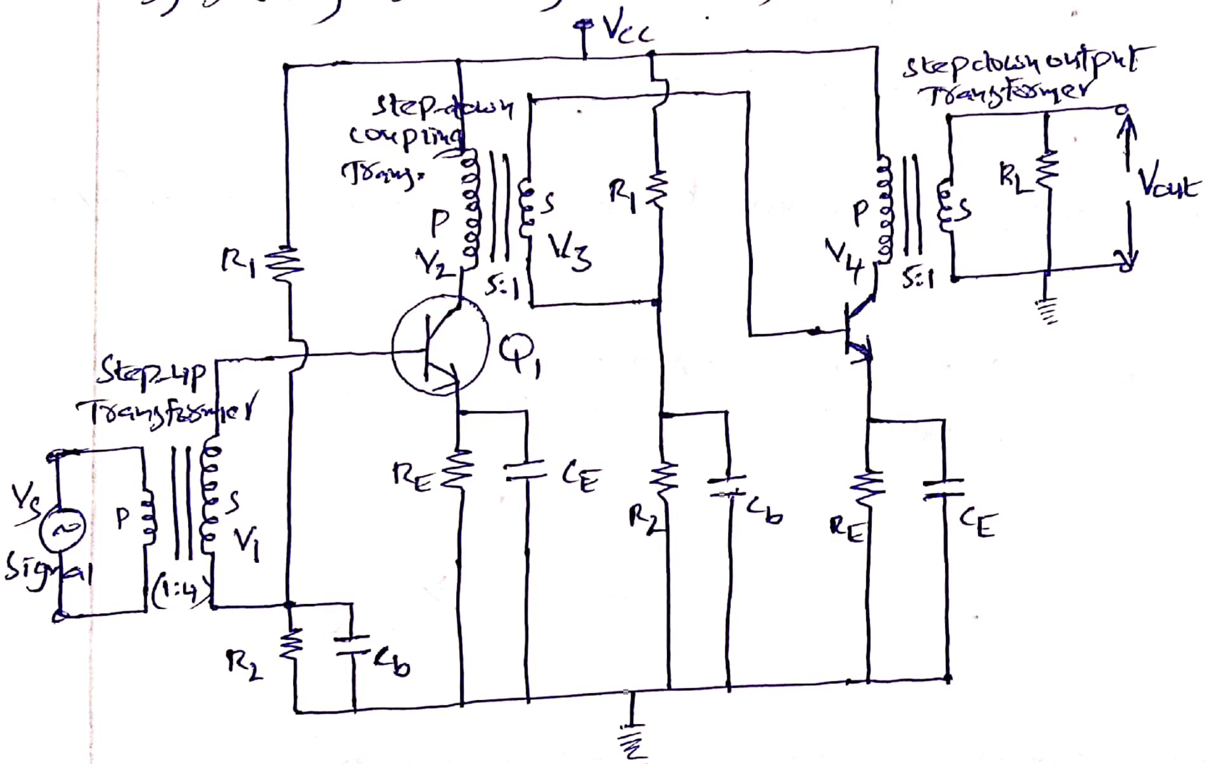
- Used as voltage amplifiers in the initial stages of public address systems. Because of poor impedance matching, this coupling is rarely employed in final stages.

Transformer Coupled Transistor Amplifier:-

- The main cause for low voltage and power gains of an R-C coupled amplifier is that the effective load of each stage is reduced due to low input impedance and high output impedance of an amplifier.

$$\underset{(\text{low})}{R_i} \parallel \underset{(\text{high})}{R_o} = \text{Low Value.}$$

This drawback has been overcome in a transformer-coupled amplifier by suitably selecting the turns ratio of transformer.



- A two stage Transformer coupled amplifier in CE configuration is shown in above figure.
- An AC signal is passed to stepup transformer to increase voltage level while step down transformers are used between stages so as to match the loading of each stage to the output impedance of preceding stage. This can be achieved by proper selection of turns-ratio of step-down coupling transformer.

From the circuit we have:

$$\frac{V_1}{V_s} = \frac{N_2}{N_1} \Rightarrow V_1 = \frac{N_2}{N_1} V_s$$

Voltage Gain for I^{st} stage, $A_{V_1} = \frac{V_2}{V_1} = \frac{-h_{fe} Z_L}{h_{ie}}$ $\left(\because A_V = \frac{A_I R_L}{R_S}\right)$

$$A_{V_1} = \frac{-h_{fe}\left(\frac{1}{h_{oe}} \| Z_2\right)}{h_{ie}}$$

Voltage gain fo 2^{nd} stage, $A_{V_2} = \frac{V_4}{V_3} = \frac{-h_{fe} Z_L}{h_{ie}}$

output voltage, $\frac{V_{out}}{V_4} = \frac{N_2}{N_1} \Rightarrow V_{out} = \frac{N_2}{N_1} V_4$.

$\therefore$ overall Voltage Gain; $A_V = \frac{V_{out}}{V_s}$.

~~Frequency Response:-~~

$$\frac{V_1}{V_s} = \frac{N_2}{N_1} \;\&\; \frac{I_1}{I_s} = \frac{N_1}{N_2} \;\&\; n = \frac{n_2}{n_1}$$

= turns ratio

$$\frac{V_s}{V_1} = \frac{1}{n} \;\&\; \frac{I_s}{I_1} = n \Leftarrow \frac{V_1}{V_s} = n \;\&\; \frac{I_1}{I_s} = \frac{1}{n}$$

$$\frac{\frac{V_s}{V_1}}{\frac{I_s}{I_1}} = \frac{1}{n^2} \Rightarrow \frac{V_s}{I_s} = \frac{1}{n^2} \times \frac{V_1}{I_1} \qquad \frac{\frac{V_1}{V_s}}{\frac{I_1}{I_s}} = \frac{\frac{1}{n}}{n} \Rightarrow \frac{V_1}{I_1} = \frac{1}{n^2}\frac{V_s}{I_s}$$

$$\boxed{R_s = \frac{1}{n^2} R_L}$$

input resistance　　output resistance.

Frequency Response :-

- Frequency Response of Transformer coupled Amplifier is very poor and gain is constant over a small range of frequency.
- output voltage, $V_{out} = I_c \times X_p$ (X_p - leakage reactance of primary winding)

At low frequency X_p drops and gain is reduced.

At high frequency, the inter winding capacitances give rise to a resonance phenomenon at some frequency and makes gain of the amplifier very high at this frequency. There will be a disproportionate amplification of frequencies in complete signal.

Advantages :-

- lower dc resistance at collector results in lower dc power loss
- provides excellent impedance matching

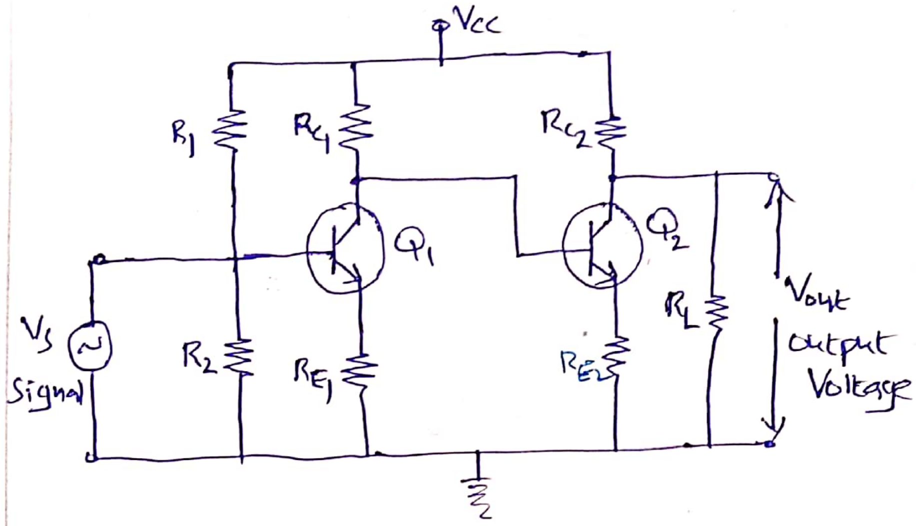
Disadvantages :-

- poor frequency response
- Bulky & costly
- Introduce hum in the output

Applications :-

- widely used for amplifying radio-frequency (above 20kHz) signals.

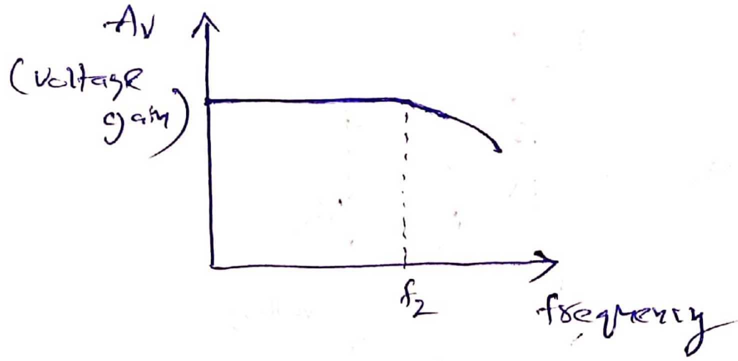
Direct Coupled Transistor Amplifier



- Direct coupling is essential for very low frequency (below 10Hz) applications such as photoelectric current, thermocouple current etc.
- At low frequency coupling capacitors C_c cause ~~sig~~ voltage drop of signal across them and reduces gain. $\left(X_{C_c} = \frac{1}{2\pi f C_c} = \frac{1}{0} = \infty \right)$
  C_E Emitter bypass capacitor become comparable with R_E and bypassing action of capacitor is affected.
- If these C_c & C_E & C_B are to be used in circuit then large value of capacitors are to be used and such capacitors are expensive and are large in size.
  To avoid this, one stage is directly coupled connected to the next stage without intervening any coupling device. Such a coupling is called the "Direct coupling" and the amplifier using such a coupling is called "direct coupled amplifier".

Frequency Response :-

It has no coupling and bypass capacitor to causes drop at low frequencies. The frequency response curve is flat upto upper cutoff frequency f_2. Above this, the gain decreases due to inter-electrode capacitances of device and wiring capacitance.



Advantages:-

- Simple circuit
- Very cheap in cost
- Amplify very low frequency signals
- flat frequency response curve upto upper cutoff frequency.

Disadvantages:-

- Not suitable for amplification of high frequency signals
- poor temperature stability.

Applications:-

- Headphones, loud speakers.
- pulse amplifiers, differential amplifiers, computer circuitry, regulator circuits of electronic power supplies.

Approximate Conversion Formulas for hybrid parameters:-

$h_{ic} = h_{ie}$

$h_{fc} = -(1+h_{fe})$

$h_{rc} = 1$

$h_{oc} = h_{oe}$

$$h_{ib} = \frac{h_{ie}}{1+h_{fe}}$$

$$h_{fb} = \frac{-h_{fe}}{1+h_{fe}}$$

$$h_{rb} = \frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$$

$$h_{ob} = \frac{h_{oe}}{1+h_{fe}}$$

$$h_{ie} = \frac{h_{ib}}{1+h_{fb}}$$

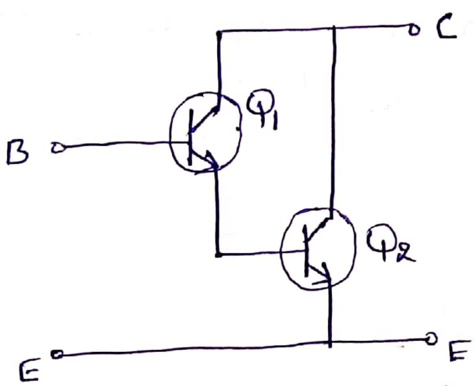
$$h_{fe} = \frac{-h_{fb}}{1+h_{fb}}$$

$$h_{oe} = \frac{h_{ob}}{1+h_{fb}}$$

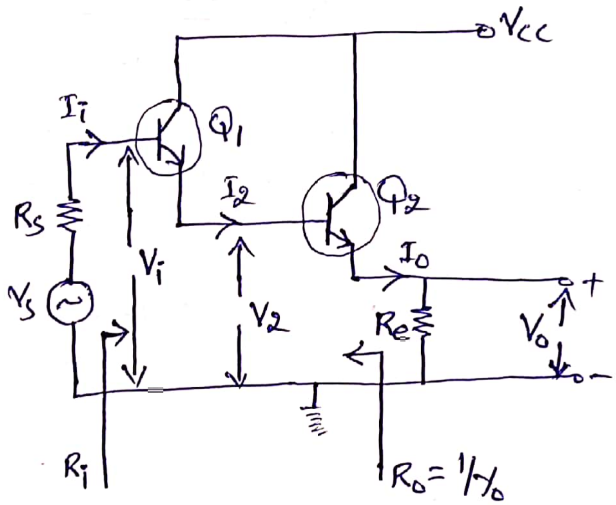
$$h_{re} = \frac{h_{ib}h_{ob}}{1+h_{fb}} - h_{rb}$$

Darlington pair :- (High input resistance transistor circuits) :-

- In some applications the need arises for an amplifier with a high input impedance. For input ~~impe~~ resistances $R_i < 500k\Omega$, the Emitter follower is used.
- To achieve larger input impedances, the "Darlington Connection" is used in Electronics.
- Darlington circuit consists of two cascaded Emitter followers with infinite emitter resistance in the first stage. ($R_{e_1} = \infty$):



a) Darlington pair



b) Darlington Emitter Follower

- The Analysis is done by considering figure ⓑ and assuming that

$$h_{oe} R_e \le 0.1 \quad \text{and} \quad h_{fe} R_e >> h_{ie}$$

For 2nd stage :-

Current Gain, $A_{I2} = \dfrac{I_O}{I_2} \approx 1 + h_{fe}$ (From Simplified CC amplifier hybrid analysis)

Input Resistance, $R_{I2} = h_{ie} + (1+h_{fe}) R_L$ ($\because R_I = h_{ic} + A_I R_L h_{rc}$, $h_{rc} = 1$, $h_{ic} = h_{ie}$)

$= h_{ie} + (1+h_{fe}) R_e$ (Since output load is R_e)

$$\boxed{R_{I2} \simeq (1+h_{fe}) R_e}$$

Voltage gain, $A_{V_2} = \frac{A_I R_L}{R_i} = \frac{A_{I2} R_e}{R_{I2}}$

$$1 - A_{V_2} = 1 - \frac{A_{I2} R_e}{R_{I2}}$$

$$= \frac{R_{I2} - A_{I2} R_e}{R_{I2}} = \frac{h_{ie} + \cancel{A_{I2} R_e} - \cancel{A_{I2} R_e}}{R_{I2}} = \frac{h_{ie}}{R_{I2}}$$

$$\boxed{A_{V_2} = 1 - \frac{h_{ie}}{R_{I2}}}$$

output Resistance, $R_{O2} = \frac{R_s + h_{ie}}{1+h_{fe}}$

where R_s' is output resistance of 'Q_1' transistor i.e, stage 1 which also act like input to 'Q_2' transistor.

$$\therefore R_{O2} = \frac{R_{O1} + h_{ie}}{1+h_{fe}}$$

$$\therefore R_{O1} = \frac{R_s + h_{ie}}{1+h_{fe}}.$$

$$R_{O2} = \frac{\frac{R_s + h_{ie}}{1+h_{fe}} + h_{ie}}{1+h_{fe}}$$

$$\left[Y_o = h_{oc} - \frac{h_{fc} h_{rc}}{R_s + h_{ic}} \right]$$

$$= h_{oe} - \frac{-(1+h_{fe}) \times 1}{R_s + h_{ie}}$$

$$= h_{oe} + \frac{1+h_{fe}}{R_s + h_{ie}}$$

$$Y_o = \frac{1+h_{fe}}{R_s + h_{ie}} \ ; \ R_o = \frac{R_s + h_{ie}}{1+h_{fe}}$$

$$\boxed{R_{O2} = \frac{R_s + h_{ie}}{(1+h_{fe})^2} + \frac{h_{ie}}{(1+h_{fe})}} \longrightarrow (1)$$

For I^{st} stage:-

since the effective load for transistor 'Q_1' is R_{i2}, which does not meet the requirement $h_{oe} R_{i2} \leq 0.1$ and therefore we use exact expressions for current gain of I^{st} transistor $\left[\because h_{oe} R_L = h_{oe} R_{i2} = h_{oe} (1+h_{fe}) R_e \gg 1 \right]$

current gain, $A_{I1} = \frac{I_2}{I_i} = \frac{-h_f}{1+h_o R_L} = \frac{-h_{fc}}{1+h_{oc} R_L} = \frac{1+h_{fe}}{1+h_{oe} R_{i2}}$ [From conversion table]

$$A_{I1} = \frac{1+h_{fe}}{1+h_{oe}(1+h_{fe}) R_e} \qquad \left[\because R_{i2} \approx (1+h_{fe}) R_e \right]$$

$$= \frac{1+h_{fe}}{1+h_{oe} R_e + h_{oe} h_{fe} R_e} \Rightarrow \boxed{A_{I1} \approx \frac{1+h_{fe}}{1+h_{oe} h_{fe} R_e}} \qquad \left[\because h_{oe} R_e \leq 0.1 \right]$$

$R_{I1} = h_i + h_r A_I R_L$

Input resistance, $R_{I1} = h_{ie} + A_I R_L h_{rc}$

$= h_{ie} + A_{I1} R_{I2}$ $\quad [\because h_{rc} = 1]$

$h_{ic} = h_{ie}$

$= h_{ie} + \left(\dfrac{1+h_{fe}}{1+h_{oe} h_{fe} R_e}\right)(1+h_{fe}) R_e.$

$= h_{ie} + \dfrac{(1+h_{fe})^2 R_e}{1+h_{oe} h_{fe} R_e}$

$$\boxed{R_{I1} \approx \frac{(1+h_{fe})^2 R_e}{1+h_{oe} h_{fe} R_e}} \longrightarrow (2)$$

Input Resistance is very much larger than that of single stage CC amplifier

Voltage gain, $A_{V_1} = \dfrac{A_I R_L}{R_i}$

$= \dfrac{A_{I1} R_{I2}}{R_{I1}}$

$1 - A_{V_1} = 1 - \dfrac{A_{I1} R_{I2}}{R_{I1}} = \dfrac{R_{I1} - A_{I1} R_{I2}}{R_{I1}} = \dfrac{h_{ie} + \cancel{A_{I1} R_{I2}} - \cancel{A_{I1} R_{I2}}}{R_{I1}}$

$$\boxed{A_{V_1} = 1 - \frac{h_{ie}}{R_{I1}}} \boxed{= 1 - \frac{h_{ie}}{A_{I1} R_{I2}}}$$

Output Resistance, $\boxed{R_{O1} = \dfrac{R_s + h_{ie}}{1+h_{fe}}}$

Overall :-

Overall current gain, $A_I = \dfrac{I_o}{I_i} = \dfrac{I_o}{I_2} \times \dfrac{I_2}{I_i} = A_{I2} \times A_{I1} = (1+h_{fe})\left(\dfrac{1+h_{fe}}{1+h_{oe} h_{fe} R_e}\right)$

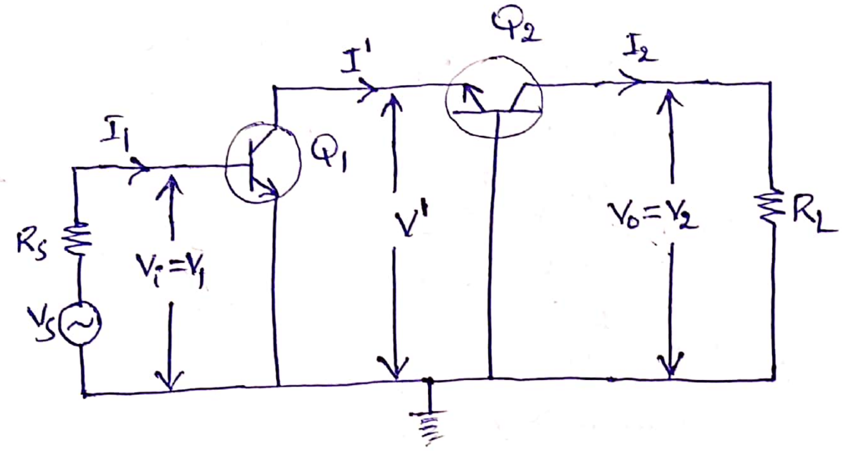
$$\boxed{A_I \approx \frac{(1+h_{fe})^2}{1+h_{oe} h_{fe} R_e}.} \longrightarrow (3)$$

Overall Voltage Gain, $A_V = \dfrac{V_o}{V_i} = \dfrac{V_o}{V_2} \times \dfrac{V_2}{V_i} = A_{V_2} \times A_{V_1} = \left(1 - \dfrac{h_{ie}}{R_{i2}}\right)\left(1 - \dfrac{h_{ie}}{A_{I1} R_{i2}}\right)$

$$\boxed{A_V \approx 1 - \frac{h_{ie}}{R_{i2}}} \rightarrow (4) \quad (\because A_{I1} R_{i2} >> R_{i2})$$

From (1), (2), (3) & (4) equations Darlington Emitter Follower has high current gain, high input resistance, voltage gain close to unity and lower output resistance than single CC Amplifier

Cascode Amplifier :-



- The cascode transistor configuration shown in above figure consists of a CE stage in series with a CB stage.
- Transistors Q_1 and Q_2 in cascode act like a single CE transistor with negligible internal feedback (negligible h_{re}) and very small output conductance for an open-circuited input.
- To verify the above statement let us compute the h-parameters of the $Q_1 - Q_2$ combination.

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2 .$$

i) $h_{11} = \frac{V_1}{I_1} \Big|_{V_2 = 0}$

If $V_2 = 0$, then load of Q_1 consists h_{ib2} (a small value). Hence transistor Q_1 is effectively short-circuited

$\therefore \boxed{h_{11} \approx h_{ie}}$

ii) $h_{21} = \frac{I_2}{I_1} \Big|_{V_2 = 0}$

$$= \frac{I_2}{I'} \times \frac{I'}{I_1} = -h_{fb} h_{fe} \approx h_{fe} \quad (\because -h_{fb} = 1)$$

$\therefore \boxed{h_{21} \approx h_{fe}}$

iii) $h_{22} = \frac{I_2}{V_2} \Big| I_1 = 0$

If $I_1 = 0$, the output resistance of Q_1 is equal to $\frac{1}{h_{oe}}$, hence equivalent source resistance for transistor Q_2 is $\frac{1}{h_{oe}}$ and output conductance of Q_2 transistor is h_{ob}

$$\boxed{h_{22} = \frac{1}{R_o} \approx h_{ob}}$$

iv) $h_{12} = \frac{V_1}{V_2} \Big| I_1 = 0$

$$= \frac{V_1}{V'} \times \frac{V'}{V_2} \approx h_{re} h_{rb}$$

$$\boxed{h_{12} \approx h_{re} h_{rb}}$$

Typical h-parameter values of transistors

parameter	CE	CC	CB
$h_i = h_{11}$	1100	1100	21.6
$h_r = h_{12}$	2.5×10^{-4}	~ 1	2.9×10^{-4}
$h_f = h_{21}$	50	-51	-0.98
$h_o = h_{22}$	$24 \mu A/V$	$25 \mu A/V$	$0.49 \mu A/V$
$R_o = 1/h_o$	40K	40K	2.04 M

Using h-parameter values we have

$h_i = h_{11} \approx h_{ie} = 1100 \, \Omega$

$h_f = h_{21} = h_{fb} h_{fe} = 0.98 \times 50 = 49 \approx h_{fe}$

$h_o = h_{22} = h_{ob} = 0.49 \, \mu A/V$

$h_r = h_{12} = h_{re} h_{rb} = 2.5 \times 10^{-4} \times 2.9 \times 10^{-4} = 7.25 \times 10^{-8}$

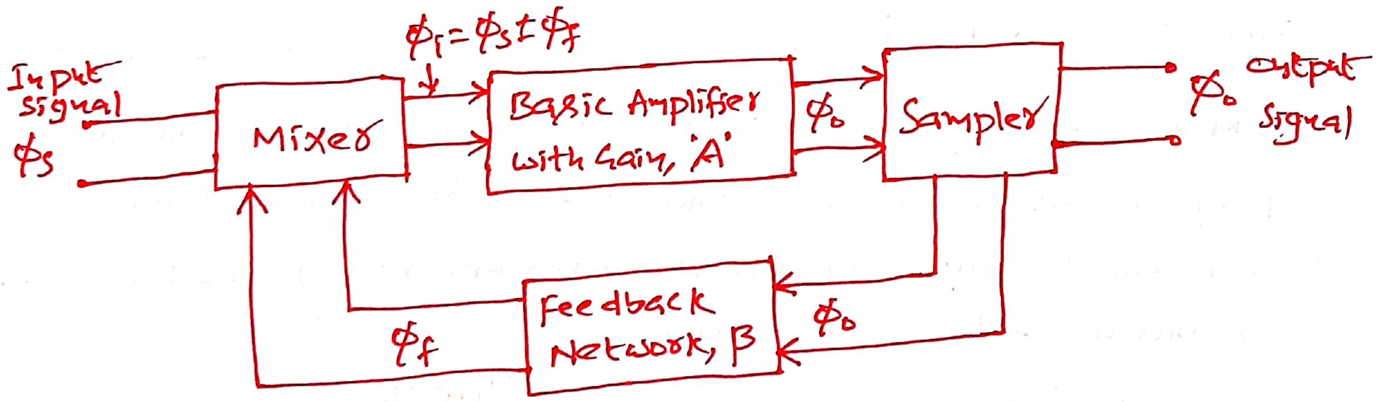
- Note that input resistance and current gain are nominally equal to the corresponding parameter values for a single CE stage.
- The small value of h_r for the cascode transistor pair makes this circuit particularly useful in tuned-amplifier design.
- The reduction in the "internal feedback" of the compound device reduces the probability of oscillation and results in improved stability of the circuit.

FEEDBACK AMPLIFIERS

Concept of Feedback:-

In large signal amplifiers and electronic measuring instruments, the major problem of distortion should be avoided and the gain must be independent of external factors such as variation in the voltage of the d.c supply and the values of circuit components. All this can be achieved by feedback.

A portion of output signal is taken from the output of the amplifier and is combined with the normal input signal and thereby the feedback is accomplished.

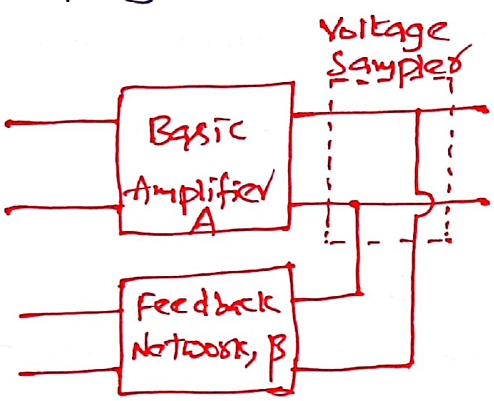


Block diagram of an amplifier with feedback

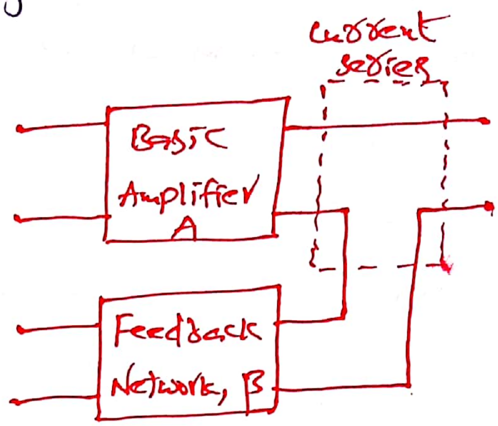
Feedback Network:- This block is a passive two-port network which may contain resistors, capacitors and inductors. Most often it is simply a resistive configuration.

Sampling Network (or) Sampler:- The output voltage is sampled by connecting the feedback network in shunt across the output. This type of connection is referred to as voltage sampling which is shown in fig. below:

Another feedback connection which samples the output current where the feedback network is connected in series with the output. This type of connection is referred to as current sampling which is shown in figure below:

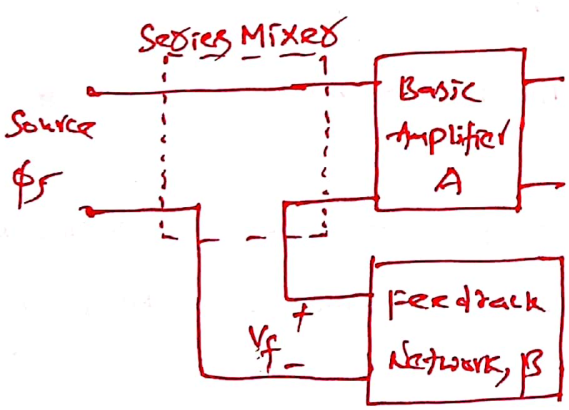


Voltage Sampling

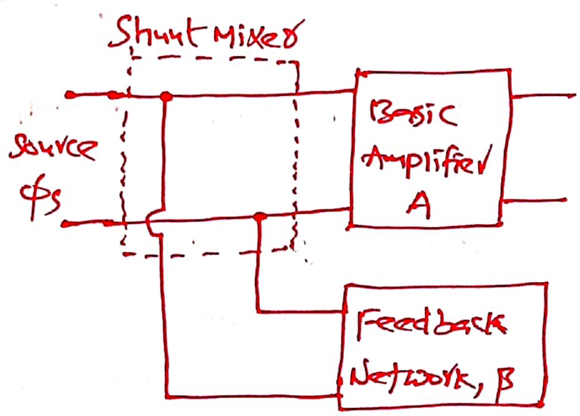


Current Sampling

Mixer (or) Comparator: A differential amplifier is also used as a mixer. Such an amplifier has two inputs and gives an output proportional to the difference between the signals at the two inputs. There are two types of mixers series mixer and shunt mixer which are shown in the figure below.



Series Input



Shunt Input

Mixer also known as comparator, is of two types, namely, series mixer and shunt mixer.

Gain of Basic amplifier — $A = \frac{\phi_o}{\phi_i}$

Feedback ratio — $\beta = \frac{\phi_f}{\phi_o}$

Gain of the Feedback amplifier — $A_f = \frac{\phi_o}{\phi_s}$

where ϕ_s is a.c. signal in the input side (current or voltage)

ϕ_f is feedback signal (current or voltage)

There are two types of feedback

- positive feedback
- Negative feedback

i) positive feedback:-

If the feedback signal 'ϕ_f' is "inphase" with input signal 'ϕ_s', then the net effect of the feedback will increase the input signal given to the amplifier.

i.e; $\phi_i = \phi_s + \phi_f$

Hence, the input voltage applied to the basic amplifier is increased thereby increasing ϕ_o exponentially. This type of feedback is said to be "positive or Regenerative feedback".

Gain of Amplifier with positive feedback is : $A_f = \frac{\phi_o}{\phi_s} = \frac{\phi_o}{\phi_i - \phi_f}$

$$A_f = \frac{1}{\frac{\phi_i}{\phi_o} - \frac{\phi_f}{\phi_o}} = \frac{1}{\frac{1}{A} - \beta} = \frac{A}{1-A\beta}$$

$$\therefore \boxed{A_f = \frac{A}{1-A\beta}} \qquad \because A = \frac{\phi_o}{\phi_i}$$. is called openloop gain.

Here $|A_f| > |A|$.

The product of open loop gain and feedback factor is called "Loop Gain", i.e; loop Gain $= A\beta$.

If $|A\beta| = 1$; $A_f = \infty$.

Hence, the gain of amplifier with positive feedback is infinite and the amplifier gives an a.c. output with out a.c. input signal. Thus amplifier acts as an "oscillator."
the positive feedback increases the instability of an amplifier, which reduces the bandwidth and increases the distortion and noise.

ii) Negative feedback:-

If the feedback signal ϕ_f is out of phase with the input signal ϕ_s, then

$$\phi_i = \phi_s - \phi_f$$

The input Voltage applied to basic amplifier is decreased and correspondingly the output is decreased. Hence, the Voltage gain is reduced. This type of feedback is known as "negative or degenerative feedback".

Gain of amplifier with negative feedback is : $A_f = \frac{\phi_o}{\phi_s}$

$$A_f = \frac{\phi_o}{\phi_i + \phi_f} = \frac{1}{\frac{\phi_i}{\phi_o} + \frac{\phi_f}{\phi_o}} = \frac{1}{\frac{1}{A} + \beta} = \frac{A}{1+A\beta}.$$

$$\boxed{A_f = \frac{A}{1+A\beta}}$$

Here, $|A_f| < |A|$.

If $|A\beta| \gg 1$, then $\boxed{A_f \approx \frac{1}{\beta}}$.

Thus the gain depends entirely on feedback network.

Negative feedback keeps operating point constant in the case of change in temperature (or) h_{fe} (or) β of a transistor.

Negative feedback helps to increase the bandwidth, decrease distortion and noise and also used to improve the performance of electronic amplifiers.

General characteristics of Negative feedback Amplifiers :-

i) Stability of gain :-

~~Stability of~~ The gain of amplifier with negative feedback is

$$A_f = \frac{A}{1+A\beta}$$

Differentiating w.r.t to 'A'
$$\frac{dA_f}{dA} = \frac{(1+A\beta) - A(\beta)}{(1+A\beta)^2} = \frac{1}{(1+A\beta)} \cdot \frac{1}{(1+A\beta)}$$

$$= \frac{A_f}{A} \times \frac{1}{(1+A\beta)} \qquad \Big| \because \frac{1}{1+A\beta} = \frac{A_f}{A}.$$

$$\frac{dA_f}{A_f} = \frac{dA}{A} \times \frac{1}{(1+A\beta)}$$

$\frac{dA_f}{A_f}$ represents fractional change in amplifier voltage gain with feedback

$\frac{dA}{A}$ represents fractional change in voltage gain without feedback

$\frac{1}{1+A\beta}$ is called "sensitivity".

$$\text{Sensitivity} = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}} = \frac{1}{1+A\beta}.$$

Reciprocal of sensitivity is called "Desensitivity" i.e; $= (1+A\beta)$.

ii) Increase of Bandwidth :-

$$B.W = \underset{(\text{upper})}{f_2} - \underset{(\text{Lower})}{f_1}$$

The product of voltage gain and bandwidth of an amplifier without feedback and with feedback remains the same, i.e;

$$A_f \times B.W_f = A \times B.W$$

As voltage gain of Negative feedback amplifier reduces by the factor $\frac{1}{1+A\beta}$, its Band width would be increased by $(1+A\beta)$, i.e;

$$\boxed{BW_f = (1+A\beta)\, BW.}$$

upper cut-off frequency $f_{2f} = (1+A\beta) f_2$ &

lower cut-off frequency $f_{1f} = \frac{f_1}{(1+A\beta)}$

iii) Decreased distortion:-

Consider an amplifier with an open loop voltage gain and a total harmonic distortion 'D'.

For negative feed back the distortion is $\boxed{D_f = \frac{D}{1+A\beta}.}$

iv) Decreased Noise:-

Noise 'N' for Negative feedback amplifier is reduced by a factor of $1/(1+A\beta)$.

i.e; $\boxed{N_f = \frac{N}{(1+A\beta)}}$

v) Increase in Input Impedance:-

The input Impedance with feedback is given by

$$\boxed{Z_{if} = Z_i(1+A\beta).}$$

vi) Decrease in output Impedance:

$$Z_{of} = \frac{Z_o}{(1+A\beta)}.$$

(P1) An Amplifier has an open-loop gain of 1000 and a feedback ratio of 0.04. If the open-loop gain changes by 10% due to temperature, find the percentage change in gain of the amplifier with feedback.

Sol

$A = 1000.$

$\beta = 0.04$

$\frac{dA}{A} = 10\% \quad \frac{10}{100} = 0.1$

$$\frac{dA_f}{A_f} = \frac{dA}{A} \times \frac{1}{(1+A\beta)}$$

$$= \frac{10}{1+40} = 0.25\%. = 0.0025$$

(P2) An Amplifier has voltage gain with feedback is 100. If the gain without feedback changes by 20% and the gain with feedback should not vary more than 2%, determine the values of open loop gain 'A' and feedback ratio 'β'.

Sol

$A_f = 100$

$\frac{dA}{A} = 20\% = 0.2$

$\frac{dA_f}{A_f} = 2\% = 0.02$

$$\frac{dA_f}{A_f} = \frac{dA}{A} \times \frac{1}{(1+A\beta)}$$

$$0.02 = 0.2 \times \frac{1}{1+A\beta} \Rightarrow 1+A\beta = 10$$

$$A\beta = 9$$

$$A_f = \frac{A}{1+A\beta} \Rightarrow 100 = \frac{A}{10} \quad \boxed{A = 1000}$$

$$\boxed{\beta = 0.009}$$

(P3) The gain of an amplifier is decreased to 1000 with negative feedback from its gain of 5000. Calculate the feedback factor and the amount of negative feedback in dB.

Sol: $A_f = 1000$

$A = 5000$

$$A_f = \frac{A}{1+A\beta}$$

$$1000 = \frac{5000}{1+5000\beta} \Rightarrow 1+5000\beta = 5$$

$$\beta = \frac{4}{5000} = 0.8\times10^{-3}$$

$$\beta = 20\log 0.8\times10^{-3} = -62\,dB.$$

(P4) An Amplifier has a mid band gain of 125 and a bandwidth of 250KHz.

a) If 4% negative feedback is introduced, find new bandwidth and gain.

b) if bandwidth is to be restricted to 1MHz, find the feedback ratio.

Sol: $A = 125$

$B.W = 250K$

a) $\beta = 4\% = 0.04.$

$$BW_f = BW(1+A\beta)$$

$$= 250K(1+125\times0.04) = 1.5MHz.$$

$$A_f = \frac{A}{1+A\beta} = \frac{125}{1+125\times0.04} = 20.83.$$

b) $BW_f = 1MHz$

$$BW_f = BW(1+A\beta)$$

$$1M = 250K(1+125\beta') \Rightarrow 1+125\beta' = 4 \Rightarrow \beta' = \frac{3}{125} = 0.024$$

$$= 2.4\%.$$

(P) An Amplifier has a Voltage gain of 400, $f_1 = 50Hz$, $f_2 = 200kHz$ and a distortion of 10%. without feedback. Determine the amplifier Voltage gain, f_{1f}, f_{2f} and D_f when a negative feedback is applied with feedback ratio of 0.01.

A)

$A = 400$

$f_1 = 50$

$f_2 = 200k$

$D = 10\% = 0.1$

$\beta = 0.01$

$$A_f = \frac{A}{1+A\beta} = \frac{400}{1+400\times0.01} = 80.$$

$$f_{1f} = \frac{f_1}{1+A\beta} = \frac{50}{1+400\times0.01} = 10\,Hz$$

$$f_{2f} = f_2(1+A\beta) = 200k(1+400\times0.01) = 1MHz$$

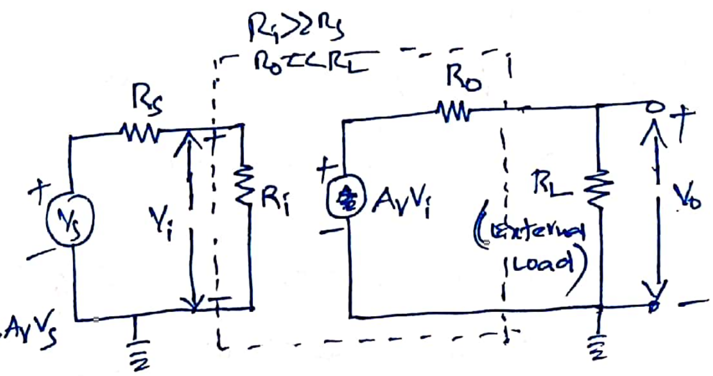
$$D_f = \frac{D}{1+A\beta} = \frac{0.1}{1+400\times0.01} = \frac{0.1}{5} = 0.02 = 2\%$$

Classification of ~~feedback~~ amplifiers:-

Amplifiers are classified into four broad categories:

i) Voltage amplifier ii) current amplifier iii) Transconductance amplifier iv) Transresistance amplifier.

i) Voltage Amplifier:-



If $R_i >> R_s$ then $V_i \approx V_s$

$R_L >> R_o$ then $V_o \approx A_v V_i \approx A_v V_s$

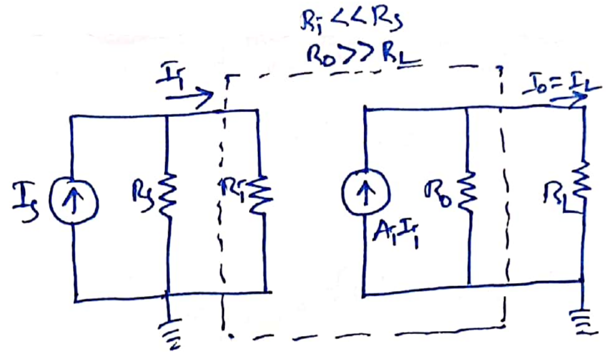
This amplifier provides a Voltage output proportional to the Voltage input, and the proportionality factor is independent of the magnitudes of the source and load resistances. Such a circuit is called a Voltage amplifier.

An Ideal Voltage amplifier must have $R_i = \infty$ and $R_o = 0$

ii) Current amplifier:

if $R_i << R_s$, then $I_i \approx I_s$

$R_o >> R_L$, $I_L \approx A_i I_i \approx A_i I_s$



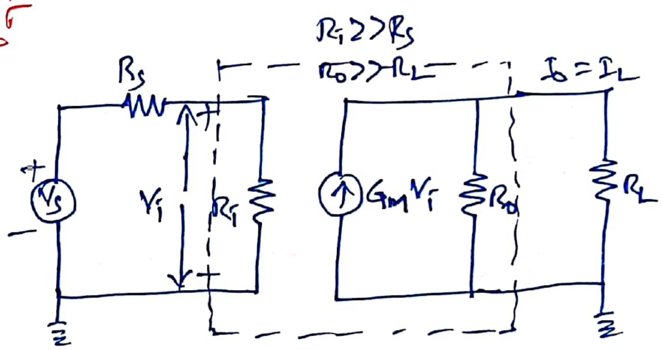
An ideal current amplifier is defined as an amplifier which provides an output current proportional to the signal current, and the proportionality factor is independent of R_s and R_L.

An ideal current amplifier must have $R_i = 0$ & $R_o = \infty$.

iii) Transconductance amplifier:

if $R_i >> R_s$, then $V_i \approx V_s$

$R_o >> R_L$, $I_L \approx G_m V_i \approx G_m V_s$



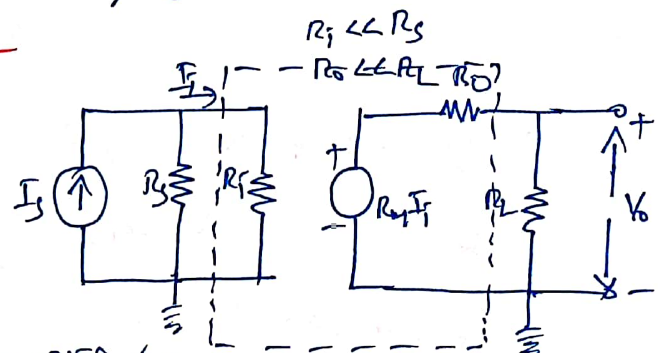
An ideal, Transconductance amplifier supplies an output current which is proportional to the signal voltage, independently of the magnitudes of R_s and R_L.

This amplifier has $R_i = \infty$ & $R_o = \infty$.

iv) Transresistance amplifier:

if $R_i << R_s$; $I_i \approx I_s$

$R_o << R_L$; $V_o = R_m I_i \approx R_m I_s$



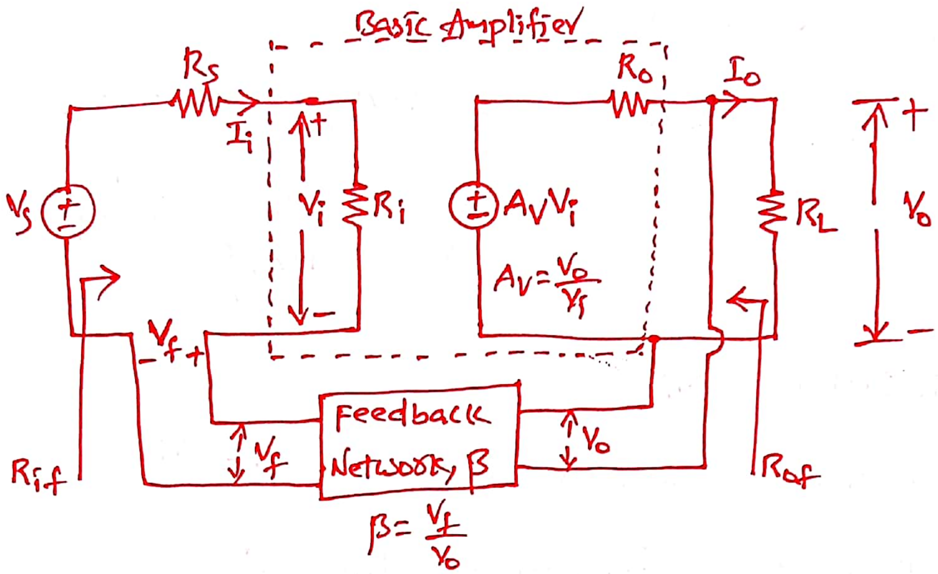
The ideal Transresistance amplifier supplies an output voltage 'V_o' in proportion to the signal current 'I_s' independent of R_s and R_L

$R_i = 0$ & $R_o = 0$.

Feedback Topologies :-

The Four types of negative feedback topologies configurations are :-

i) Voltage-series Feedback :- (Voltage Amplifier)



In this case the amplifier is a true voltage amplifier.

Voltage Gain, $A_V = \frac{V_o}{V_i}$; Voltage Gain with feedback, $A_f = \frac{V_o}{V_s}$

Feedback ratio, $\beta = \frac{V_f}{V_o}$

A fraction of output voltage is taken in shunt and applied to the feedback network and is then applied in series with input voltage.

Voltage Gain (A_f) :-

From the figure applying KVL at input circuit, we have:

$$V_s = I_i R_s + V_i + V_f$$

$$V_s = I_i R_s + I_i R_i + V_f$$

$$V_s = I_i R_i + V_f \quad (\because R_i >> R_s \text{ for voltage Amplifier})$$

$$V_s = V_i + V_f$$

$$V_i = V_s - V_f.$$

Voltage Gain, $A_V = \frac{V_o}{V_i} \Rightarrow V_o = A_V V_i$

$$V_o = A_V (V_s - V_f)$$

$$V_o = A_V (V_s - \beta V_o)$$

$\because \beta = \frac{V_f}{V_o} \Rightarrow V_f = \beta V_o.$

$V_o = A_V (V_s - \beta V_o)$

$V_o = A_V V_s - A_V \beta V_o$

$V_o + A_V \beta V_o = A_V V_s \Rightarrow V_o [1 + A_V \beta] = A_V V_s.$

$$\frac{V_o}{V_s} = \frac{A_V}{1 + A_V \beta} \Rightarrow \boxed{A_f = \frac{A_V}{1 + A_V \beta}}.$$

Input Resistance, R_{if}

Input Resistance without feedback, $R_i = \frac{V_i}{I_i}$

Input Resistance with feedback, $R_{if} = \frac{V_s}{I_i}$

$$R_i = \frac{V_i}{I_i}$$

$$= \frac{V_s - V_f}{I_i} \qquad [\because V_i = V_s - V_f]$$

$$= \frac{V_s - \beta V_o}{I_i} \qquad [\because \beta = \frac{V_f}{V_o}]$$

$$R_i = \frac{V_s - \beta A_V V_i}{I_i} \qquad [\because A_V = \frac{V_o}{V_i} \Rightarrow V_o = A_V V_i]$$

$R_i I_i = V_s - \beta A_V V_i$

$R_i I_i = V_s - \beta A_V I_i R_i \qquad [\because V_i = I_i R_i]$

$R_i I_i + \beta A_V I_i R_i = V_s$

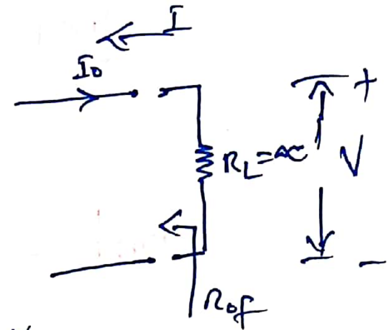
$R_i I_i [1 + \beta A_V] = V_s \Rightarrow \frac{V_s}{I_i} = R_i [1 + A_V \beta]$

$$\boxed{R_{if} = R_i [1 + A_V \beta]}$$

$\therefore$ For voltage series feedback Input Resistance with feedback increases.

output Resistance, R_{of} :-

For measuring output resistance, the voltage source is short circuited i.e; $V_s = 0$ and load resistance is open circuited i.e; $R_L = \infty$. Then an external voltage 'V' is applied across the output terminals, which delivers current 'I'.



The output resistance with feedback is given by $R_{of} = \frac{V}{I}$ and

From input KVL $V_s = V_i + V_f$

$$0 = V_i + V_f \Rightarrow V_i = -V_f \quad \Rightarrow V_f = -V_i$$

Applying KVL at output circuit we have

$$A_V V_i = i_o R_o + V$$

$$A_V V_i = -iR_o + V \qquad [\because I_o = -I] \;\&\; V_o = V]$$

$$A_V(-\beta V) = -iR_o + V \qquad \& \; \beta = \frac{V_f}{V_o} = \frac{-V_i}{V} \Rightarrow V_i = -\beta V$$

$$iR_o = V + A_V \beta V$$

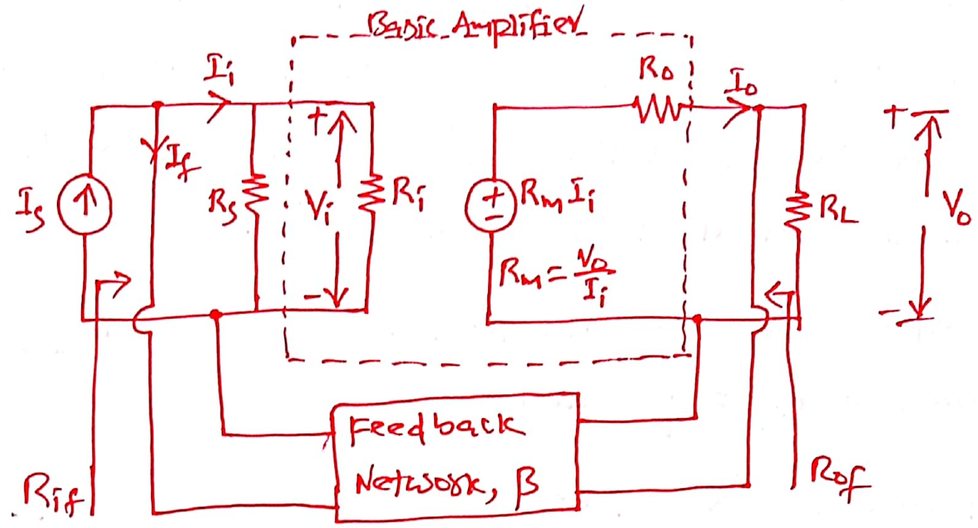
$$iR_o = V\left(1 + A_V \beta\right)$$

$$\frac{V}{i} = \frac{R_o}{1 + A_V\beta}$$

$$\boxed{R_{of} = \frac{R_o}{1 + A_V\beta}}$$

∴ The output resistance with feedback decreases for voltage series feedback than that of without feedback output resistance.

ii) Voltage Shunt feedback : [Transresistance Amplifier]



$$\beta = \frac{I_f}{V_o}$$

This type of feedback is also called Transresistance Amplifier.

Gain of Amplifier without feedback, $A_m = \frac{V_o}{I_i}$

Gain of Amplifier with feedback, $A_f = \frac{V_o}{I_s}$

Voltage Gain; (A_f) :

From input circuit we have by KCL the following equation:

$$I_s = I_i + I_f$$

$$I_s = \frac{V_o}{A_m} + \beta V_o \qquad \left[\because R_m = \frac{V_o}{I_i}\right]$$

$$= V_o\left[\frac{1}{A_m} + \beta\right]$$

$$= V_o\left[\frac{1 + A_m\beta}{A_m}\right]$$

$$\frac{V_o}{I_s} = \frac{A_m}{1 + A_m\beta}$$

$$\boxed{A_f = \frac{A_m}{1 + A_m\beta}} \Rightarrow \boxed{A_f = \frac{R_m}{1 + R_m\beta}}$$

Input Resistance, R_{if} :-

Input Resistance with feedback, $R_{if} = \frac{V_i}{I_s}$

From Input circuit applying KCL we have.

$$I_s = I_i + I_f$$

$$= I_i + \beta V_o \qquad \left[\because \beta = \frac{I_f}{V_o}\right]$$

$$= I_i + \beta R_m I_i \qquad \left[\because R_m = \frac{V_o}{I_i}\right]$$

$$= I_i \left[1 + \beta R_m\right]$$

$$I_s = \frac{V_i}{R_i}\left(1 + \beta R_m\right) \qquad \left[\because V_i = I_i R_i\right]$$

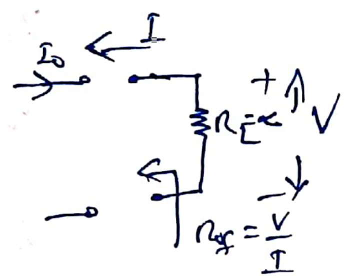
$$\frac{V_i}{I_s} = \frac{R_i}{1+\beta R_m} \Rightarrow \boxed{R_{if} = \frac{R_i}{1+\beta R_m}}$$

Input Resistance decreases as that of with out feedback.

Output Resistance, R_{of} :-

To find output Resistance make $V_s = 0$ & $R_L = \infty$ and applying Voltage, 'V' across output terminals which produces current, 'I'.

Applying KVL to output circuit we have



$$R_m I_i = R_o I_o + V$$

$$R_m I_i = -R_o I + V \qquad \left[\because I_o = -I\right]$$

$$R_m(-\beta V) = -R_o I + V \qquad \left[\begin{aligned} I_s &= I_i + I_f \\ 0 &= I_i + I_f \\ I_i &= -I_f \end{aligned}\right]$$

$$I_i = -\beta V \qquad \because \beta = \frac{I_f}{V_o} = \frac{I_f}{V}$$

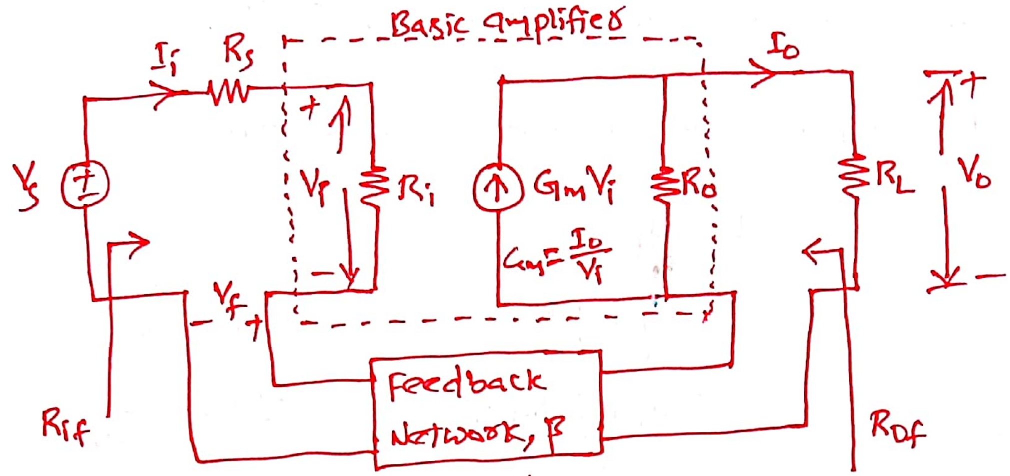
$$R_o I = V + R_m \beta V$$

$$R_o I = V\left[1 + \beta R_m\right]$$

$$\frac{V}{I} = \frac{R_o}{1+\beta R_m} \Rightarrow \boxed{R_{of} = \frac{R_o}{1+\beta R_m}}$$

$\therefore$ The output Resistance with feedback decreases as that of R_o.

iii) Current Series feedback :- (Transconductance Amplifier)



$$\beta = \frac{V_f}{I_o}$$

This type of feedback amplifier is called Transconductance amplifier.

Gain of the amplifier without feedback, $G_m = \frac{I_o}{V_i}$

Gain of the amplifier with feedback, $G_f = \frac{I_o}{V_s}$

Voltage Gain (G_f) :-

Apply KVL for input circuit $\Rightarrow$ $V_s = I_i R_s + I_i R_i + V_f$

$$V_s = I_i R_i + V_f \qquad [\because R_s << R_i \text{ for Transconductance amplifier}]$$

$$V_s = V_i + V_f \rightarrow (1)$$

$$V_s = \frac{I_o}{G_m} + \beta I_o \qquad \left[\because G_m = \frac{I_o}{V_i} \Rightarrow V_i = \frac{I_o}{G_m} \text{ \& } \beta = \frac{V_f}{I_o} \Rightarrow V_f = \beta I_o\right]$$

$$V_s = I_o \left[\frac{1}{G_m} + \beta\right]$$

$$V_s = I_o \left[\frac{1 + G_m \beta}{G_m}\right]$$

$$\frac{I_o}{V_s} = \frac{G_m}{1 + G_m \beta} \Rightarrow \boxed{G_f = \frac{G_m}{1 + G_m \beta}}$$

Input Resistance, R_{if} :-

Input Resistance without feedback, $R_i = \frac{V_i}{I_i}$

Input Resistance with feedback, $R_{if} = \frac{V_s}{I_i}$

Apply KVL at input circuit we have from equation (1)

$$V_s = V_i + V_f$$

$$V_s = I_i R_i + \beta I_o$$

$$V_s = I_i R_i + \beta G_m V_i \qquad \left[\because G_m = \frac{I_o}{V_i} \Rightarrow I_o = G_m V_i\right]$$

$$= I_i R_i + \beta G_m I_i R_i$$

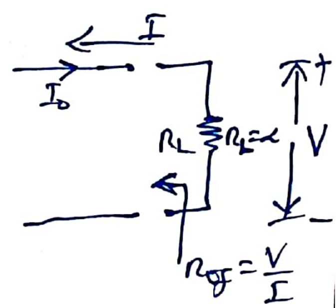
$$= I_i R_i \left[1 + \beta G_m\right]$$

$$\frac{V_s}{I_i} = R_i \left[1+\beta G_m\right] \Rightarrow \boxed{R_{if} = R_i \left(1+\beta G_m\right)}$$

$\therefore$ Input resistance increases as that of without feedback.

Output Resistance, R_{of} :-

To calculate output resistance, R_{of} make $V_s = 0$ & $R_L = \infty$ and apply Voltage, 'V' across output terminals which gives current, 'I'.



Input KVL becomes $V_s = V_i + V_f$

$$0 = V_i + V_f \Rightarrow V_f = -V_i$$

Applying KCL at output circuit we have

$$G_m V_i = \frac{V}{R_o} + I_o$$

$$G_m V_i = \frac{V}{R_o} - I \qquad \left[\because I_o = -I\right. \;\&\; \left. V_i = -V_f\right]$$

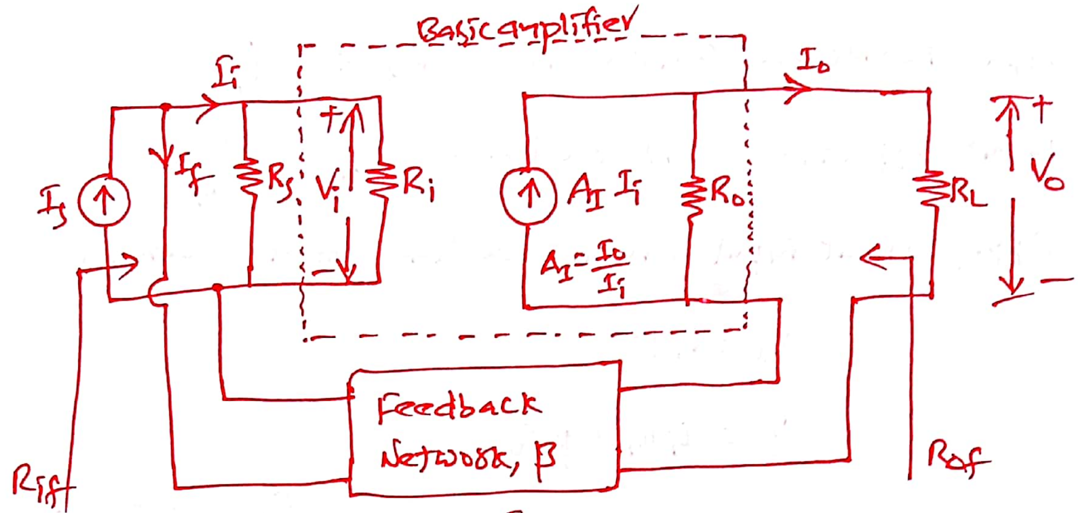
$$G_m(-V_f) = \frac{V}{R_o} - I \qquad \left[\& \; \beta = \frac{V_f}{I_o} = \frac{V_f}{-I} \Rightarrow V_f = -\beta I\right]$$

$$G_m(-(-\beta I)) = \frac{V}{R_o} - I$$

$$G_m \beta I + I = \frac{V}{R_o} \Rightarrow I\left[1+\beta G_m\right] = \frac{V}{R_o} \Rightarrow \frac{V}{I} = R_o(1+G_m\beta)$$

$\therefore$ Output Resistance with feedback increases as that of without feedback. $\boxed{R_{of} = R_o(1+G_m\beta)}$

iv) Current Shunt feedback :- (Current Amplifier)



$$\beta = \frac{I_f}{I_o}$$

Current Gain without feedback, $A_I = \frac{I_o}{I_i}$

Current Gain with feedback, $A_f = \frac{I_o}{I_s}$

Feedback ratio, $\beta = \frac{I_f}{I_o}$

Current Gain, A_f :-

Apply KCL at input circuit we have $I_s = I_i + I_f \rightarrow (1)$

$$I_s = \frac{I_o}{A_I} + \beta I_o$$

$\left[\because \beta = \frac{I_f}{I_o} \right.$

$\left. I_f = \beta I_o \right]$

$\left. \& \; A_I = \frac{I_o}{I_i} \Rightarrow I_i = \frac{I_o}{A_I} \right]$

$$I_s = I_o \left[\frac{1}{A_I} + \beta \right]$$

$$I_s = I_o \left[\frac{1 + A_I \beta}{A_I} \right]$$

$$\frac{I_o}{I_s} = \frac{A_I}{1 + A_I \beta}$$

$$\boxed{A_f = \frac{A_I}{1 + A_I \beta}}$$

Input Resistance, R_{if} :-

Input Resistance without feedback ; $R_i = \frac{V_i}{I_i}$

Input Resistance with feedback, $R_{if} = \frac{V_i}{I_s}$

From eq/① we have $I_s = I_i + I_f$

$$I_s = \frac{V_i}{R_i} + \beta I_o$$

$$I_s = \frac{V_i}{R_i} + \beta A_I I_i \quad \left[\because A_I = \frac{I_o}{I_i}\right]$$

$$I_s = \frac{V_i}{R_i} + \beta A_I \frac{V_i}{R_i}$$

$$I_s = \frac{V_i}{R_i}\left\{1 + \beta A_I\right\} \Rightarrow \frac{V_i}{I_s} = \frac{R_i}{1 + A_I\beta}$$

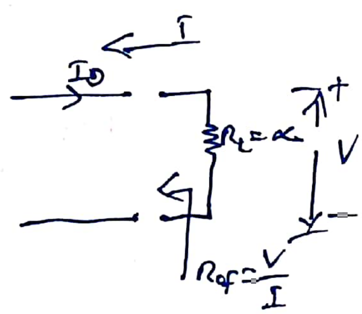
$$\boxed{R_{if} = \frac{R_i}{1 + A_I\beta}}$$

∴ Input Resistance with feedback decreases.

Output Resistance, R_{of} :-

Output Resistance, R_{of} is found by making $V_s = 0$ & $R_L = \infty$ and inserting voltage source, 'V' at output terminals which gives current, 'I'.

Applying KCL at output circuit we have:



$$A_I I_i = \frac{V}{R_o} + I_o$$

$$A_I(-I_f) = \frac{V}{R_o} - I \quad \left[\because I_s = I_i + I_f,\ 0 = I_i + I_f,\ I_i = -I_f \ \& \ I_o = -I\right]$$

$$A_I(-(-\beta I)) = \frac{V}{R_o} - I \quad \left[I_f = \beta I_o = \beta(-I) = -\beta I\right]$$

$$A_I \beta I + I = \frac{V}{R_o}$$

$$I\left[1 + A_I\beta\right] = \frac{V}{R_o}$$

$$\frac{V}{I} = R_o(1 + A_I\beta) \Rightarrow \boxed{R_{of} = R_o(1 + A_I\beta)}$$

∴ Output Resistance with feedback increases as that of without feedback.

characteristic	Voltage-Series feedback	Voltage-shunt feedback	Current-series feedback	current-shunt feedback
1) Voltage Gain	Decreases	Decreases	Decreases	Decreases
2) Input Resistance	Increases	Decreases	Increases	Decreases
3) output Resistance	Decreases	Decreases	Increases	Increases
4) Bandwidth	Increases	Increases	Increases	Increases
5) Distortion	Decreases	Decreases	Decreases	Decreases
6) Noise	Decreases	Decreases	Decreases	Decreases
7) Amplifier type	Voltage Amp.	Transresistance Amp.	Trans Conductance Amp.	Current Amp.

(P) A voltage-Series negative feedback amplifier has a voltage gain without feedback of 500, input resistance of 3kΩ, output resistance of 20kΩ and feedback ratio of 0.01. Calculate the voltage Gain A_f, input and output resistance of the amplifier with feedback.

Sol: Given data: $A_V = 500$; $R_i = 3k$; $R_o = 20k$; $\beta = 0.01$

$$A_f = \frac{A}{1+A\beta} = \frac{500}{1+500\times0.01} = 83.33$$

$$R_{if} = R_i(1+A\beta)$$

$$= 3k(1+500\times0.01) = 18k\Omega$$

$$R_{of} = \frac{R_o}{1+A\beta}$$

$$= \frac{20k}{1+500\times0.01} = 3.33k\Omega.$$

(P) If an amplifier with gain of -1000 and feedback of $\beta=-0.1$ has a gain change of 20% due to temperature, calculate the change in gain of the feedback amplifier.

Sol: $A=-1000$; $\beta=-0.1$;

$\frac{dA}{A} = 20\% = 0.2$

$$\frac{dA_f}{A_f} = \frac{dA}{A} \times \frac{1}{1+A\beta}$$

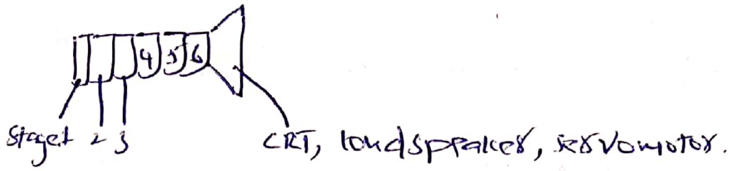
$$= 0.2 \times \frac{1}{1+100} = 0.2\%$$

LARGE SIGNAL AMPLIFIERS

or

POWER AMPLIFIERS

An Amplifying System consists of several stages in cascade.



The input and output intermediate stages operate in a small-signal class A mode and amplify the small input excitation to a large value which drives the final device. This output stage feeds a transducer such as a CRT, loud speaker and hence must be capable of delivering a large voltage or current or power.

Each active device in the small-signal stage is replaced by a linear model and final stage is in Non-linear model.
A new type of distortion due to nonlinearity is introduced such as frequency components into the output which are not present in the input signal.

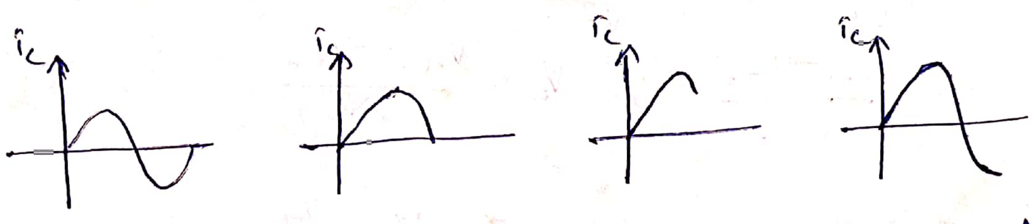
Types of Large Signal Amplifiers based on conduction angle's

Class 'A' : Active device conducts for full 360°.

class 'B' : conduction for 180°.

class 'C' : conduction for < 180°.

class AB : conduction angle is between 180° and 360°.



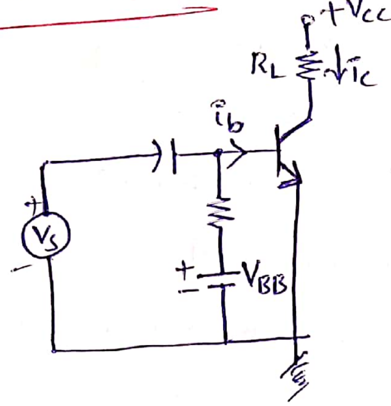
class A   class B   class C   class AB

Class 'A' power Amplifier:-

There are two types of operations:

1) Series fed 2) Transformer coupled.

1) Series fed class 'A' Amplifier:-



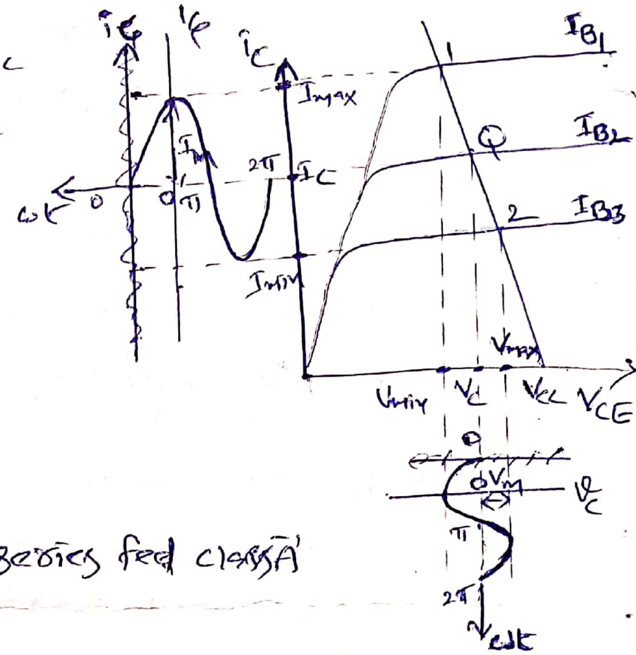


Figure above represents a simple series fed class 'A' amplifier with resistive load R_L.

The input current is i_b which is base current and output is collector current i_c.

If input signal is sinusoid, the output current and voltage are also sinusoidal.

The power output is $P = V_c i_c = i_c^2 R_L \quad [\because V_c = i_c R_L]$

where V_c & i_c are rms output voltage & current of v_c & i_c respectively.

I_m is peak current; R_L is load resistance.

$$i_c = \frac{I_m}{\sqrt{2}} \; ; \quad V_c = \frac{V_m}{\sqrt{2}}$$

$[\because I_{max} - I_{min} = 2 I_m]$

$$i_c = \frac{I_{max} - I_{min}}{2\sqrt{2}} \; , \quad V_c = \frac{V_{max} - V_{min}}{2\sqrt{2}}$$

$$\therefore \text{power } P = V_c i_c = \frac{I_{max} - I_{min}}{2\sqrt{2}} \cdot \frac{V_{max} - V_{min}}{2\sqrt{2}}$$

$$\boxed{\therefore P = \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8}}$$

Harmonic Distortion:

From the figure the nonlinearity is observed, as output characteristics are not equidistant straight lines for constant increments of input excitation. Distortion of this type is called "Nonlinear" or "Amplitude distortion".

Thus relation b/w input & output is

$$i_c = G_1 i_b + G_2 i_b^2 + G_3 i_b^3$$ | where G is constant.

if $i_b = I_m \cos\omega t$

$$i_c = G_1 i_m \cos\omega t + G_2 i_m^2 \cos^2\omega t$$

$\because \cos^2\omega t = \frac{1+\cos 2\omega t}{2}$

~~$i_c = G_1 i_m \cos\omega t$~~

The instantaneous total current is

I_C – quiescent collector current

i_C – total instantaneous collector current

i_c – alternating output current

$$i_C = I_C + i_c$$

$$i_C = I_C + G_1 i_m \cos\omega t + G_2 i_m^2 \left[\frac{1+\cos 2\omega t}{2}\right]$$

$$i_C = I_C + B_0 + B_1 \cos\omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t + \cdots \quad (1)$$

where B's are constants in terms of G's.

The amplitudes B_0, B_1 & B_2 are found as

at $\omega t = 0$; $i_C = I_{max}$

at $\omega t = \pi/2$; $i_C = I_C$

at $\omega t = \pi$; $i_C = I_{min}$

substituting in (1) we get

$$I_{max} = I_C + B_0 + B_1 + B_2 \quad \rightarrow (2)$$

$$I_C = I_C + B_0 - B_2 \quad \rightarrow (3)$$

$$I_{min} = I_C + B_0 - B_1 + B_2 \quad \rightarrow (4)$$

From (3) $\quad B_0 - B_2 = 0$

$$B_0 = B_2$$

(2) − (4) $\Rightarrow$

$$I_{max} = \cancel{I_c} + \cancel{B_0} + B_1 + \cancel{B_2}$$

$$I_{min} = \cancel{I_c} + \cancel{B_0} - B_1 + \cancel{B_2}$$

$$(-) \qquad (-) \quad (-) \quad (+) \quad (-)$$

$$2B_1 = I_{max} - I_{min}$$

$$\boxed{B_1 = \frac{I_{max} - I_{min}}{2}}$$

$$I_{max} = I_c + B_2 + \frac{I_{max} - I_{min}}{2} + B_2$$

$$\frac{I_{max}}{2} = \frac{2I_c + 4B_2 - I_{min}}{2}$$

$$I_{max} + I_{min} - 2I_c = 4B_2$$

$$\boxed{\therefore B_2 = \frac{I_{max} + I_{min} - 2I_c}{4}}$$

second-harmonic distortion, $D_2 = \dfrac{|B_2|}{|B_1|}$

||ly $\quad D_3 = \dfrac{|B_3|}{|B_1|}$

$$D_4 = \frac{|B_4|}{|B_1|}$$

If Distortion is not negligible, the power delivered at the fundamental frequency is

$$P_1 = \frac{B_1^2 \cdot R_L}{2}$$

The total power output is

$$P = (B_1^2 + B_2^2 + B_3^2 + \cdots)\frac{R_L}{2}$$

$$= \frac{B_1^2 R_L}{2}\left[1 + \frac{B_2^2}{B_1^2} + \frac{B_3^2}{B_1^2} + \cdots\right]$$

$$P = P_1 (1 + D_2^2 + D_3^2 + \cdots)$$

$$\therefore \boxed{P = (1 + D^2) P_1}$$

$\therefore$ Total distortion or distortion factor is defined as

$$\boxed{D \equiv \sqrt{D_2^2 + D_3^2 + D_4^2 + \cdots}}$$

ex: if total distortion is 10% of fundamental, then

$$P = (1 + (0.1)^2) P_1 = 1.01 P_1$$

$\therefore$ Total power output is only 1% (0.01) higher than fundamental power when the distortion is 10%.

Q) If total distortion in the amplifier is 9%. calculate its contribution to total power.

S: $P = (1 + (0.09)^2) P_1 = P_1 (1.0081)$

$P = \cancel{(1 + 0}.$

Efficiency of class A :-

A measure of the ability of an active device to convert the dc power of supply into ac power delivered to the load is called the "conversion efficiency (or) theoretical efficiency".

This figure of merit, 'η' is also called collector-circuit efficiency.

$$\eta = \frac{\text{Signal power delivered to load}}{\text{dc power supplied to output circuit}} \times 100\%.$$

$$\eta = \frac{\frac{1}{2} B_1^2 R_L}{V_{CC}(I_C + B_0)} \times 100\%$$

neglecting distortion,

$$\eta = \frac{\frac{1}{2} V_m I_m}{V_{CC} \cdot I_C} \times 100\%.$$

$$\eta = \frac{50\, V_m I_m}{V_{CC} \cdot I_C}\ \%.$$

ac. power $P_{ac} = V_{rms} \cdot I_{rms}$

$= \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}$

$= \frac{V_m \cdot I_m}{2}.$

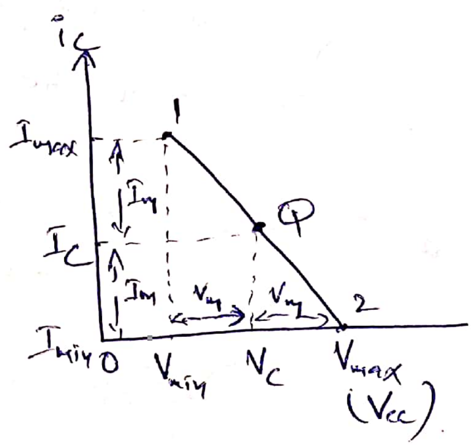
$P_{dc} = V_{CC} \cdot I_C.$

From the figure:

$$I_C = I_m \ ; \quad V_m = \frac{V_{max} - V_{min}}{2}$$

$$\therefore \eta = \frac{50 \times (V_{max} - V_{min}) \times \cancel{I_C}}{V_{CC} \cdot 2\, \cancel{I_C}}$$

$$\boxed{\eta = \frac{25\,(V_{max} - V_{min})}{V_{CC}}\ \%.}$$



Ideal distortionless amplifier

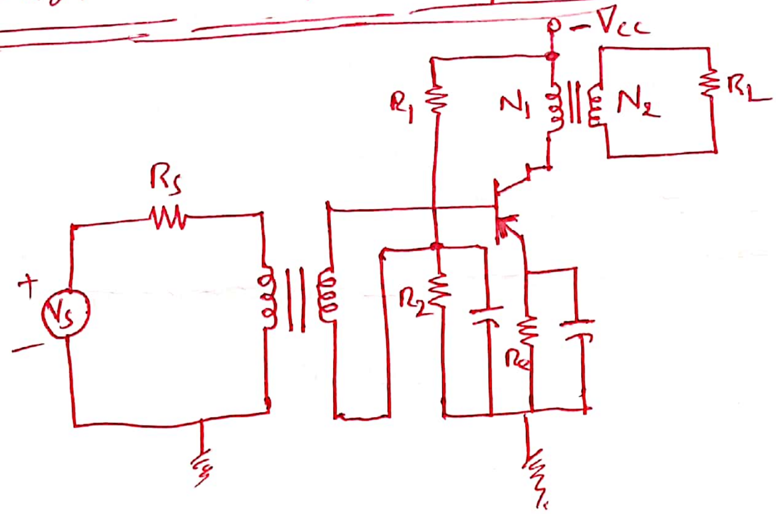
For series fed load $V_{CC} = V_{max}.$

$$\boxed{\therefore \eta = \frac{25\,(V_{max} - V_{min})}{V_{max}}\ \%}$$

$$\Rightarrow \eta = 25\left(1 - \frac{V_{min}}{V_{max}}\right)\ \%$$

$$\therefore \boxed{\eta = 25\%.}$$

ii) Transformer coupled Amplifiers:



Reason for the above circuit:

If load resistance 'R_L' is connected directly in the output circuit of series-fed amplifier, the quiescent current (dc) passes through this resistance.

This current represents a considerable waste of power, since it does not contribute to the ac component of power.

∴ It is inadvisable to pass the dc component of current through the output device (i.e; loud speaker).

For these reasons an arrangement using an output transformer is employed as shown in above fig.

$$V_1 = \frac{N_1}{N_2} V_2 \quad \text{and} \quad I_1 = \frac{N_2}{N_1} I_2$$

V_1 – primary voltage

V_2 – secondary voltage

I_1 – primary current

I_2 – secondary current

N_1 – No. of primary turns

N_2 – No. of secondary turns

When $N_1 > N_2$, the transformer reduces the voltage in proportion to the turns ratio $n = \frac{N_2}{N_1}$ and increases the current in same ratio.

$$V_1 = \frac{1}{n} V_2 \; ; \quad I_1 = n \cdot I_2 .$$

$$\frac{V_1}{I_1} = \frac{1}{n^2} \frac{V_2}{I_2} .$$

input resistance $R_i = \frac{V_1}{I_1}$

$$\boxed{R_i = \frac{1}{n^2} R_L .}$$

output resistance $R_L = \frac{V_2}{I_2}$.

Efficiency: we have $\eta = \frac{25(V_{max} - V_{min})}{V_{CC}}$ %.

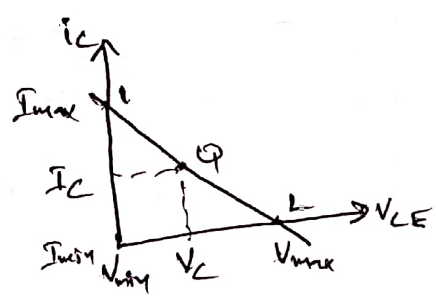
If the load is coupled to the stage through a transformer, then

$$V_{CC} = V_C = \frac{V_{max} + V_{min}}{2}$$

$$\therefore \eta = \frac{25(V_{max} - V_{min})}{(V_{max} + V_{min})/2} =$$

$$\boxed{\eta = \frac{50 (V_{max} - V_{min})}{(V_{max} + V_{min})} \%}$$

The theoretical efficiency for a transformer coupled power amplifier is 50%, or twice that of the series-fed circuit.



(P) Calculate the turns ratio required to match a 8Ω speaker load to an amplifier so that the effective load resistance is $3.2k\Omega$.

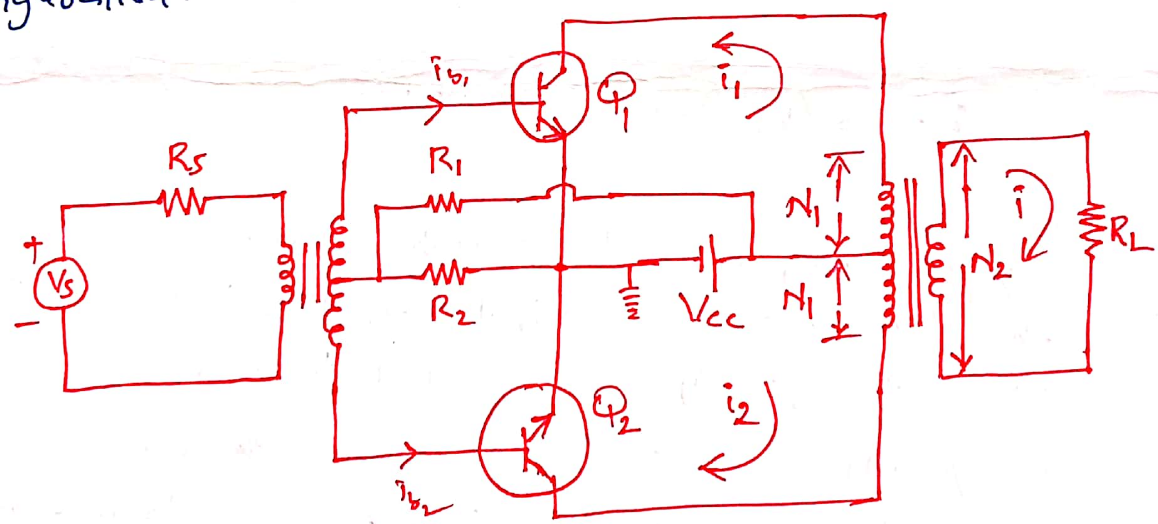
Sol

$$R_i = \frac{1}{n^2} R_L \Rightarrow 3.2k = \frac{1}{n^2} 8\Omega$$

$$n^2 = \frac{8}{3.2k} \Rightarrow n = \sqrt{\frac{8}{3.2k}} = 0.05$$

push-pull Amplifiers

The distortion introduced by the nonlinearity may be eliminated by the circuit shown below (known as "push-pull configuration").



- The excitation is introduced through a center-tapped transformer
- When the signal on Q_1 is positive, the signal on Q_2 is negative by an equal amount.
- consider an input base current $i_{b_1} = i_m \cos\omega t$ applied to Q_1.

The output current of this transistor is

$$i_1 = I_C + B_0 + B_1 \cos\omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t + \text{———}$$

The input signal to 'Q_2' is

$$i_{b_1} = -i_{b_2} = i_m \cos(\omega t + \pi)$$

The output current of this transistor is

$$i_2 = I_c + B_0 + B_1 \cos(\omega t + \pi) + B_2 \cos 2(\omega t + \pi) + \text{---}$$

$$i_2 = I_c + B_0 - B_1 \cos\omega t + B_2 \cos 2\omega t - B_3 \cos 3\omega t + \text{---}$$

currents i_1 & i_2 are in opposite directions. The total output current is then

$$i = K(i_1 - i_2)$$

$$= K\left(I_c + B_0 + B_1 \cos\omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t - I_c - B_0 + B_1 \cos\omega t - B_2 \cos 2\omega t + B_3 \cos 3\omega t\right)$$

$$\boxed{i = 2K(B_1 \cos\omega t + B_3 \cos 3\omega t + \text{---})}$$

This expression shows that a push-pull circuit will balance out all even harmonics in the output and will leave the third harmonic term as the principal source of distortion.

As this output current does not contain even harmonics terms means that the push-pull system possesses "Half-wave" (or) "mirror" symmetry.

The bottom loop of the wave, when shifted 180° along the axis, become mirror image of the top loop.

The condition for mirror symmetry is represented as

$$i(\omega t) = -i(\omega t + \pi).$$

Advantages of

1) No even harmonics are present in the output, such a circuit will give more output per active device

2) No DC components in transformer core

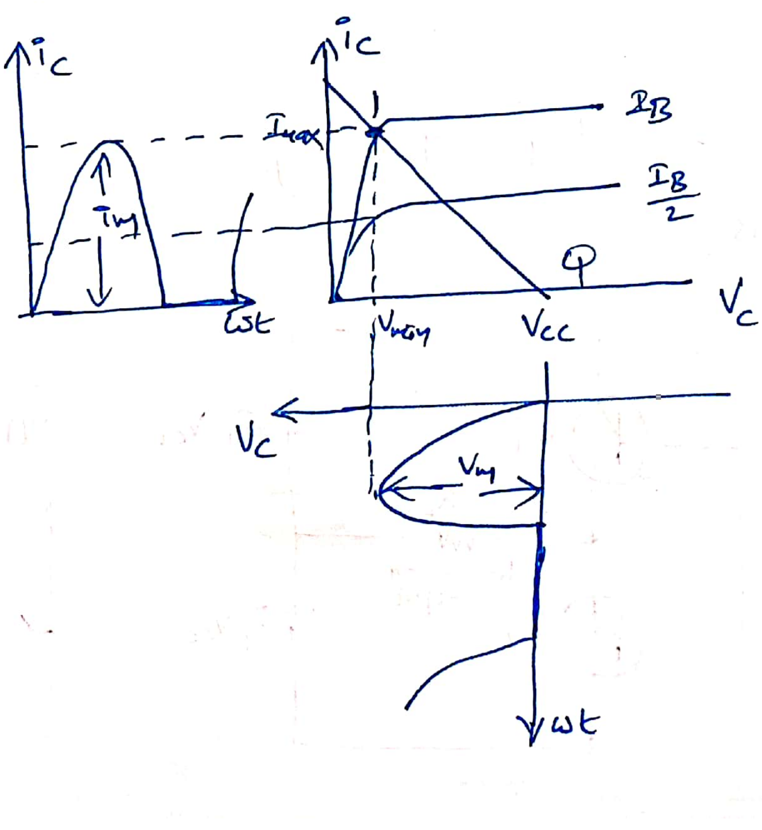
3) Effect of ripple voltages will be balanced out.

Class "B" Amplifiers :-

- The circuit for class B push-pull system is same as that for class A system except that the devices are biased approximately at cutoff.
- The advantages of class B as compared with class A operation are :
  i) It is possible to obtain greater output power.
  ii) The Efficiency is higher
  iii) Negligible power loss at no signal.

For these reasons, in systems where the power supply is limited, i.e, operating from solar cells or Battery, the output power is delivered through a push-pull class B transistor circuit.

- The disadvantages are :
  i) Harmonic distortion is higher
  ii) self-bias cannot be used
  iii) supply Voltages must have good regulation.



The output power is $P_o = \frac{V_m I_m}{2} = \frac{I_m}{2}\left[V_{CC} - V_{min}\right]$

The D.C input power from the supply is $P_i = V_{CC} I_{dc}$

$$P_i = V_{CC} \frac{2 I_m}{\pi}$$

The factor 2 in this expression arises because two transistors are used in the push-pull system.

$$\text{Efficiency}, \eta = \frac{P_o}{P_i} \times 100\%$$

$$= \frac{\frac{I_m}{2}\left[V_{CC} - V_{min}\right]}{V_{CC} \times \frac{2 I_m}{\pi}} = \frac{\pi}{4} \frac{V_{CC} - V_{min}}{V_{CC}} \times 100\%$$

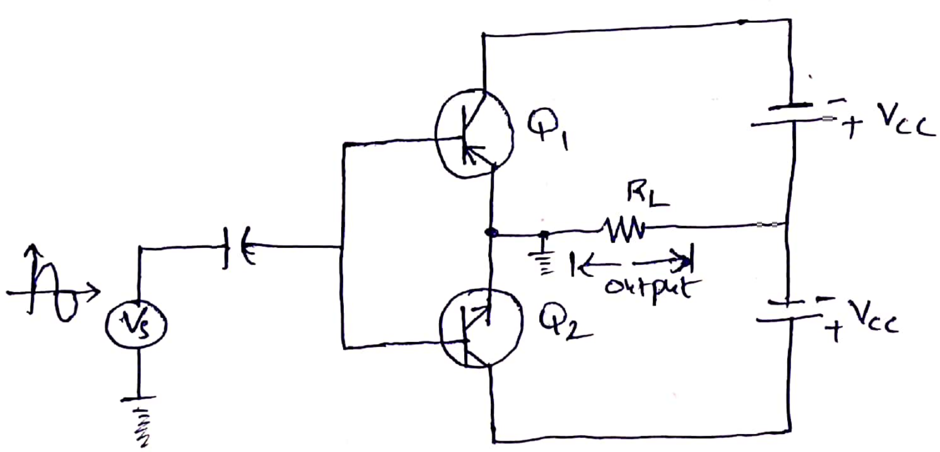
$$\eta = \frac{\pi}{4}\left[1 - \frac{V_{min}}{V_{CC}}\right] \times 100\%$$

for $V_{min} << V_{CC}$ $\Rightarrow \eta = \frac{\pi}{4} \times 100\%$

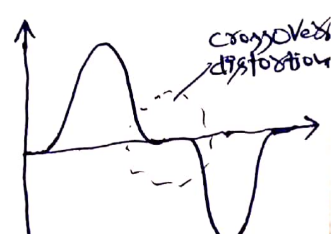
$$\eta = 25\pi\ \%$$

$$\boxed{\eta = 78.5\%}$$

Circuit of class "B" :-



o/p waveform is :-



The circuit of class B power amplifier uses neither an output nor an input transformer. The arrangement uses transistors having complementary symmetry (one P-N-P and one N-P-N)

The output is direct coupled since output is taken directly across R_L.

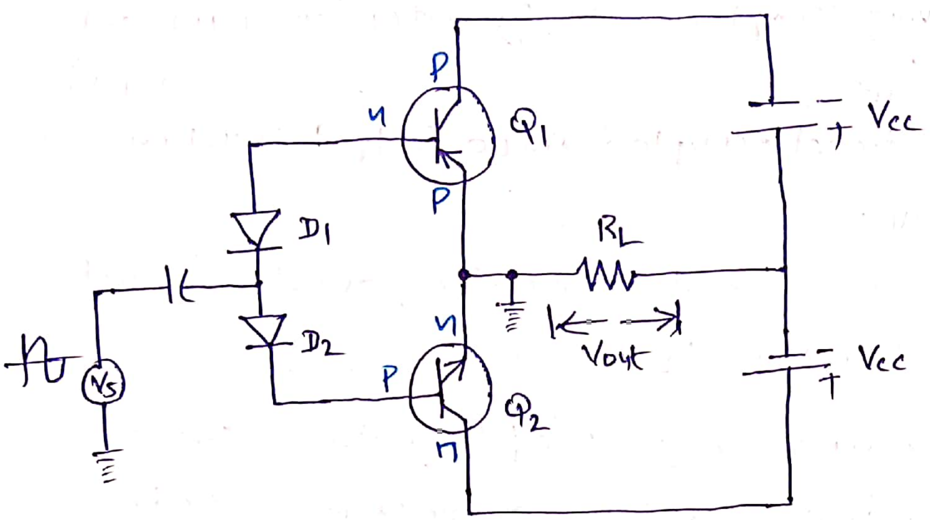
- With no input signal both transistors do not conduct then current through R_L is zero.
- With input a positive signal: Q_1 transistor is cut-off since base is 'n' type and Q_2 conducts since its base input is 'p' type positive. The resulting current flows through R_L.
- With input a negative signal: Q_2 goes off and Q_1 turns on. current flows through R_L.

Hence there is no DC current through R_L Hence an electro-magnetic load such as loud speaker can be connected directly without any problems.

- This class B amplifier is more efficient than class A, but the problem is that it can create distortion at the zero-crossings point of the waveform due to transistor dead band of input base voltages from $-0.7V$ to $+0.7V$.
- In transistor Base-Emitter Voltage must be about 0.7 Volts to get transistor to start conducting. In class B amplifier, the transistors are not biased to "ON" state until this Voltage is exceeded.
- To overcome this zero-crossing distortion (crossover Distortion) class AB amplifiers were developed.

Class AB Amplifier:-

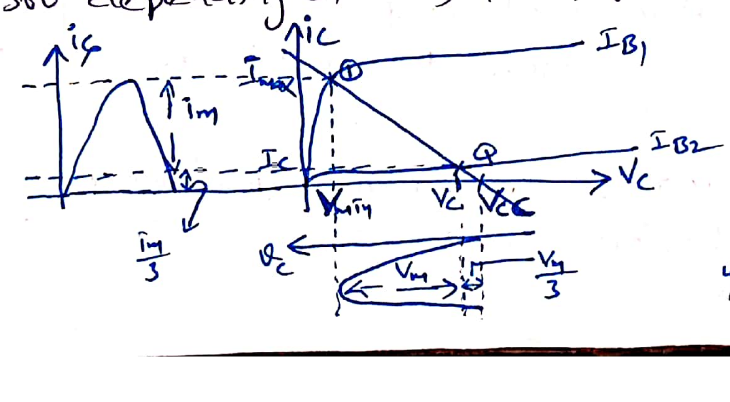
Circuit:-



$V_s < 0.6 \rightarrow D_1$ is ON
Q_1 is ON
D_2 is OFF

$V_s > 0.6 \rightarrow D_1$ is OFF
D_2 is ON
Q_2 is ON

- class AB amplifier is a combination of "class A" & "class B" type amplifiers.
- This is commonly used audio power amplifier design.
- class AB amplifier is a variation of a class B amplifier, except that both devices are allowed to conduct at the same time around the waveforms crossover point eliminating the crossover distortion problems of class B amplifier.
- The two transistors have a very small bias voltage to bias the transistors just above its cut-off point. Then the conducting device, BJT, will be "ON" for more than one half cycle, but much less than one full cycle of the input signal.
- The conduction angle of class AB amplifier is between 180° and 360° depending on chosen bias point.



$$\eta = \frac{V_m i_m / 2}{V_{cc} i_c} = \frac{\frac{3}{4}(V_{cc} - V_{min}) \frac{i_m}{2}}{V_{cc} I_{DC}}$$

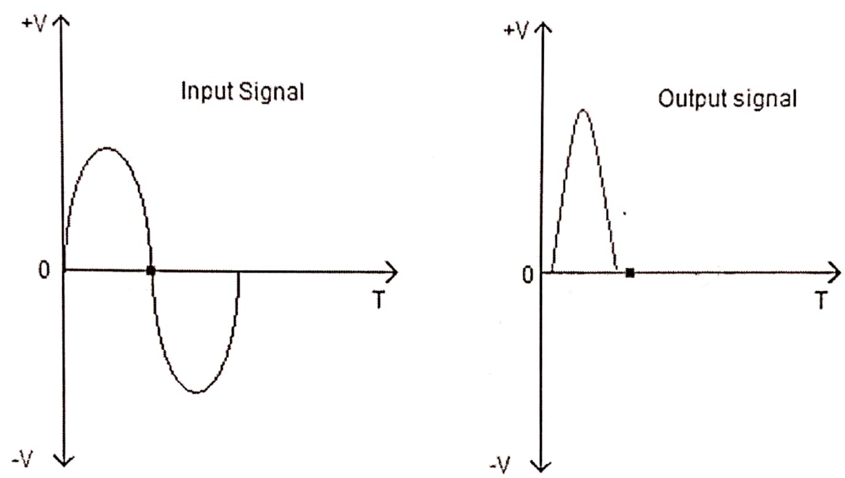
$$\eta = \frac{3}{8}\left(1 - \frac{V_{min}}{V_{cc}}\right) \frac{i_m}{\frac{2 i_m}{\pi}}$$

$$\eta = \frac{3\pi}{16} \times 100\% \Rightarrow \boxed{\eta = 58.9\%}$$

Class C power amplifier

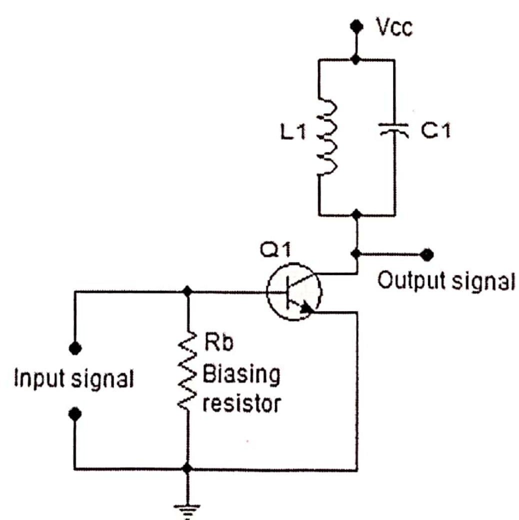
Class C power amplifier is a type of amplifier where the active element (transistor) conduct for less than one half cycle of the input signal. Less than one half cycle means the conduction angle is less than 180° and its typical value is 80° to 120°. The reduced conduction angle improves the efficiency to a great extend but causes a lot of distortion. Theoretical maximum efficiency of a Class C amplifier is around 90%.

Due to the huge amounts of distortion, the Class C configurations are not used in audio applications. The most common application of the Class C amplifier is the RF (radio frequency) circuits like RF oscillator, RF amplifier etc where there are additional tuned circuits for retrieving the original input signal from the pulsed output of the Class C amplifier and so the distortion caused by the amplifier has little effect on the final output. Input and output waveforms of a typical Class C power amplifier is shown in the figure below.



From the above figure it is clear that more than half of the input signal is missing in the output and the output is in the form of some sort of a pulse.

Circuit diagram:

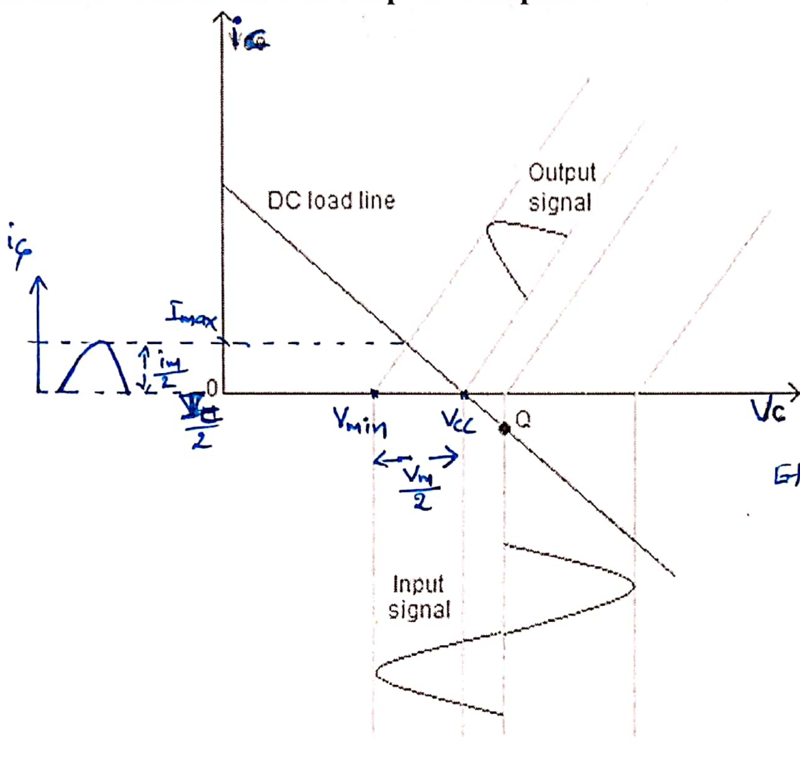


Class C power amplifier

Biasing resistor Rb pulls the base of Q1 further downwards and the Q-point will be set some way below the cut-off point in the DC load line. As a result the transistor will start conducting only after the input signal amplitude has risen above the base emitter voltage (Vbe~0.7V) plus the downward bias voltage caused by Rb. That is the reason why the major portion of the input signal is absent in the output signal.

Inductor L1 and capacitor C1 forms a tank circuit which aids in the extraction of the required signal from the pulsed output of the transistor. Actual job of the active element (transistor) here is to produce a series of current pulses according to the input and make it flow through the resonant circuit. Values of L1 and C1 are so selected that the resonant circuit oscillates in the frequency of the input signal. Since the resonant circuit oscillates in one frequency (generally the carrier frequency) all other frequencies are attenuated and the required frequency can be squeezed out using a suitably tuned load. Harmonics or noise present in the output signal can be eliminated using additional filters. A coupling transformer can be used for transferring the power to the load.

Output characteristics of Class C power amplifier



Class C power amplifier output characteristics

$$\text{Efficiency}, \eta = \frac{V_c I_c}{V_{cc} I_c} = \frac{\frac{V_m i_m}{2}}{V_{cc} I_c}$$

$$= \frac{\cancel{2}(V_{cc} - V_{min}) \frac{i_m}{\cancel{2}}}{V_{cc} \cdot i_m} 100\%$$

$$= \left(1 - \frac{V_{min}}{V_{cc}}\right) 100\%$$

$$\boxed{\eta = 100\%}$$

In the above figure you can see that the operating point is placed some way below the cut-off point in the DC load-line and so only a fraction of the input waveform is available at the output.

Advantages of Class C power amplifier

- High efficiency.
- Excellent in RF applications.
- Lowest physical size for a given power output.

Disadvantages of Class C power amplifier

- Lowest linearity.
- Not suitable in audio applications.
- Creates a lot of RF interference.
- It is difficult to obtain ideal inductors and coupling transformers.
- Reduced dynamic range.

Applications of Class C power amplifier

- RF oscillators.
- RF amplifier.
- FM transmitters.
- Booster amplifiers.
- High frequency repeaters.
- Tuned amplifiers etc.

CLASS D Amplifier: A class D Amplifier is designed to operate with digital (or) pulse-type signals. An efficiency of over 90% is achieved using this circuit

amplifiers. It is necessary, however, to convert any input signal into a pulse-type waveform before using it to drive a large power load and to convert the signal back into a sinusoidal-type signal to recover the original signal. Figure 12.26 shows how a sinusoidal signal may be converted into a pulse-type signal using some form of sawtooth or chopping waveform to be applied with the input into a comparator-type op-amp circuit so that a representative pulse-type signal is produced. Although the letter D is used to describe the next type of bias operation after class C, the D could also be considered to stand for "Digital," since that is the nature of the signals provided to the class D amplifier.

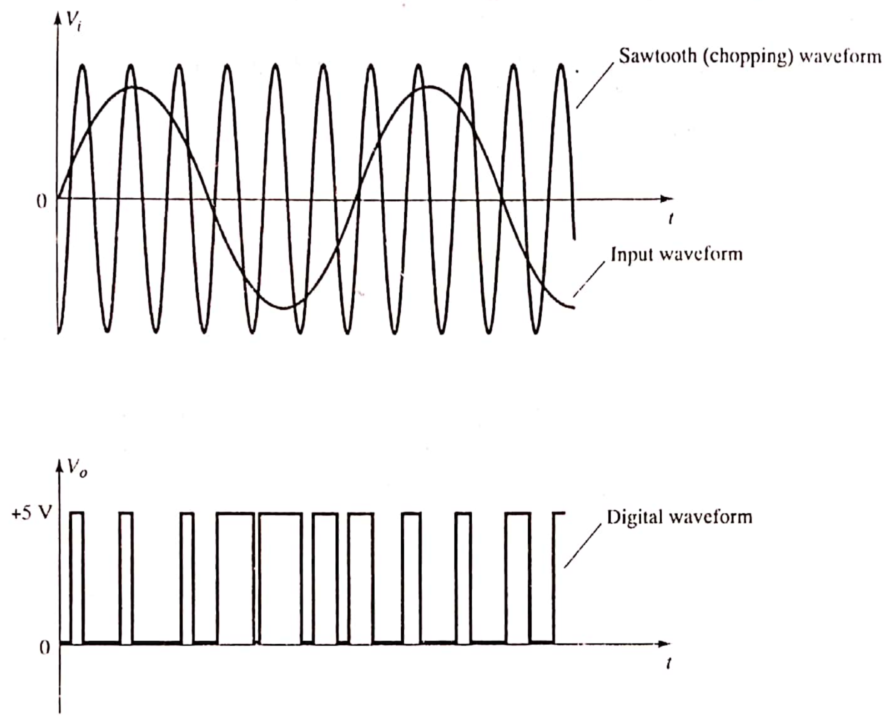


FIG. 12.26
Chopping of a sinusoidal waveform to produce a digital waveform.

Figure 12.27 shows a block diagram of the unit needed to amplify the class D signal and then convert back into the sinusoidal-type signal using a low-pass filter. Since the amplifier's transistor devices used to provide the output are basically either off or on, they provide current only when they are turned on, with little power loss due to their low "on" voltage. Since most of the power applied to the amplifier is transferred to the load, the efficiency of the circuit is typically very high. Power MOSFET devices have been quite popular as the driver devices for the class D amplifier.

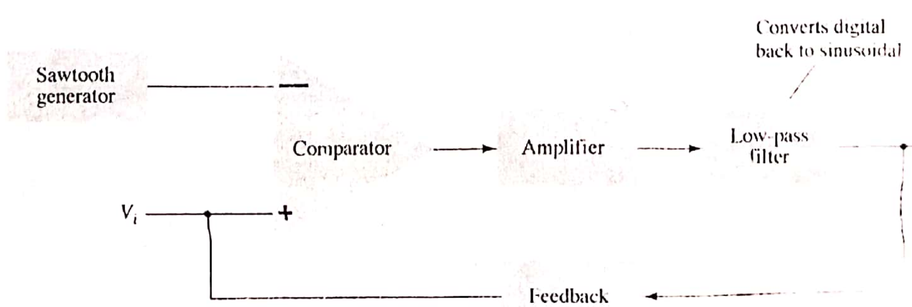


FIG. 12.27
Block diagram of class D amplifier.

(P) In a class A amplifier, $V_{CE,max} = 15V$, $V_{CE,min} = 1V$. Find the overall efficiency for (i) series-fed load,

ii) transformer coupled load.

Sol

(i) for series-fed load $\quad \eta = \dfrac{25\,(V_{CEmax} - V_{CEmin})}{V_{max}}\ \%$

$$\eta = \frac{25\,(15-1)}{15} = 23.33\%$$

(ii) Transformer coupled load $\quad \eta = \dfrac{50\,(V_{max} - V_{min})}{V_{max} + V_{min}}\ \%$

$$= \frac{50\,(15-1)}{15+1} = 43.75\%.$$

(P) For a given transistor, the thermal resistance is $8°C/W$ and for the ambient temperature T_A is $27°C$. If the transistor dissipates 3W of power, calculate the junction temperature, T_j.

Sol

$\theta = 8\,°C/W$

$T_A = 27°C$

$P_D = 3W$

$$T_j - T_A = \theta P_D$$

$$T_j = 27 + 8 \times 3 \Rightarrow 51°C.$$

(P) Calculate the effective resistance seen looking into the primary of a 15:1 transformer connected to an $8\,\Omega$ load.

Sol

$$R_p = \frac{1}{n^2} R_L \Rightarrow R_i = \frac{1}{\left(\frac{1}{15}\right)^2} \times 8 \qquad n = \frac{N_2}{N_1} = \frac{1}{15}$$

$$R_i = 15^2 \times 8 = 1.8\,k\Omega$$

(P) Calculate the harmonic distortion components for an output signal having fundamental amplitude of 2.5 V, second harmonic amplitude of 0.25 V, third harmonic amplitude of 0.1 V, and fourth harmonic amplitude of 0.05 V. Also find total harmonic distortion.

Sol: $B_1 = 2.5$; $B_2 = 0.25$; $B_3 = 0.1V$, $B_4 = 0.05$

$$D_2 = \frac{B_2}{B_1} = \frac{0.25}{2.5} \times 100\% = 10\%$$

$$D_3 = \frac{B_3}{B_1} = \frac{0.1}{2.5} \times 100\% = 4\%$$

$$D_4 = \frac{B_4}{B_1} = \frac{0.05}{2.5} \times 100\% = 2\%$$

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2} \times 100\% = \sqrt{(0.1)^2 + (0.04)^2 + (0.02)^2} \times 100\%$$

$$D = 10.95\%$$

(P) For a harmonic distortion reading of $D_2 = 0.1$, $D_3 = 0.02$, and $D_4 = 0.01$, with $I_1 = 4A$ and $R_C = 8\Omega$, calculate the total harmonic distortion, fundamental power component and total power.

Sol: $$D = \sqrt{D_2^2 + D_3^2 + D_4^2} = \sqrt{(0.1)^2 + (0.02)^2 + (0.01)^2} = 0.1$$

Fundamental power $$P_1 = \frac{I_1^2 R_C}{\cancel{2}} = \frac{4^2 \times 8}{\cancel{2}} = \cancel{64}\ 128 \text{ Watts}$$

Total power $$P = (1 + D^2) P_1$$

$$= \left[1 + (0.1)^2\right] \cancel{64}\ 128 = \cancel{64.64}\ 129.3 \text{ Watts}$$

If $R_1 = R_2$ output Voltages are same.

If output is taken across R_2 it is common collector configuration.

If output is taken across R_1 it is common Emitter configuration

So, both will not be the same since $R_{oe} \neq R_{oc}$

$\therefore$ V_{01} is in phase and V_{02} is having no phase shift.

V_{01} & V_{02} are out of phase by 180°.

Thermal Runaway:- [power Transistor Heat Sinking]

The maximum average power $P_D(max)$ which a transistor can dissipate depends upon the transistor construction and may lie in the range from a few milliwatts to 200W.

The junction temperature may raise either because of the ambient temperature rises or because of self-heating. This in turn increases the collector current, increasing power dissipation.

This results in permanently damaging the transistor which is referred to as "Thermal Runaway".

Experimentally, it is found that the steady-state temperature rise at the collector junction is proportional to the power dissipated at the junction.

$$\Delta T \propto P_D$$

$$\boxed{T_j - T_A = \Theta P_D}$$

$$\boxed{\Theta = \frac{T_j - T_A}{P_D} \ ^\circ C/W}$$

T_j – junction temp.

T_A – Ambient temp.

P_D – power dissipated in watts

Θ – thermal Resistance in $^\circ C/W$.

Condition ~~for~~ to prevent Thermal Runaway is $\boxed{\frac{\partial P_c}{\partial T_j} < \frac{1}{\theta}}$.

Where P_c is maximum collector power..

"The rate at which heat is released at the collector junction must not exceed the rate at which the heat can be dissipated."

Heat Sinks :-

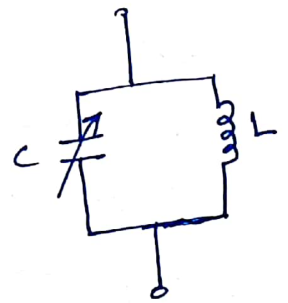
To prevent Thermal Runaway Heat Sinks are placed, which dissipate power to surroundings and keep the temperature low.

Unit-5

Tuned Amplifiers

Amplifier amplifying a signal of specific frequency or narrowband of frequencies is known as tuned amplifier.

A tuned amplifier employs a tuned circuit as shown in below figure.



Tuned Circuit

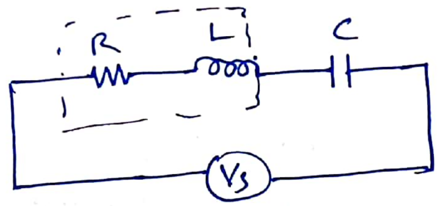
Because of the well known phenomenon called "Resonance", the tuned circuit is capable of selecting a particular or relatively narrowband of frequencies. The centre of this frequency band is the 'Resonant frequency' of the tuned circuit.

Resonant L-C circuit as a load provides high impedance and so the tuned transistor amplifiers can provide high gain because gain of a transistor amplifier depends directly on the value of its load impedance. ($A_v = \frac{A_i R_L}{R_i}$).

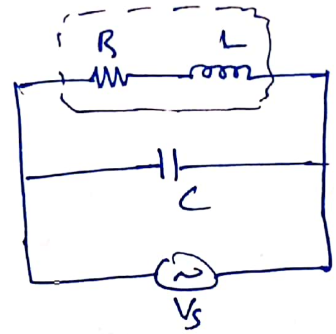
The difference between the tuned amplifier and other amplifiers is that tuned amplifiers are designed for specific, usually narrow bandwidth.

There are two types of Resonant Circuits i) series Resonance Circuit

ii) parallel Resonance Circuit.



Series resonance circuit



parallel Resonance circuit

The resistance 'R' is the effective resistance of coil itself.

At a particular frequency the inductive reactance becomes equal to capacitive reactance and the circuit then behaves as a purely resistive circuit. This phenomenon is called the "resonance" and the corresponding frequency is called the resonant frequency.

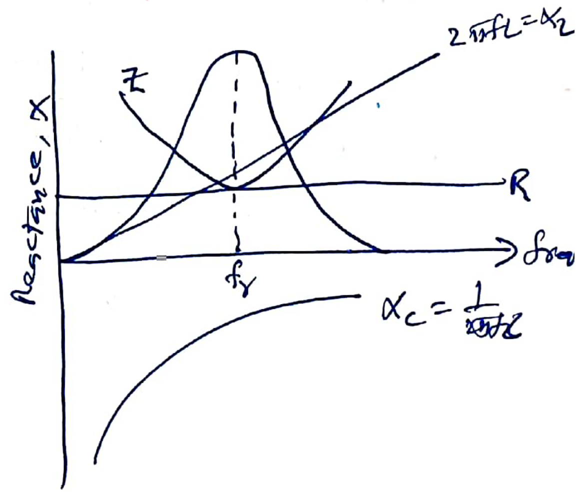
i.e., $X_L = X_C$

$$j\omega L = \frac{1}{j\omega C}$$

$$\omega^2 = \frac{1}{LC} \Rightarrow \omega = \frac{1}{\sqrt{LC}} \Rightarrow 2\pi f_r = \frac{1}{\sqrt{LC}}$$

$$\boxed{f_r = \frac{1}{2\pi\sqrt{LC}}}$$

series Impedance $Z = \sqrt{R^2 + (X_L - X_C)^2}$



Q-factor (Quality factor):

Quality factor is given as the voltage magnification that the circuit produces at resonance.

$$\text{Voltage magnification}, Q = \frac{I_{max} X_L}{I_{max} R} = \frac{X_L}{R} = \frac{\omega_r L}{R} \text{ (or) } \frac{1}{\omega_r R C}$$

$$\text{at Resonance } Q_r = \frac{\omega_r L}{R} = \frac{2\pi f_r L}{R} = \frac{2\pi L}{R} \cdot \frac{1}{2\pi\sqrt{LC}} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Higher value of Q-factor means higher selectivity of tuning Ckt.

$$\boxed{Q_r = \frac{f_r}{B.W}} = \frac{f_r}{\Delta f_r}$$

As $B.W \uparrow$ $Q_r \downarrow$ and $B.W \downarrow$: $Q \uparrow$.

Advantages of tuned circuits:

i) High selectivity ; capable of selecting desired frequency.

ii) Small collector voltage, V_{cc} ; because small 'R' is used.

iii) Small power loss ; because of reactive components L & C

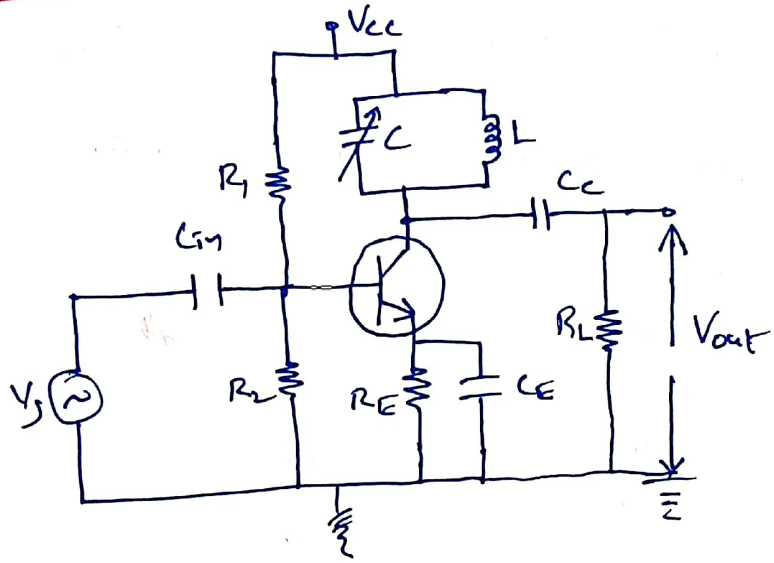
Classification of tuned amplifiers:

- Small signal tuned Amplifiers
  - Single tuned Amplifiers
    - Capacitive coupled
    - Inductive coupled
    - Transformer coupled
  - Double tuned Amplifiers
  - Stagger tuned Amplifiers
- Large signal tuned amplifiers

Single Tuned Amplifier :-

- Single tuned capacitive coupled Amplifier
- Single tuned Inductive coupled Amplifier
- Single tuned transformer coupled Amplifier.

Single tuned capacitive coupled Amplifier :-



R_1, R_2, R_E form the biasing and stabilization circuits and C_E is emitter bypass capacitor which provides low reactance path.

A parallel tuned L-C circuit connected in the collector circuit, the impedance of which depends upon the frequency, acts as a collector load.

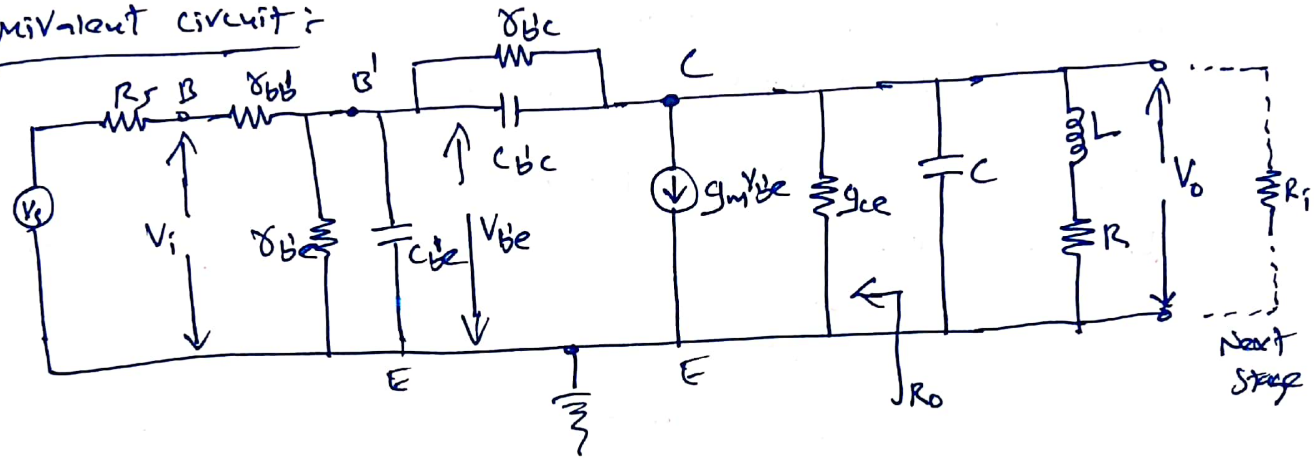
Capacitance 'C' is generally variable so that the resonant frequency of the circuit may be varied. Inductor 'L' also can be varied.

If the input signal has same frequency as the resonant frequency of L-C circuit, large amplification will be obtained because of high impedance of L-C circuit at resonant frequency.

Operation :-

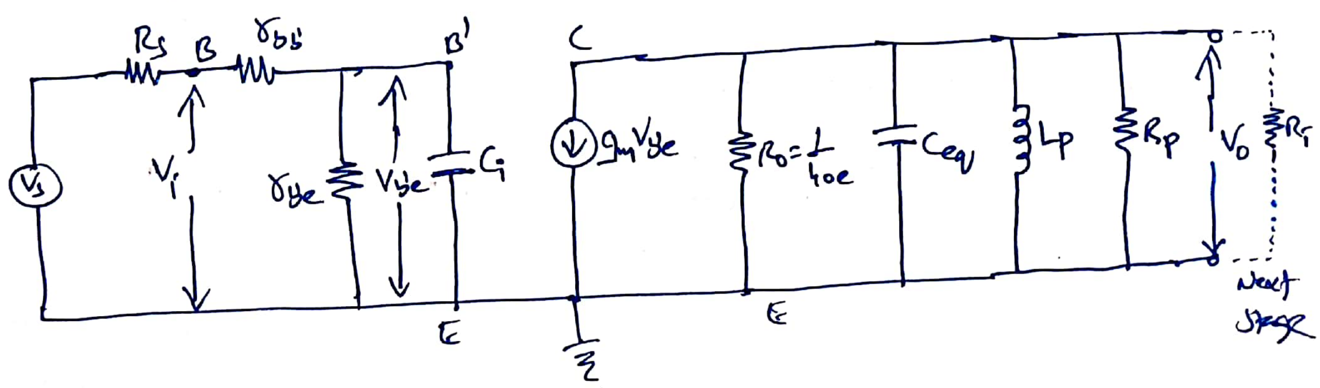
The high frequency signal to be amplified is applied between base and emitter. The resonant frequency of parallel L-C circuit is made equal to frequency of input signal by varying C (or) L. Now the tuned circuit will offer very high impedance to the signal frequency and thus large output will appear across it.

Equivalent circuit :-



'R_i' is the input resistance of next stage and 'R_o' is the output resistance of current generator $g_m V_{b'e}$.

Reactances of the bypass capacitor C_E and coupling capacitor C_c are negligibly small at the operating frequency and hence these elements are neglected in the equivalent circuit. It is simplified by applying Miller's theorem.



Here C_i & C_{eq} represent input and output circuit capacitances

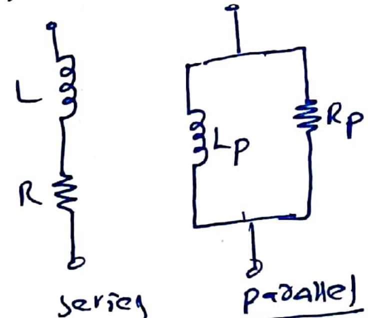
$$C_i = C_{b'e} + C_{b'c}(1-A)$$ where 'A' is voltage gain of amplifier.

$$C_{eq} = C_{b'c}\left(1-\frac{1}{A}\right) + C$$ where 'C' is tuned circuit capacitance.

$$g_{ce} = \frac{1}{r_{ce}} = h_{oe} - g_m h_{re} \approx h_{oe} = \frac{1}{R_o}$$

The series RL circuit is represented by its equivalent parallel circuit with R_p & L_p.

The conditions for equivalence are most easily established by equating the admittances of the two circuits.



Admittance of the series combination of RL is given as:

$$Y = \frac{1}{R+j\omega L}$$

$$Y = \frac{1}{R+j\omega L} \times \frac{R-j\omega L}{R-j\omega L}$$

$$Y = \frac{R-j\omega L}{R^2+\omega^2L^2} = \frac{R}{R^2+\omega^2L^2} - \frac{j\omega L}{R^2+\omega^2L^2}$$

$$Y = \frac{R}{R^2+\omega^2L^2} - \frac{j\omega^2 L}{\omega(R^2+\omega^2L^2)}$$

$$Y = \frac{1}{R_p} + \frac{1}{j\omega L_p}$$ where $R_p = \frac{R^2+\omega^2L^2}{R}$

& $L_p = \frac{R^2+\omega^2L^2}{\omega^2 L}$

Centre frequency (or) Resonant frequency:

$$f_r = \frac{1}{2\pi\sqrt{L_p C_{eq}}}$$ where $C_{eq} = C_{b'c}\left(1-\frac{1}{A}\right) + C$

$= C_o + C$

= Transistor o/p capacitance + tuned circuit capacitance.

Quality factor Q: at resonance is given as

$$Q_r = \frac{\omega_r L}{R}$$

we know that

$$R_p = \frac{R^2+\omega^2L^2}{R} = R + \frac{\omega^2L^2}{R}$$

$$\boxed{R_p \approx \frac{\omega^2L^2}{R}} \quad \because \frac{\omega^2L^2}{R} \gg 1$$

$\therefore$ Rp at resonance is

$$R_p = \frac{\omega_r^2 L^2}{R}$$

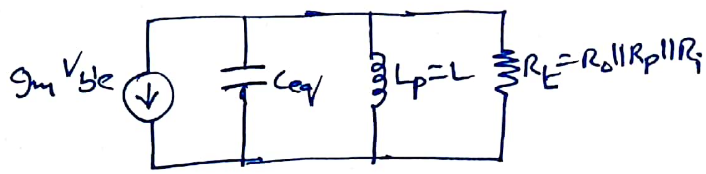
$$L_p = \frac{R^2+\omega^2L^2}{\omega^2 L} = \frac{R^2}{\omega^2 L} + L$$

$$\boxed{L_p \approx L} \quad \because \omega L \gg R.$$

$$\boxed{R_p = \omega_r Q_r L} \quad \because Q_r = \frac{\omega_r L}{R}$$

$$\& \boxed{Q_r = \frac{R_p}{\omega_r L}}.$$ this is without load.

The effective quality factor including load can be calculated looking at the simplified equivalent output circuit for single tuned amplifier.



$$Q_{eff} = \frac{\text{Susceptance of } L \text{ (or) } C}{\text{Conductance of shunt Resistance, } R_t}$$

$$Q_{eff} = \frac{1/\omega_r L}{1/R_t} = \frac{R_t}{\omega_r L} \text{ (or) } \omega_r C_{eq} R_t \Rightarrow \boxed{Q_{eff} = \frac{R_t}{\omega_r L} = \omega_r C_{eq} R_t.}$$

Voltage gain (A_v) for single tuned amplifier is given by

$$A_v = -g_m \frac{r_{b'e}}{r_{bb'}+r_{b'e}} \times \frac{R_t}{1+j2Q_{eff}\delta}$$

where δ = fraction variation in the resonant frequency

$$A_v(\text{at resonance}) = -g_m \frac{r_{b'e}}{r_{bb'}+r_{b'e}} \times R_t$$

$$\left|\frac{A_v}{A_v(\text{at resonance})}\right| = \frac{1}{\sqrt{1+(2\delta Q_{eff})^2}}$$

3dB Bandwidth of a single tuned amplifier is given by

$$\Delta f = \frac{1}{2\pi R_t C_{eq}}$$

$$= \frac{\omega_r}{2\pi Q_{eff}} \qquad \because Q_{eff} = \omega_r R_t C_{eq}$$

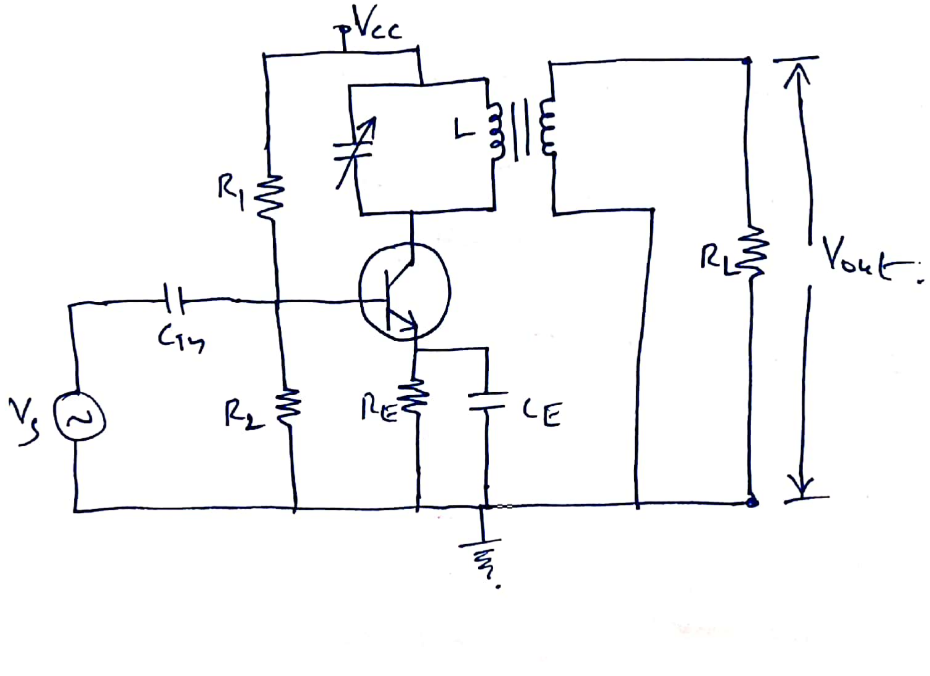
$$\Delta f = \frac{\cancel{2\pi} f_r}{\cancel{2\pi} Q_{eff}} \Rightarrow \boxed{\Delta f = \frac{f_r}{Q_{eff}}}$$

Limitations :-

Tuned Amplifiers are required to be highly selective. But high selectivity requires a tuned circuit with a high Q-factor. High Q-factor will give a high voltage gain, but at the same time it will give much reduced bandwidth because $\left(Q \propto \frac{1}{B.W}\right)$.

It means that a tuned amplifier with reduced bandwidth may not be able to amplify equally the complete band of signals and result in poor reproduction. This is called the potential "Instability" in tuned amplifiers.

Tuned Amplifier with Inductive Coupling :-



Effect of Cascading Single tuned Amplifiers on Bandwidth:

In order to obtain a high overall gain, several identical stages of tuned amplifiers can be used in cascade. When two or more identical stages are cascaded, the stages are said to be 'synchronously tuned'. In synchronously tuned amplifiers each stage is tuned to same frequency. The overall gain is the product of the voltage gains of individual stages. The effect of Bandwidth on cascading stages is as follows:

Relative gain of single tuned amplifier with respect to the gain at resonant frequency 'f_r' is given by

$$\left|\frac{A_V}{A_V(\text{at resonance})}\right| = \frac{1}{\sqrt{1+(2\delta Q_{eff})^2}}$$

Gain of 'n' stage cascaded amplifier becomes

$$\left|\frac{A_V}{A_V(\text{at resonance})}\right|^n = \left[\frac{1}{\sqrt{1+(2\delta Q_{eff})^2}}\right]^n$$

$$= \frac{1}{\left[1+(2\delta Q_{eff})^2\right]^{n/2}}$$

The 3dB frequencies for the n-stage cascaded amplifier can be found by equating $\left|\frac{A_V}{A_V(\text{at resonance})}\right|^n = 1/\sqrt{2}$

$$\left|\frac{A_V}{A_V(\text{at resonance})}\right|^n = \frac{1}{\left[1+(2\delta Q_{eff})^2\right]^{n/2}} = \frac{1}{\sqrt{2}}$$

$$\left[1+(2\delta Q_{eff})^2\right]^{n/2} = 2^{1/2}$$

$$\left[1+(2\delta Q_{eff})^2\right]^{n} = 2$$

$$1+(2\delta Q_{eff})^2 = 2^{1/n}$$

$$2\delta Q_{eff} = \sqrt{2^{1/n}-1}$$

The fractional frequency variation, $\delta = \frac{\omega-\omega_r}{\omega_r} = \frac{f-f_r}{f_r}$

$$\therefore \quad 2\left(\frac{f-f_r}{f_r}\right) Q_{eff} = \sqrt{2^{1/n}-1}$$

$$2(f-f_r)\, Q_{eff} = f_r\sqrt{2^{1/n}-1}$$

$$f-f_r = \frac{f_r}{2Q_{eff}}\sqrt{2^{1/n}-1}$$

let f_1 and f_2 are lower 3dB and upper 3dB frequencies, then

$$f_2-f_r = \frac{f_r}{2Q_{eff}}\sqrt{2^{1/n}-1}$$

lly $$f_r-f_1 = \frac{f_r}{2Q_{eff}}\sqrt{2^{1/n}-1}$$

The Bandwidth of n stage identical amplifier is given as

$$BW_n = f_2-f_1 = (f_2-f_r)+(f_r-f_1)$$

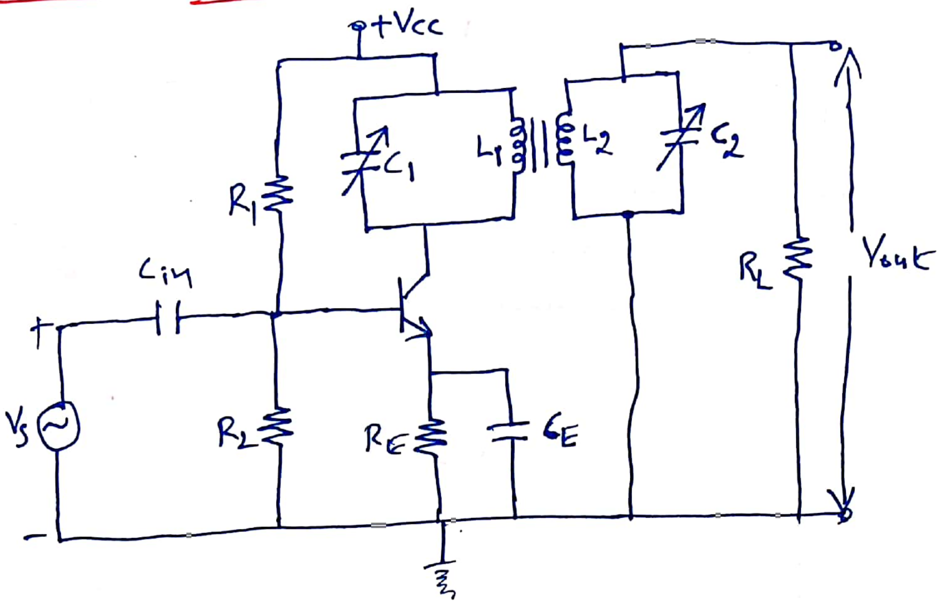
$$= \frac{f_r}{2Q_{eff}}\sqrt{2^{1/n}-1} + \frac{f_r}{2Q_{eff}}\sqrt{2^{1/n}-1}$$

$$= \frac{f_r}{Q_{eff}}\sqrt{2^{1/n}-1}$$

$$\boxed{BW_n = BW_1\sqrt{2^{1/n}-1}}$$

where BW_1 is the Bandwidth of single stage and BW_n is the Bandwidth of 'n' stages.

Double tuned Amplifier:

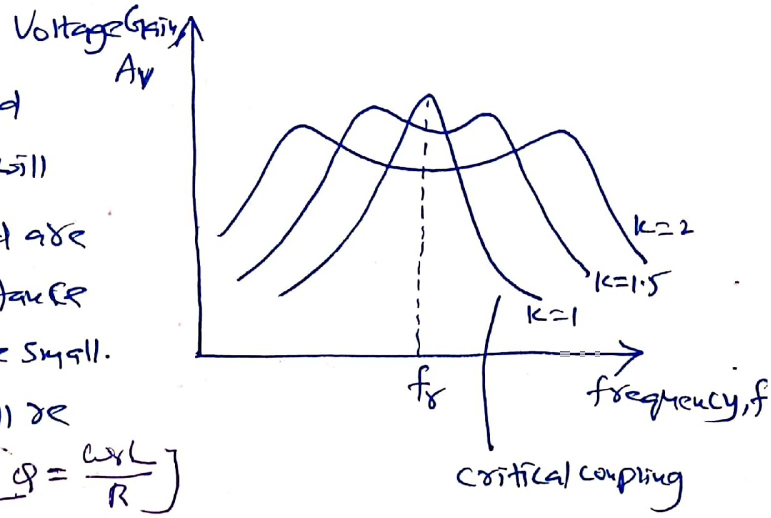


The problem of potential instability with a single tuned amplifier is overcome in a double tuned amplifier which consists of inductively coupled two tuned circuits — one (L_1, C_1) in the collector circuit and the other (L_2, C_2) in the output circuit shown in fig. above.

A change in the coupling of the two tuned circuits results in change in the shape of frequency response curve. By proper adjustment of the coupling between the two coils of the two tuned circuits, the required results (high selectivity, high voltage gain and required bandwidth) may be obtained.

- The Resonant frequency of tuned circuit connected in collector circuit is made equal to signal frequency by varying the value of C_1. Now the tuned circuit (L_1, C_1) offers very high impedance to the signal frequency and large output is developed across it.
- The output from this tuned circuit (L_1, C_1) is transferred to the second tuned circuit (L_2, C_2) through mutual induction.

Frequency Response Curve:-



- When the coils L_1 & L_2 are spaced apart, flux created by coil L_1 will not link the secondary coil, and are loosely coupled and the resistance reflected from the load will be small. Thus the resonance curve will be sharp with high value of Q. $\left[Q = \frac{\omega_r L}{R} \right]$
- When L_1 & L_2 are placed very close together, they are said to be tightly ~~packed~~ coupled, and the reflected resistance will be larger and 'Q' will be smaller.
- From the fig. Bandwidth increases with the increase in degree of coupling. Naturally, the determining factor in a double tuned circuit is the coupling, not the Q-factor. For a given frequency the tighter the coupling, the greater is the Bandwidth.

Effect of Cascading double tuned amplifiers on Bandwidth:-

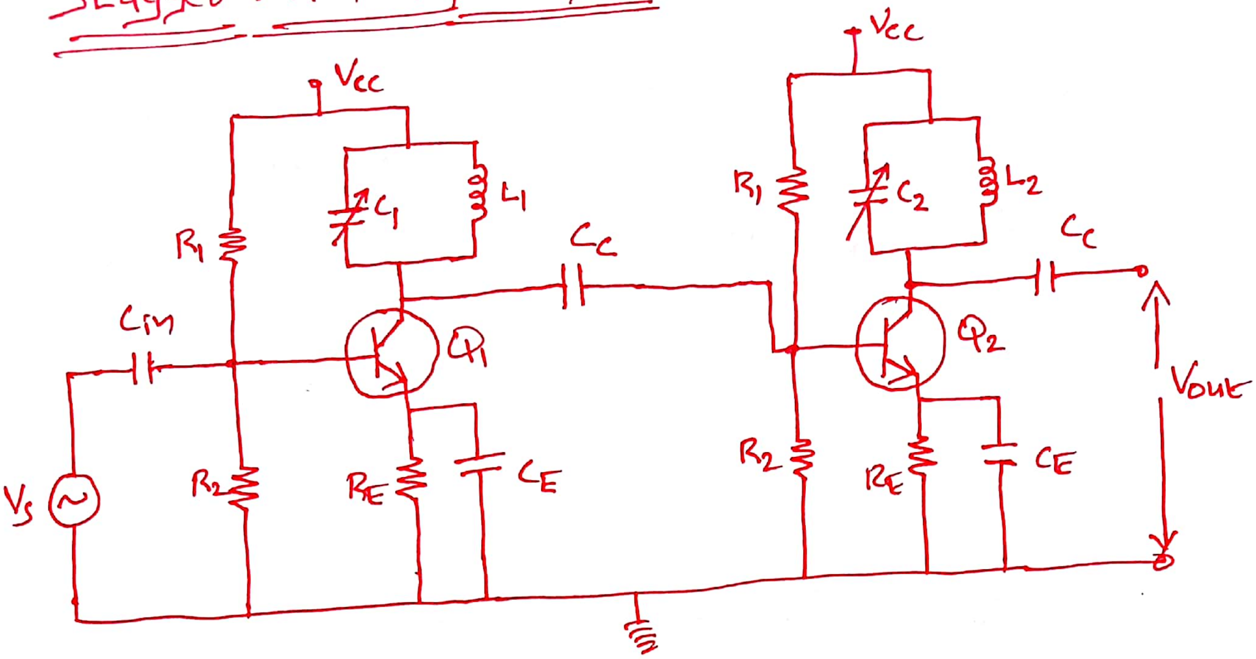
When a number of identical double tuned amplifier stages are connected in cascade the overall bandwidth of the system is narrowed and the steepness of sides of response is increased.

$$\boxed{BW_n = BW_1 \left(2^{1/n} - 1\right)^{1/4}}$$

where BW_n is n identical stage double tuned amplifiers

BW_1 is 3dB Bandwidth of single stage double tuned amplifier.

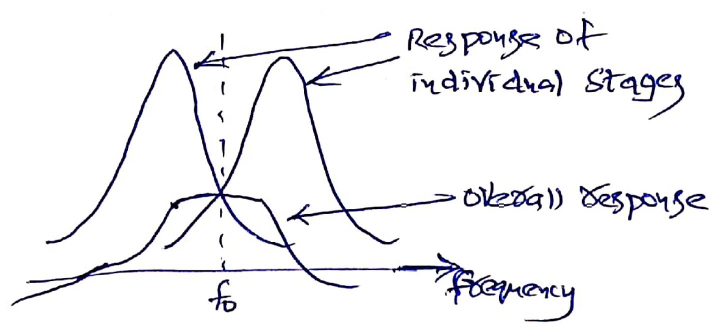
Stagger Tuned Amplifiers:-



Stagger tuned amplifiers are usually designed so that the overall response exhibits maximal flatness around the centre frequency 'f_0'.

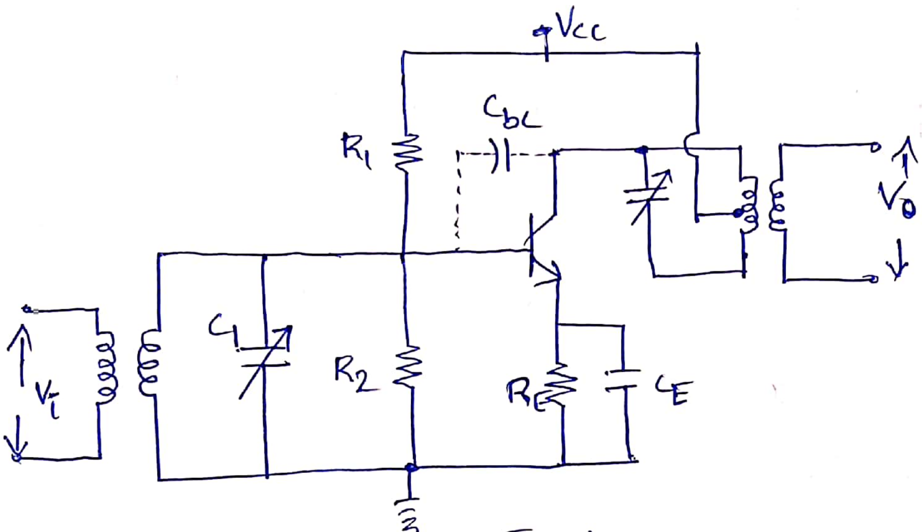
The overall frequency response of a stagger tuned amplifier is obtained by adding the individual response together. Since the resonant frequencies of different tuned circuits are displaced or staggered, they are referred to as "stagger tuned amplifier."

The main advantage of stagger tuned amplifier is increased bandwidth. Its drawbacks are reduced selectivity and they are used in RF amplifier stage in radio receivers.



Stability of Tuned Amplifiers:

In tuned RF Amplifiers, transistors are used at the frequencies nearer to their unity gain bandwidths, to amplify a narrow band of high frequencies centered around a radio frequency. At this frequency, the inter junction capacitance between base and collector (C_{bc}) of the transistor becomes dominant.



Tuned RF Stage

With this circuit condition, if some feedback signal manages to reach the input from output in a positive manner with proper phase shift, then there is possibility of circuit converted to an unstable one, generating its own oscillations and can stop working as an amplifier.

In order to prevent oscillations it is necessary to reduce the stage gain to a level that ensured circuit stability.
This could be possible by lowering the Q of tuned circuits.
Instead of loosing the circuit performance to achieve stability, professor L. A. Hazeltine introduced a circuit in which it neutralizes the troublesome effect which cancels the signal coupled through the collector to base capacitance.

(P1) A single tuned RF amplifier uses a transistor with an output resistance of 50k, output capacitance of 15pF and input resistance of next stage is 20kΩ. The tuned circuit consists of 47pF capacitance in parallel with series combination of 1μH inductance and 2Ω resistance. Calculate i) Resonant frequency

ii) Effective Quality factor

iii) Bandwidth of the circuit.

Sol: $R_o = 50k$; $C_o = 15pF$; $L = 1\times10^{-6}$; $C_{eq} = 15pF + 47pF = 62pF$.

$R_i = 20k$; $C = 47pF$; $R = 2\Omega$

i) Resonant Frequency, $F_r = \frac{1}{2\pi\sqrt{L C_{eq}}} = \frac{1}{2\pi\sqrt{1\times10^{-6}\times 62pF}} = 20.2\ MHz.$

ii) Effective Quality Factor, $Q_{eff} = \omega_r C_{eq} R_t$

$= 2\pi f_r C_{eq} (R_o \parallel R_p \parallel R_i)$

$R_p = \frac{\omega_r^2 L^2}{R}$ &

$R_p = \frac{(2\pi\ 20.2M)^2 (1\times10^{-6})^2}{2} = 8054\Omega.$

$Q_{eff} = 2\pi(20.2M)\ 62p \times (50k \parallel 8054 \parallel 20k) = 40.52$

iii) Bandwidth of the circuit is

$B.W = \frac{f_r}{Q_{eff}} = \frac{20.2M}{40.52} = 498.5\ KHz.$

(P2) The Bandwidth for single tuned amplifier is 20kHz. Calculate the bandwidth if such three stages are cascaded. Also calculate the Bandwidth for four stages.

Sol: $B.W_1 = 20k\ Hz$; $n=3$ & $n=4$.

i) $B.W_n = B.W_1\left(\sqrt{2^{1/n}-1}\right) = 20k\sqrt{2^{1/3}-1} = 10.196\ KHz.$

ii) $B.W_4 = 20k\sqrt{2^{1/4}-1} = 8.7KHz.$

(P3) The Bandwidth for double tuned amplifier is 20KHz. calculate the Bandwidth if such three stages are cascaded.

Sol

$B.W = 20KHz$; $n=3$

$B.W_n = B.W_1 \left[2^{1/n}-1\right]^{1/4}$

$B.W_3 = 20K\left[2^{1/3}-1\right]^{1/4} = \underline{\underline{14.28\ KHz.}}$

Oscillators

Any circuit which is used to generate an ac voltage without an ac input signal is called an oscillator.

To generate ac voltage, the circuit is supplied with energy from a dc source.

Conditions for oscillation :- [Barkhausen criterion]:

For positive feedback we have

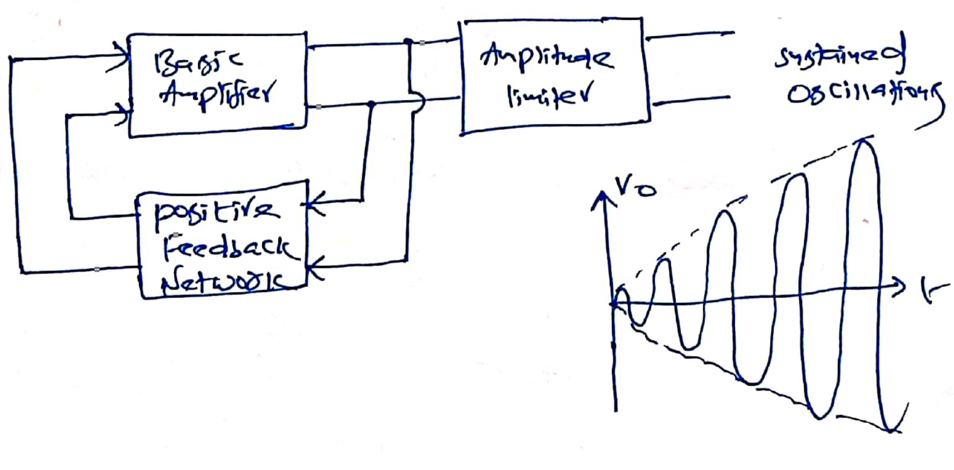
$$A_f = \frac{A}{1 - A\beta}$$

if $A\beta = 1$; $A_f = \infty$. oscillations exists

∴ The essential conditions for maintaining oscillations are;

i) $|A\beta| = 1$; the magnitude of loop gain must be unity.

ii) The total phase shift around the closed loop is zero or 360 degrees. [i.e., Inphase]



Block diagram of an oscillator

Low Freq — High Freq

RC — LC

RC Oscillators :-

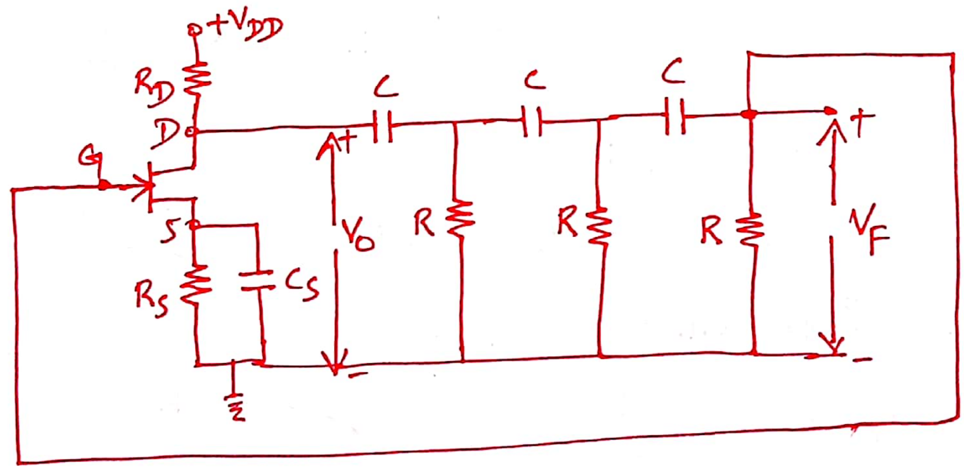
All LC oscillators are very popular for generating high frequency oscillations but they cannot be employed for generation of low frequency oscillations as they become too bulky and expensive.

RC oscillators are found more suitable for generating audio frequencies as they provide good frequency stability and proper waveform.

R-C phase Shift Oscillator — Wien-Bridge Oscillator

RC phase Shift Oscillator using FET:-

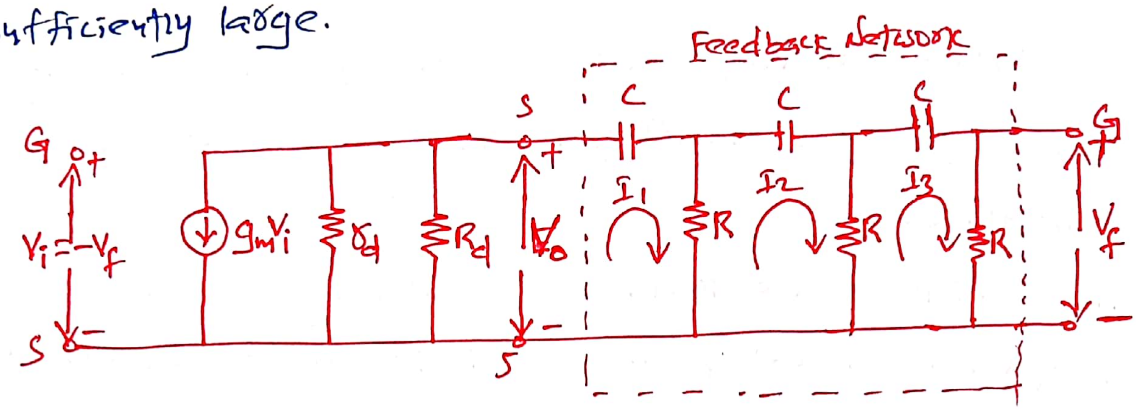
Circuit:-



— Here FET amplifier is followed by three cascaded arrangements of capacitor 'C' and a resistor 'R'. The output of last RC combination being returned to the Gate.

The amplifier shifts by 180 the phase of any voltage which appears on the gate and the RC network shifts by 180°, and at this frequency the total phase shift is 360° or 0°.

This particular frequency is the one at which the circuit will oscillate, provided the magnitude of amplification is sufficiently large.



Small-Signal Equivalent circuit

From the loop equations according to KVL we get:

$$V_o = \frac{I_1}{j\omega C_f} + R(I_1 - I_2) \Rightarrow V_o = I_1\left[\frac{1}{j\omega C_f} + R\right] - RI_2 \longrightarrow (1)$$

$$R(I_2 - I_1) + \frac{I_2}{j\omega C} + R(I_2 - I_3) = 0 \Rightarrow -I_1 R + I_2\left(2R + \frac{1}{j\omega C}\right) - I_3 R = 0 \longrightarrow (2)$$

$$R(I_3 - I_2) + \frac{I_3}{j\omega C} + I_3 R = 0 \Rightarrow -I_2 R + I_3\left(2R + \frac{1}{j\omega C}\right) = 0 \longrightarrow (3)$$

From equation (3) we get

$$-I_2 R = -I_3 R\left[2 + \frac{1}{j\omega RC}\right] \Rightarrow I_2 = I_3\left(2 + \frac{1}{j\omega RC}\right) \longrightarrow (4)$$

Substituting (4) in equation (2) we get.

$$-I_1 R + I_3\left(2 + \frac{1}{j\omega RC}\right)\left(2R + \frac{1}{j\omega C}\right) - I_3 R = 0$$

$$-I_1 R + I_3\left(2 + \frac{1}{j\omega RC}\right) R\left(2 + \frac{1}{j\omega RC}\right) - I_3 R = 0$$

$$-I_1 R + I_3 R\left[\left(2 + \frac{1}{j\omega RC}\right)\left(2 + \frac{1}{j\omega RC}\right) - 1\right] = 0$$

$$I_1 = I_3\left[\left(2 + \frac{1}{j\omega RC}\right)^2 - 1\right] \longrightarrow (5)$$

Substituting (4) & (5) in equation (1), we get

$$V_0 = I_1\left(\frac{1}{j\omega C} + R\right) - R I_2$$

$$V_0 = I_3\left[\left(2+\frac{1}{j\omega RC}\right)^2 - 1\right]\left[\frac{1}{j\omega C} + R\right] - R\, I_3\left(2+\frac{1}{j\omega RC}\right)$$

$$V_0 = I_3\left[\left(2+\frac{1}{j\omega RC}\right)^2 - 1\right]\left[R\left(1+\frac{1}{j\omega RC}\right)\right] - R\cdot I_3\left(2+\frac{1}{j\omega RC}\right)$$

$$V_0 = I_3 R\left[\left[\left(2+\frac{1}{j\omega RC}\right)^2 - 1\right]\left[1+\frac{1}{j\omega RC}\right] - 2 - \frac{1}{j\omega RC}\right]$$

substitute $\frac{1}{\omega RC} = \alpha$ & $V_F = I_3 R$

$$V_0 = V_F\left[\left[\left(2+\frac{\alpha}{j}\right)^2 - 1\right]\left[1+\frac{\alpha}{j}\right] - 2 - \frac{\alpha}{j}\right]$$

$$V_0 = V_F\left\{\left(4-\alpha^2+\frac{4\alpha}{j}-1\right)\left(1+\frac{\alpha}{j}\right) - 2 - \frac{\alpha}{j}\right\}$$

$$V_0 = V_F\left\{\left(3-\alpha^2+\frac{4\alpha}{j}\right)\left(1+\frac{\alpha}{j}\right) - 2 - \frac{\alpha}{j}\right\}$$

$$V_0 = V_F\left\{3-\alpha^2+\frac{4\alpha}{j}+\frac{3\alpha}{j}-\frac{\alpha^3}{j}-4\alpha^2-2-\frac{\alpha}{j}\right\}$$

$$V_0 = V_F\left\{1-5\alpha^2-\frac{\alpha^3}{j}+\frac{6\alpha}{j}\right\}$$

$$V_0 = V_F\left\{1-5\alpha^2+j\alpha^3-j6\alpha\right\}$$

$$\frac{V_F}{V_0} = \frac{1}{1-5\alpha^2+j\alpha(\alpha^2-6)} \Rightarrow \beta = \frac{V_F}{V_0} = \frac{1}{1-5\alpha^2+j\alpha(\alpha^2-6)} \rightarrow (6)$$

For determining frequency of oscillations, the imaginary part must be equal to zero.

$$\alpha(\alpha^2-6)=0\ ;\ \alpha^2=6 \Rightarrow \alpha=\sqrt{6}$$

$$\frac{1}{\omega_r RC} = \sqrt{6} \Rightarrow \omega_r = \frac{1}{RC\sqrt{6}}$$

$$\therefore\ \boxed{f_r = \frac{1}{2\pi RC\sqrt{6}}}$$

The condition for maintaining sustained oscillations is obtained by substituting 'f_r' value in equation ⑥ i.e; $\alpha = \sqrt{6}$ in eq/⑥, then

$$\beta = \frac{1}{1-5\alpha^2 + j0}$$

$$\beta = \frac{1}{1-5\times 6} = \frac{-1}{29} = \frac{1}{29}\angle 180^\circ .$$

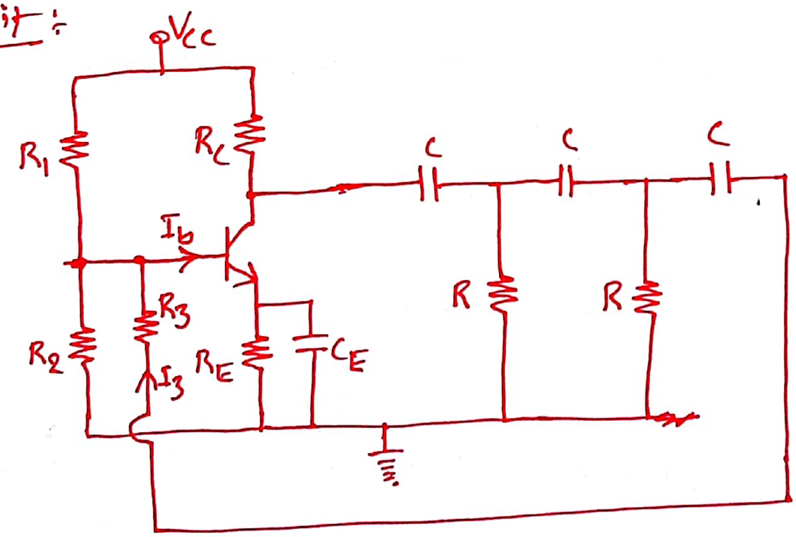
$$|A\beta| = 1$$

$$\left| A \times \frac{-1}{29} \right| = 1 \Rightarrow \boxed{A \geq 29}$$

In order that $A\beta$ shall not be less than unity, it is required that $|A|$ must be at least 29, otherwise the circuit cannot made to oscillate. In this voltage-series feedback is used.

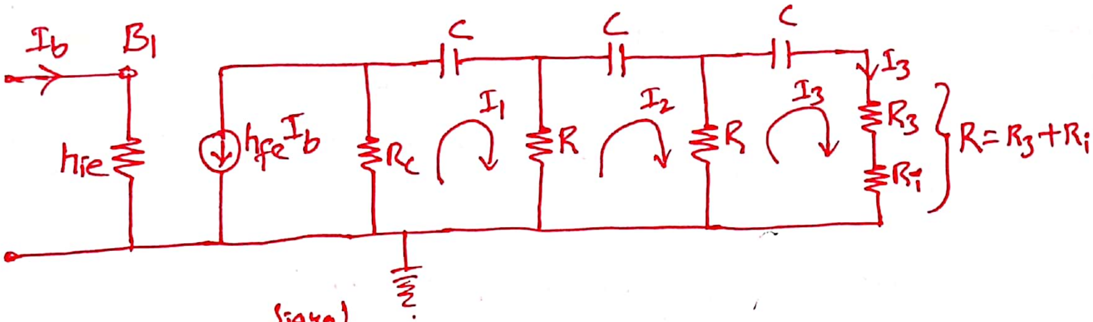
RC phase Shift Oscillator using Transistor:

Circuit:



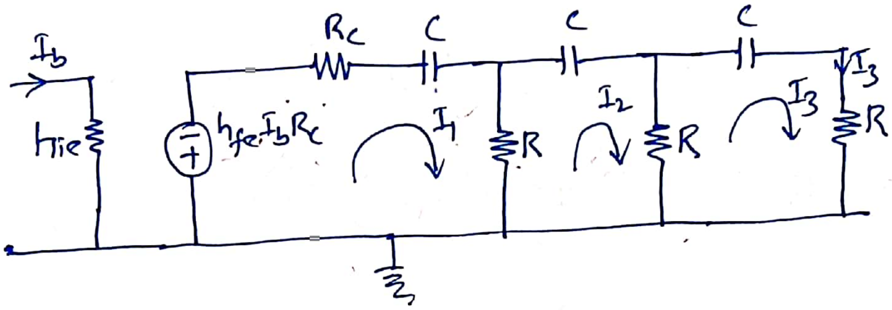
This circuit employs voltage-shunt feedback by the feed back network. Here, the Resistor ~~R_3~~ $R_i = h_{ie}$ is the input resistance of the transistor.

R_1, R_2, R_C, R_E are used for biasing the transistor.



Signal
Small Equivalent circuit

The above circuit can be again simplified as :



writing Loop equations for the above circuit we have:

$$h_{fe}I_bR_c + R_cI_1 + \frac{I_1}{j\omega C} + R(I_1 - I_2) = 0 \Rightarrow h_{fe}I_bR_c + I_1\left(R_c + \frac{1}{j\omega C} + R\right) - I_2R = 0 \rightarrow (1)$$

$$R(I_2 - I_1) + \frac{I_2}{j\omega C} + R(I_2 - I_3) = 0 \Rightarrow -I_1R + I_2\left(2R + \frac{1}{j\omega C}\right) - I_3R = 0 \rightarrow (2)$$

$$R(I_3 - I_2) + \frac{I_3}{j\omega C} + I_3R = 0 \Rightarrow -I_2R + I_3\left(2R + \frac{1}{j\omega C}\right) = 0 \rightarrow (3)$$

From equation (3) ;

$$-I_2R = -I_3R\left(2 + \frac{1}{j\omega RC}\right) \Rightarrow I_2 = I_3\left(2 + \frac{1}{j\omega RC}\right) \rightarrow (4)$$

Substituting eq (4) in eq (2) we get

$$-I_1R + I_3\left(2 + \frac{1}{j\omega RC}\right)\left(2R + \frac{1}{j\omega C}\right) - I_3R = 0$$

$$-I_1R + I_3\left(2 + \frac{1}{j\omega RC}\right)R\left(2 + \frac{1}{j\omega RC}\right) - I_3R = 0$$

$$-I_1R + I_3R\left[\left(2 + \frac{1}{j\omega RC}\right)^2 - 1\right] = 0$$

$$I_1 = I_3\left[\left(2 + \frac{1}{j\omega RC}\right)^2 - 1\right] \rightarrow (5)$$

Substituting equations (4) & (5) in equation (1), we get

$$h_{fe} I_b R_c + I_3\left(R_c + \frac{1}{j\omega C} + R\right) - I_2 R = 0$$

$$h_{fe} I_b R_c + I_3\left[\left(2+\frac{1}{j\omega RC}\right)^2 - 1\right] R\left[\frac{R_c}{R} + \frac{1}{j\omega RC} + 1\right] - I_3\left(2+\frac{1}{j\omega RC}\right)R = 0$$

$$h_{fe} I_b R_c + I_3 R\left\{\left[\left(2+\frac{1}{j\omega RC}\right)^2 - 1\right]\left[\frac{R_c}{R} + \frac{1}{j\omega RC} + 1\right] - 2 - \frac{1}{j\omega RC}\right\} = 0$$

Substituting $\frac{1}{\omega RC} = \alpha$ & $I_3 = I_b$ [bcz output current I_3 is feed back to input base]

& $\frac{R_c}{R} = k$

$$h_{fe} I_b R_c + I_b R\left\{\left[\left(2+\frac{\alpha}{j}\right)^2 - 1\right]\left[\cancel{\frac{R_c}{R}} k + \frac{\alpha}{j} + 1\right] - 2 - \frac{\alpha}{j}\right\} = 0$$

$$h_{fe} I_b R_c + I_b R\left\{\left(3 - \alpha^2 + \frac{4\alpha}{j}\right)\left(k + \frac{\alpha}{j} + 1\right) - 2 - \frac{\alpha}{j}\right\} = 0$$

$$I_b R\left[h_{fe}\frac{R_c}{R} + \left\{\left(3-\alpha^2+\frac{4\alpha}{j}\right)k + \frac{3\alpha}{j} - \frac{\alpha^3}{j} - 4\alpha^2 + 3 - \alpha^2 + \frac{4\alpha}{j} - 2 - \frac{\alpha}{j}\right\}\right] = 0$$

$$h_{fe} k + 3k - \alpha^2 k + \frac{4\alpha k}{j} + \frac{6\alpha}{j} - \frac{\alpha^3}{j} - 5\alpha^2 + 1 = 0$$

$$h_{fe} k + 3k - \alpha^2 k - 5\alpha^2 + 1 - j4\alpha k - j6\alpha + j\alpha^3 = 0$$

$$h_{fe} k + 3k - \alpha^2 k - 5\alpha^2 + 1 + j\alpha\left(\alpha^2 - 6 - 4k\right) = 0 \rightarrow (6)$$

For determining frequency of oscillations, the imaginary part is zero.

$$\alpha\left(\alpha^2 - 6 - 4k\right) = 0 \Rightarrow \alpha^2 - 6 - 4k = 0$$

$$\alpha^2 = 6 + 4k \Rightarrow \alpha = \sqrt{6+4k}$$

$$\frac{1}{\omega_r RC} = \sqrt{6+4k} \Rightarrow \omega_r = \frac{1}{RC\sqrt{6+4k}}$$

$$2\pi f_r = \frac{1}{RC\sqrt{6+4k}}$$

$$\therefore \boxed{f_r = \frac{1}{2\pi RC\sqrt{6+4k}}}$$

The condition for maintaining sustained oscillations is obtained by substituting 'f' value in equation ⑥ i.e; $\alpha^2 = 6+4k$ into eq ⑥, then

$$h_{fe}k + 3k - \alpha^2 k - 5\alpha^2 + 1 + j\alpha(0) = 0$$

$$h_{fe}k + 3k - (6+4k)k - 5(6+4k) + 1 = 0$$

$$h_{fe}k + 3k - 6k - 4k^2 - 30 - 20k + 1 = 0$$

$$k\left[h_{fe} + 3 - 6 - 4k - \frac{30}{k} - 20 + \frac{1}{k}\right] = 0$$

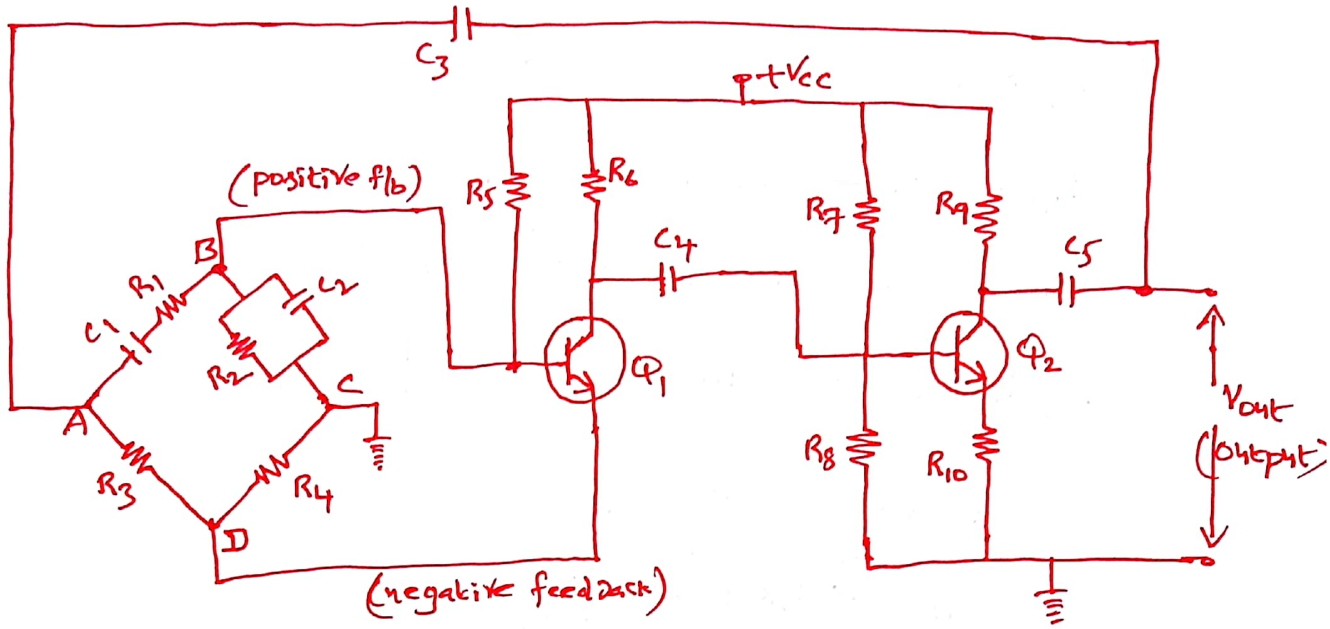
$$h_{fe} + (-23) - 4k - \frac{29}{k} = 0$$

$$\therefore \boxed{h_{fe} \geq 4k + 23 + \frac{29}{k}.}$$

The value of 'k' (where $k = \frac{R_C}{R}$) which gives minimum h_{fe} turns out to be 2.7, and for this optimum value of $\frac{R_C}{R}$, we find $h_{fe} = 44.5$.

A transistor with a small-signal common-emitter short-circuit current gain less than 44.5 cannot be used in this phase-shift oscillator.

Wien-Bridge Oscillator:



This type of oscillator is simple in design, compact in size, stable in frequency output. It is popular oscillator used in audio and sub-audio frequency ranges (20–20kHz).

It is a two stage amplifier with an RC bridge circuit.

RC Bridge circuit (Wien Bridge) is a lead-lag network in which frequency stability increases. If it is not present this results in poor frequency stability.

In this circuit $R_1 - C_1$ acts as lead network

$R_2 - C_2$ acts as Lag network

& $R_3 - R_4$ acts as a voltage divider network.

'R_1' is in series with 'C_1' and R_3, R_4 & R_2 are in parallel with 'C_2'.

From the analysis the Bridge will be balanced only when it follows the below condition:

$$R_3 \times [R_2 \| C_2] = R_4 \times \left[R_1 + \frac{1}{j\omega C_1}\right]$$

$$R_3 \times \left[\frac{R_2 \times \frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}}\right] = R_4 \left[R_1 + \frac{1}{j\omega C_1}\right]$$

$$\frac{R_3 R_2}{1 + j\omega R_2 C_2} = R_4 R_1 + \frac{R_4}{j\omega C_1}$$

$$R_3 R_2 = R_4 R_1 (1 + j\omega R_2 C_2) + \frac{R_4}{j\omega C_1}(1 + j\omega R_2 C_2)$$

$$R_3 R_2 = R_4 R_1 + j\omega R_1 R_2 R_4 C_2 + \frac{R_4}{j\omega C_1} + \frac{R_2 R_4 C_2}{C_1}$$

$$R_3 R_2 - R_4 R_1 - R_2 R_4 \frac{C_2}{C_1} - j\omega R_1 R_2 R_4 C_2 - \frac{R_4}{j\omega C_1} = 0$$

$$R_3 R_2 - R_4 R_1 - R_2 R_4 \frac{C_2}{C_1} - j\left[\omega R_1 R_2 R_4 C_2 - \frac{R_4}{\omega C_1}\right] = 0 \rightarrow (1)$$

To find frequency of oscillations make imaginary part to zero.

$$-\left(\omega R_1 R_2 R_4 C_2 - \frac{R_4}{\omega C_1}\right) = 0$$

$$\omega_r R_1 R_2 \cancel{R_4} C_2 = \frac{\cancel{R_4}}{\omega_r C_1} \Rightarrow \omega_r^2 = \frac{1}{R_1 R_2 C_1 C_2}$$

$$\omega_r = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \Rightarrow 2\pi f_r = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

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

if $C_1 = C_2 = C$ & $R_1 = R_2 = R$ then $\boxed{f_r = \frac{1}{2\pi RC}}$

In a Bridge circuit the output will be inphase with input only when the bridge is balanced i.e; at resonant frequency. At all other frequencies the bridge is off-balance.

Substituting $f_r = \frac{1}{2\pi RC}$ in eq① we get

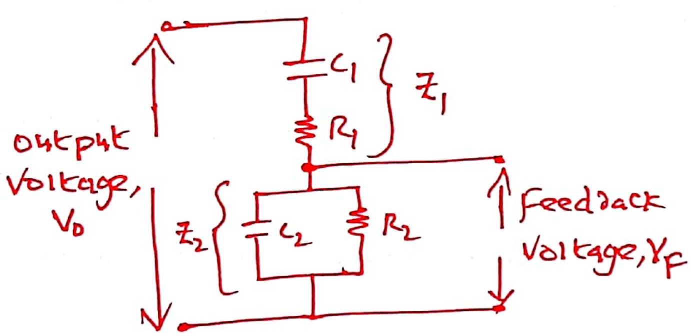
$$R_3 R_2 - R_4 R_1 - R_2 R_4 \frac{C_2}{C_1} - 0 = 0$$

for $R_1 = R_2 = R$ & $C_1 = C_2 = C$ then

$$R_3 R - R_4 R - R \cdot R_4 \frac{\cancel{C}}{\cancel{C}} = 0$$

$$R_3 - 2R_4 = 0 \Rightarrow \boxed{R_3 = 2R_4}$$

Feedback factor, β :-



Feedback factor (or) gain of feedback network (β) is defined as:

$$\beta = \frac{V_F}{V_0}$$

From the circuit we have

$$V_F = \frac{Z_2}{Z_1 + Z_2} V_0$$

$$\frac{V_F}{V_0} = \frac{Z_2}{Z_1 + Z_2}$$

$$Z_2 = R_2 \parallel \frac{1}{j\omega C_2}$$

$$Z_1 = R_1 + \frac{1}{j\omega C_1}$$

$$\therefore \beta = \frac{Z_2}{Z_1 + Z_2}$$

$$= \frac{R_2 \parallel \frac{1}{j\omega C_2}}{R_1 + \frac{1}{j\omega C_1} + \left(R_2 \parallel \frac{1}{j\omega C_2}\right)}$$

$$= \frac{R_2 \times \frac{1}{j\omega C_2} \Big/ R_2 + \frac{1}{j\omega C_2}}{R_1 + \frac{1}{j\omega C_1} + \frac{R_2 \times \frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}}}$$

$$\beta = \frac{\dfrac{R_2}{1+j\omega R_2 C_2}}{R_1 + \dfrac{1}{j\omega C_1} + \dfrac{R_2}{1+j\omega R_2 C_2}}$$

$$\beta = \frac{R_2}{\left(R_1 + \frac{1}{j\omega C_1}\right)(1+j\omega R_2 C_2) + R_2}$$

for $R_1 = R_2 = R$ & $C_1 = C_2 = C$

& $f_0 = \frac{1}{2\pi RC}$

$\omega_0 = \frac{1}{RC}$

$$\beta = \frac{R}{\left(R + \frac{1}{j\omega_0 C}\right)(1+j\omega_0 RC) + R}$$

$$= \frac{R}{\left(R + \frac{1}{j\frac{1}{R\cancel{C}}\times\cancel{C}}\right)\left(1+j\frac{1}{\cancel{RC}}\times\cancel{RC}\right) + R}$$

$$= \frac{R}{\left(R + \frac{R}{j}\right)(1+j) + R} = \frac{R}{(R-jR)(1+j)+R}$$

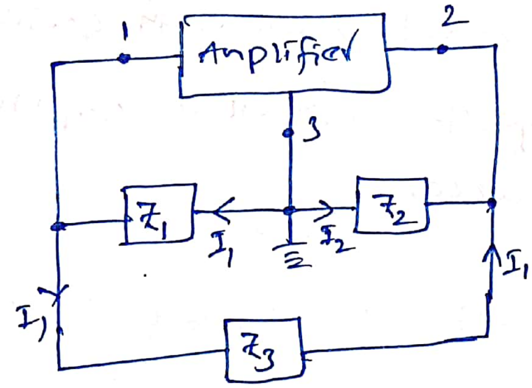
$$\beta = \frac{R}{R - \cancel{jR} + \cancel{jR} + R + R} = \frac{\cancel{R}}{3\cancel{R}} = \frac{1}{3}. \Rightarrow \boxed{\beta = 1/3}$$

$|A\beta| = 1$

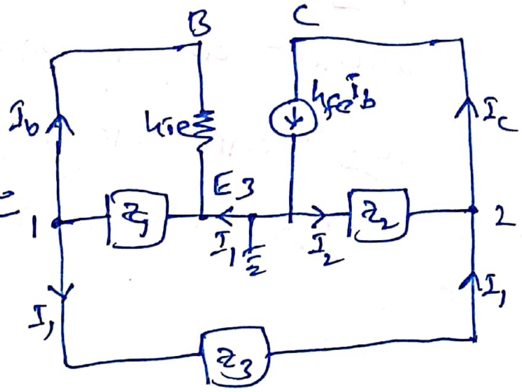
$|A \times 1/3| = 1 \Rightarrow \boxed{A \geq 3}$

∴ Amplifier gain must be atleast equal to '3' to ensure sustained oscillations.

General form of an LC oscillator:



$\approx$



Equivalent circuit

Z_1, Z_2, Z_3 are reactive elements consisting feedback tank circuit which determine frequency of oscillation.

Frequency of oscillation of LC oscillator is $f_r = \frac{1}{2\pi\sqrt{LC}}$

1 & 3 are input terminals

2 & 3 are output terminals

Condition for oscillation: $|A_v \beta| = 1$

Load Impedance:

$Z_1 \parallel h_{ie}$ equivalent impedance Z' is

$$\frac{1}{Z'} = \frac{1}{Z_1} + \frac{1}{h_{ie}} \Rightarrow Z' = \frac{Z_1 h_{ie}}{Z_1 + h_{ie}}$$

Z_L load impedance between 2 & 3 is equivalent impedance of $Z_2 \parallel (Z' + Z_3)$ i.e; $Z_L = Z_2 \parallel (Z_3 + Z')$ $[\because Z' = Z_1 \parallel h_{ie}]$

$$\therefore \frac{1}{Z_L} = \frac{1}{Z_2} + \frac{1}{Z' + Z_3}$$

$$= \frac{1}{Z_2} + \frac{1}{\frac{Z_1 h_{ie}}{Z_1 + h_{ie}} + Z_3}$$

$$= \frac{1}{z_2} + \frac{z_1 + h_{ie}}{z_1 h_{ie} + z_1 z_3 + h_{ie} z_3}$$

$$= \frac{1}{z_2} + \frac{z_1 + h_{ie}}{h_{ie}(z_1 + z_3) + z_1 z_3}$$

$$= \frac{(z_1+z_3)h_{ie} + z_1 z_3 + (z_1 + h_{ie}) z_2}{z_2 \left[h_{ie}(z_1+z_3) + z_1 z_3 \right]}$$

$$\frac{1}{z_L} = \frac{h_{ie}(z_1 + z_2 + z_3) + z_1 z_2 + z_1 z_3}{z_2 \left[h_{ie}(z_1+z_3) + z_1 z_3 \right]}$$

$$\therefore z_L = \frac{z_2 \left(h_{ie}(z_1+z_3) + z_1 z_3 \right)}{h_{ie}(z_1+z_2+z_3) + z_1 z_2 + z_1 z_3}$$

Voltage gain without feedback ; $A_V = \frac{-h_{fe} \cancel{I_b} Z_L}{h_{ie} \cancel{I_b}}$

$$A_V = \frac{-h_{fe} z_L}{h_{ie}}$$

output voltage in terms of current I_1 is

$$V_0 = -I_1 (z' + z_3) = -I_1 \left(\frac{z_1 h_{ie}}{z_1 + h_{ie}} + z_3 \right)$$

$$= -I_1 \left(\frac{h_{ie}(z_1+z_3) + z_1 z_3}{z_1 + h_{ie}} \right)$$

Voltage feedback to input terminal 1 & 3 is

$$V_{f8} = -I_1 z' = -I_1 \left[\frac{z_1 h_{ie}}{z_1 + h_{ie}} \right]$$

Feedback ratio; $\beta = \frac{V_{fb}}{V_o} = \dfrac{\cancel{-I_1}\left[\frac{z_1 h_{ie}}{z_1 + h_{ie}}\right]}{\cancel{-I_1}\left(\frac{h_{ie}(z_1+z_3)+z_1 z_3}{z_1 + h_{ie}}\right)}$

$$\beta = \frac{z_1 h_{ie}}{h_{ie}(z_1+z_3)+z_1 z_3}$$

Equation for oscillator is

$$|A_v \beta| = 1.$$

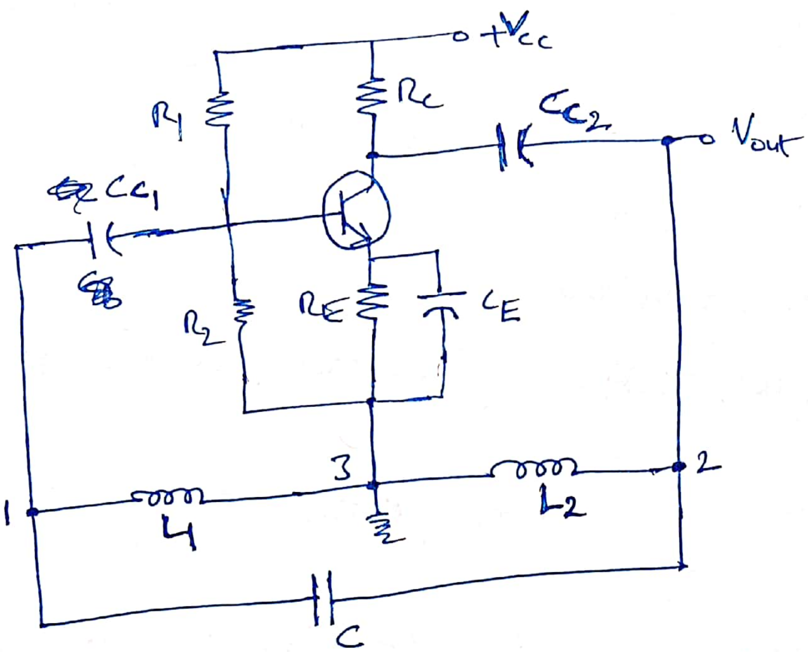
$$\left[\frac{-h_{fe} z_2}{h_{ie}}\right]\left[\frac{z_1 h_{ie}}{h_{ie}(z_1+z_3)+z_1 z_3}\right] = 1.$$

$$\frac{h_{fe} z_1 z_2}{h_{ie}(z_1+z_2+z_3)+z_1 z_2 + z_1 z_3} = -1$$

$$\boxed{h_{ie}(z_1+z_2+z_3) + z_1 z_2 (1+h_{fe}) + z_1 z_3 = 0.}$$

This is the general equation for oscillator.

Hartley Oscillator:



Z_1 & Z_2 are inductors and Z_3 is a capacitor.

Resistors R_1, R_2 & R_E provide the necessary dc bias to the transistor.

C_E is a bypass capacitor.

C_{c_1} & C_{c_2} are coupling capacitors.

The feedback network consisting of inductors L_1 & L_2 and capacitor 'C' determines the frequency of oscillator.

- When the supply voltage +Vcc is switched, a transient current is produced in the tank circuit and damped harmonic oscillations are setup in the circuit.

- If Terminal '1' is at positive potential then terminal '2' is at negative potential with respect to '3'. Thus the phase difference between the terminals 1 and 2 is always 180°. In CE mode the transistor provides phase difference of 180° between input and output.

∴ The total phase shift is 360°.

If the feedback is adjusted so that the loop gain $A\beta = 1$, the circuit acts as an oscillator.

Analysis:

$$Z_1 = j\omega L_1 + j\omega M$$ where 'M' is Mutual Inductance between inductors.

$$Z_2 = j\omega L_2 + j\omega M$$

$$Z_3 = \frac{1}{j\omega C}$$

Substituting the values in equation

$$h_{ie}(Z_1+Z_2+Z_3) + Z_1Z_2(1+h_{fe}) + Z_1Z_3 = 0$$

$$h_{ie}\left(j\omega L_1 + j\omega M + j\omega L_2 + j\omega M + \frac{1}{j\omega C}\right) + (j\omega L_1 + j\omega M)(j\omega L_2 + j\omega M)(1+h_{fe})$$

$$+ (j\omega L_1 + j\omega M) \times \frac{1}{j\omega C} = 0$$

$$j\omega h_{ie}\left(L_1 + L_2 + 2M - \frac{1}{\omega^2 C}\right) - \omega^2(L_1+M)(L_2+M)(1+h_{fe}) + \frac{(L_1+M)}{C} = 0 \rightarrow (2)$$

The frequency of oscillation $f_r = \frac{\omega_r}{2\pi}$ can be determined by equating the imaginary part of above equation to zero.

$$\therefore L_1 + L_2 + 2M - \frac{1}{\omega_r^2 C} = 0$$

$$\frac{1}{\omega_r^2 C} = L_1 + L_2 + 2M \Rightarrow \omega_r^2 = \frac{1}{(L_1+L_2+2M)C}$$

$$\omega_r = \frac{1}{\sqrt{(L_1+L_2+2M)C}} \Rightarrow 2\pi f_r = \frac{1}{\sqrt{(L_1+L_2+2M)C}}$$

$$\boxed{f_r = \frac{1}{2\pi\sqrt{(L_1+L_2+2M)C}}} \rightarrow (3)$$

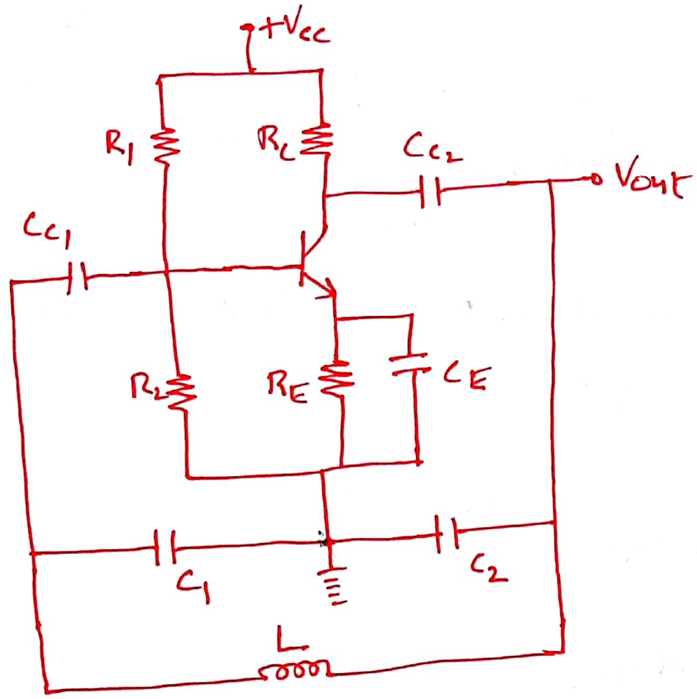
The condition for maintenance of oscillation is obtained by substituting eq (3) in eq (2) hence

$$-\omega^2(L_1+M)(L_2+M)(1+h_{fe}) + \frac{(L_1+M)}{C} = 0$$

$$(L_2+M)(1+h_{fe}) = \frac{1}{\omega_r^2 C} = L_1 + L_2 + 2M$$

$$\cancel{L_2} + M + h_{fe}(L_2+M) = L_1 + \cancel{L_2} + 2M \Rightarrow \boxed{h_{fe} = \frac{L_1+M}{L_2+M}}$$

Colpitts Oscillator:



Colpitt's oscillator circuit consists of single stage CE amplifier and an L-C phase shift network. The two series capacitors C_1 & C_2 form the potential divider used for providing the feedback voltage.

In this circuit $Z_1 = \frac{1}{j\omega C_1}$, $Z_2 = \frac{1}{j\omega C_2}$ & $Z_3 = j\omega L$

Substituting Z_1, Z_2 & Z_3 in General equation of an oscillator.

$$h_{ie}(Z_1+Z_2+Z_3) + Z_1 Z_2(1+h_{fe}) + Z_1 Z_3 = 0$$

$$h_{ie}\left(\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} + j\omega L\right) + \frac{1}{j\omega C_1} \times \frac{1}{j\omega C_2}(1+h_{fe}) + \frac{1}{\cancel{j\omega} C_1} \times \cancel{j\omega} L = 0$$

$$j\omega h_{ie}\left[L + \frac{-1}{\omega^2 C_1} - \frac{1}{\omega^2 C_2}\right] + \frac{-1}{\omega^2 C_1 C_2}(1+h_{fe}) + \frac{L}{C_1} = 0 \quad \rightarrow (1)$$

Equating the imaginary component to zero, we get

$$L + \frac{-1}{\omega_r^2 C_1} - \frac{1}{\omega_r^2 C_2} = 0$$

$$\cancel{-}\frac{1}{\omega_r^2}\left[\frac{1}{C_1} + \frac{1}{C_2}\right] = \cancel{-}L \Rightarrow \omega_r^2 = \frac{1}{L}\left[\frac{C_1+C_2}{C_1 C_2}\right]$$

$$\omega_r = \sqrt{\frac{1}{L} \times \frac{C_1 + C_2}{C_1 C_2}} \Rightarrow 2\pi f_r = \sqrt{\frac{1}{L \times \frac{C_1 C_2}{C_1 + C_2}}}$$

$$\boxed{f_r = \frac{1}{2\pi \sqrt{L \times \frac{C_1 C_2}{C_1 + C_2}}}} \quad \text{(or)} \quad f_r = \frac{1}{2\pi\sqrt{L C_{eq}}} \; ; \; C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

(2)

The condition for maintaining oscillations is obtained by substituting eq/(2) in eq/(1) we got

$$0 - \frac{1}{\omega_r^2 C_1 C_2}(1 + h_{fe}) + \frac{L}{C_1} = 0$$

$$\cancel{-} \frac{1 + h_{fe}}{\frac{1}{L} \times \frac{C_1 + C_2}{\cancel{C_1 C_2}} \times \cancel{C_1 C_2}} = \cancel{-} \frac{L}{C_1}$$

$$\frac{(1 + h_{fe})\cancel{L}}{C_1 + C_2} = \frac{\cancel{L}}{C_1} \Rightarrow 1 + h_{fe} = \frac{C_1 + C_2}{C_1}$$

$$1 + h_{fe} = \frac{C_2}{C_1} + 1$$

$$\boxed{h_{fe} = \frac{C_2}{C_1} = \frac{C_2}{C_1}} \quad \text{(or)} \quad \boxed{\beta = \frac{C_2}{C_1} = \frac{C_2}{C_1}}$$

As for oscillator circuits; the loop gain must be greater than unity to ensure that the circuit oscillates.

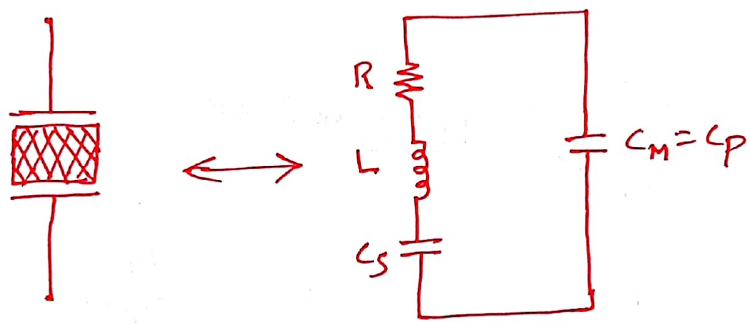
so $|A\beta| \geq 1$

$$\left|A \times \frac{C_2}{C_1}\right| \geq 1 \Rightarrow A \geq \frac{C_1}{C_2}.$$

Crystal oscillator:

The crystal (Quartz) exhibits a very important property known as "piezoelectric effect", which is defined as whenever a mechanical pressure is applied across faces of the crystal, a voltage proportional to the applied mechanical pressure appears across the crystal.

Conversely, an alternating voltage applied to a crystal causes it to vibrate at its natural frequency.



Crystal b/w two plates

Equivalent circuit of a crystal

- The crystal has a high degree of stability in holding constant at whatever frequency the crystal is originally cut to operate. The crystal oscillators are used whenever great stability is required example in communication transmitters, receivers and digital clocks etc.

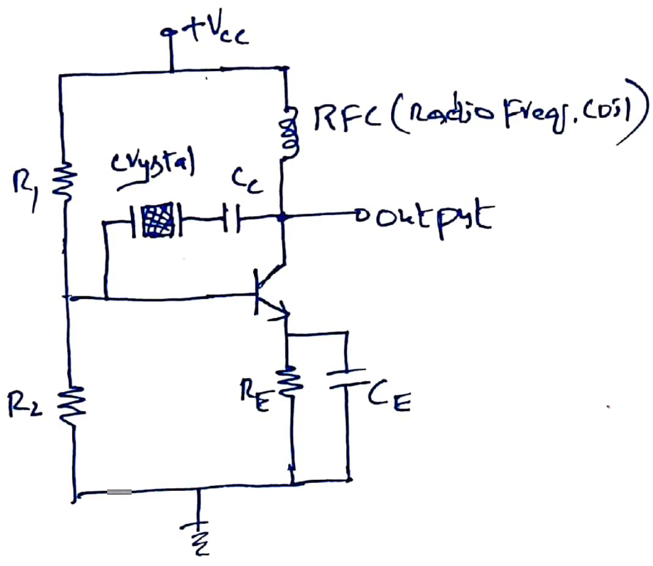
Crystal behaves like a series R-L-C circuit in parallel with 'C_M' where 'C_M' is the capacitance of mounting electrodes. Because of the presence of capacitance C_M, the crystal has two resonant frequencies:

The series resonant frequency, $f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$

where the crystal impedance is very low for this.

The parallel resonance frequency, $f_p = \frac{1}{2\pi\sqrt{\frac{L_s C_s}{1+C_s/C_M}}}$

where the crystal impedance is very high.



Oscillator with crystal operating in series resonance