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Multistage Amplifiers...

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Multistage Amplifiers:-

In amplifiers, cascading can also be done for getting an accurate input and output impedance for exact applications. Based on the kind of amplifier used within separate stages, these amplifiers are classified into different types.

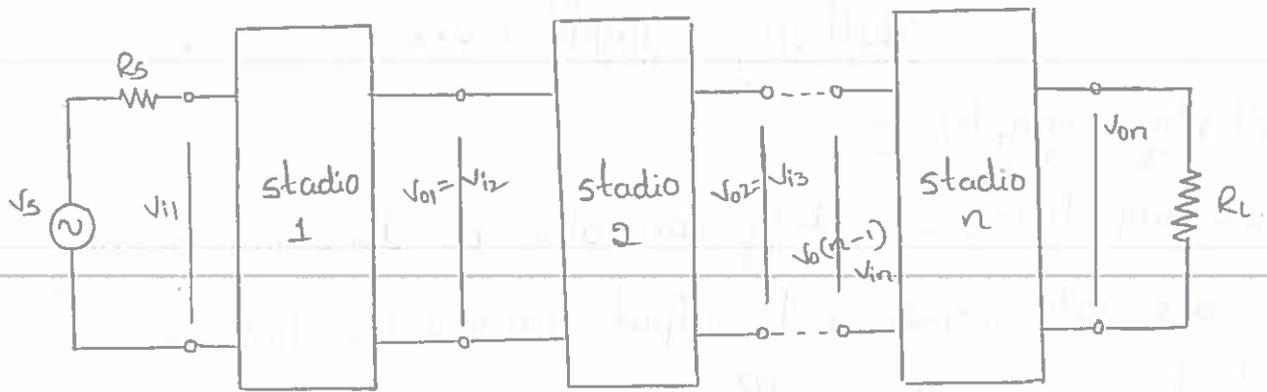
This amplifier using one or more single stage common emitter amplifier is also named as a cascaded amplifier.

A multistage amplifier design using CE (common emitter) as the primary stage as well as CB (common base) as the second stage is named as a cascade amplifier.

The connection between cascade and cascade can also be possible using FET amplifiers.

Whenever the amplifier is cascaded, then it is required to employ a coupling network among o/p of one amplifier as well as i/p^{of} the multistage amplifier. This kind of coupling is also named as interstate coupling. In this amplifier, there are three ^{multi}stage amplifier types are used like RC coupling, transformer coupling, and direct coupling.

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Classification:-

An amplifier circuit is one which strengthens the signal. The amplifier action and the important consideration for the practical circuit of transistor amplifier were also detailed in previous chapters.

Let us try to understand the classification of amplifiers. Amplifiers are classified according to many considerations.

Based on number of stages:-

Depending upon the number of stages of Amplification, there are single-stage amplifiers and multistage amplifiers.

* Single-stage Amplifiers - This has only one transistor circuit, which is a singlestage amplification.

* Multistage Amplifiers - This has multiple transistor circuit, which provides multi-stage amplification.

Based on its output:-

Depending upon the parameter that is amplifier at the output, there are voltage and power amplifiers.

* voltage amplifiers - The amplifier circuit that increases the voltage level of the input signal, is called as voltage amplifier.

* power amplifiers:- The amplifier circuit that increases the power level of the input signal, is called power amplifier.

Based on the input signals:-

Depending upon the magnitude of the input signal applied, they can be categorized as small signal and large signal amplifiers.

* Small signal Amplifiers - when the input signal is so weak so as to produce small fluctuations in the collector current compared to its quiescent value, the amplifier is known as small signal amplifier.

* Large signal amplifier - when the fluctuations in collector current are large. i.e beyond the linear position of the characteristics, the amplifier is known as large signal amplifier.

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Based on the frequency range:-

Depending upon the frequency range of the signals being used, there are audio and radio amplifiers.

* Audio Amplifiers - The amplifier circuit that amplifies the signal that lie in the audio frequency range i.e. 20Hz to 20kHz frequency range, is called as audio amplifier.

* Power Amplifiers - The amplifier circuit that amplifies the signals that lie in a very high frequency range, is called power amplifier.

Based on Biasing Conditions:-

Depending upon their mode of operation, there are class A, class B, class C amplifiers.

* class A amplifier - The biasing conditions in class A power amplifier are such that the collector current flows for the entire AC signal applied.

* class B amplifier:- The biasing conditions in class-B power amplifier are such that the collector current flows for half-cycle of input AC signal applied.

③
* class c amplifier - The biasing conditions in class c power amplifier are such that the collector current flows for less than half cycle of input Ac signal applied.

* class AB amplifier - The class AB power amplifier is one which is created by combining both class A and class B in order to have all the advantages of both the classes and to minimize the problems they have.

Based on coupling method:-

Depending upon the method of coupling one stage to the other, there are Rc coupled, transformer coupled and direct coupled amplifier.

* Rc coupled amplifier - A multi-stage amplifier circuit that is coupled to the next stage using resistor and capacitor (Rc) combination can be called as Rc coupled amplifier.

* Transformer coupled amplifier - A multi-stage amplifier circuit that is coupled to the next stage, with the help of a transformer, can be called as a transformer coupled amplifier.

* Direct coupled amplifier - A multi-stage amplifier circuit that is coupled to the next stage directly, can be called as direct coupled amplifier.

Based on the transistor configuration:-

Depending upon the type of transistor configuration, there are CE, CB and CC amplifiers.

* CE amplifier - The amplifier circuit that is formed using a CE configured transistor combination is called as CE amplifier.

* CB amplifier - The amplifier circuit that is formed using a CB configured transistor combination is called as CB amplifier.

* CC amplifier - The amplifier circuit that is formed using a CC configured transistor combination is called as CC amplifier.

Need for Multistage amplifiers:-

The power gain otherwise voltage gain can be achieved by the single stage amplifier but it is not enough in practical applications. For that, we have to use multistages of amplification

for achieving the required voltage gain or power.

This kind of amplifier is termed as multistage amplifier analysis. In this amplifier, the first stage output is fed to the next stage input. Such type of connection is commonly known as cascading.

Basic parameters of a transistor Amplifier

We need to consider the following specifications before choosing the amplifier. A good amplifier must have all the following specifications.

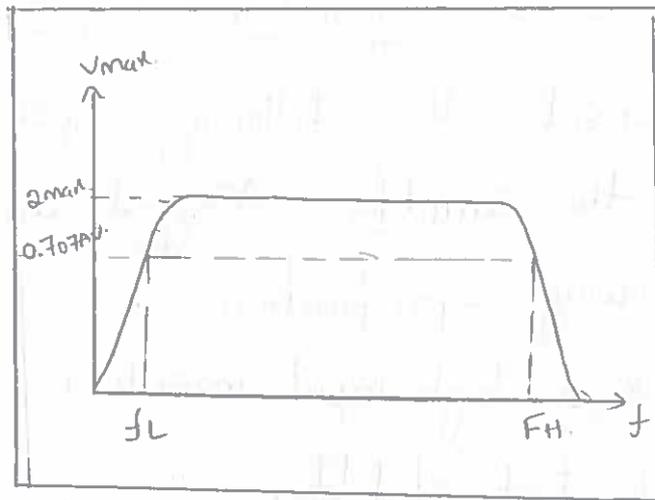
- * It should have a high input impedance.
- * It should have high stability.
- * It must have high linearity.
- * It should have high gain and bandwidth.
- * It must have high efficiency.

Bandwidth:-

The range of frequency that an amplifier circuit can amplify properly is known as the bandwidth of that particular amplifier. The curve below represents the frequency response of the single-stage RC coupled amplifier.

The curve which represents the variation of gain of an amplifier with frequency is called the frequency response curve. The bandwidth is measured between

the lower half power and upper half power points. P_1 point is lower half power and P_2 is upper half power respectively. A good audio amplifier must have a bandwidth from 20Hz to 20kHz because that is frequency range that is audible.



RC coupled frequency response

Gain :-

The gain of an amplifier is defined as the ratio of output power to the input power. Gain can be expressed either in decibel (dB) or in numbers. The gain represents how much an amplifier is able to amplify a signal given to it.

The below equation represents a gain in number

$$\Rightarrow G = P_{out} / P_{in}$$

where P_{out} is the output power of an amplifier.

The P_{in} is the input power of an amplifier

The equation below represents a gain in decibel (DB): ⑤

$$\text{Gain in dB} = 10 \log (P_{\text{out}} / P_{\text{in}})$$

Gain can also be expressed in voltage and current. The gain in voltage is the ratio of the output voltage to the input voltage and gain in current is ratio of output current to the input current. The equation for gain in voltage and current is known shown below.

$$\text{Gain in voltage} = \text{output voltage} / \text{input voltage.}$$

$$\text{Gain in current} = \text{output current} / \text{input current.}$$

High input impedance:

Input impedance is the impedance that is offered by an amplifier circuit when it is connected to the voltage source. The transistor amplifier must have high input impedance in order to prevent it from loading the input voltage source. So that is the reason for having high impedance in the amplifier.

Noise:-
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Noise refers to unwanted fluctuation or frequencies present in a signal. It may be due to

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the interaction between two or more signals present in a system, component failures, design flaws, external interference, or maybe by virtue of certain components used in the amplifier circuit.

Linearity:-

An amplifier is said to be linear if there is any linear relationship between the input power and the output power. Linearity represents the flatness of the gain. Practically it is not possible to get 100% linearity as the amplifiers use active devices like BJTs, JFETs, or MOSFETs, which tend to lose gain at high frequencies due to internal parasitic capacitance. In addition to this, the input DC decoupling capacitors set a lower cut-off frequency.

Efficiency:-

The efficiency of an amplifier represents how an amplifier can utilize the power supply efficiently. And also measure how much power from the power supply is gainfully converted at the output.

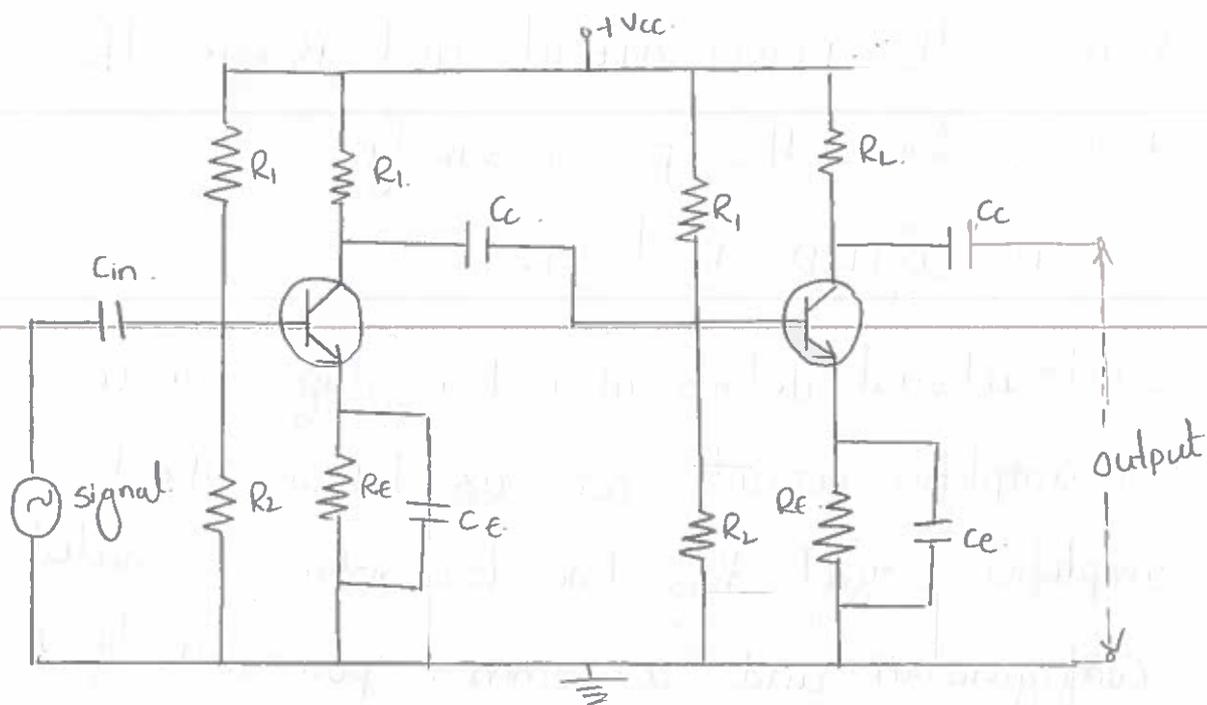
Efficiency is usually expressed in percentage and the equation for efficiency is given as $(P_{out}/P_s) \times 100$.

where P_{out} is the power output and P_s is the power drawn from the power supply.

Two-stage RC COUPLED Amplifier...

The constructional details of a two-stage RC coupled transistor amplifier circuit are as follows. The two stage amplifier circuit has two transistors, connected in CE configuration and a common power supply V_{CC} is used. The potential divider network R_1 & R_2 and the resistor R_e form the biasing and stabilization network. The emitter by-pass capacitor C_e offers a low reactance path to the signal.

The resistor R_L is used as a load impedance. The input capacitor C_{in} present at the initial stage of the amplifier couples AC signal to the base of the transistor. The capacitor C_c is the coupling capacitor that connects two stages and prevents DC interference between the stages and controls the shift of operating point. The figure below shows the circuit diagram of RC coupled amplifier.



Operation of RC Coupled Amplifier:-

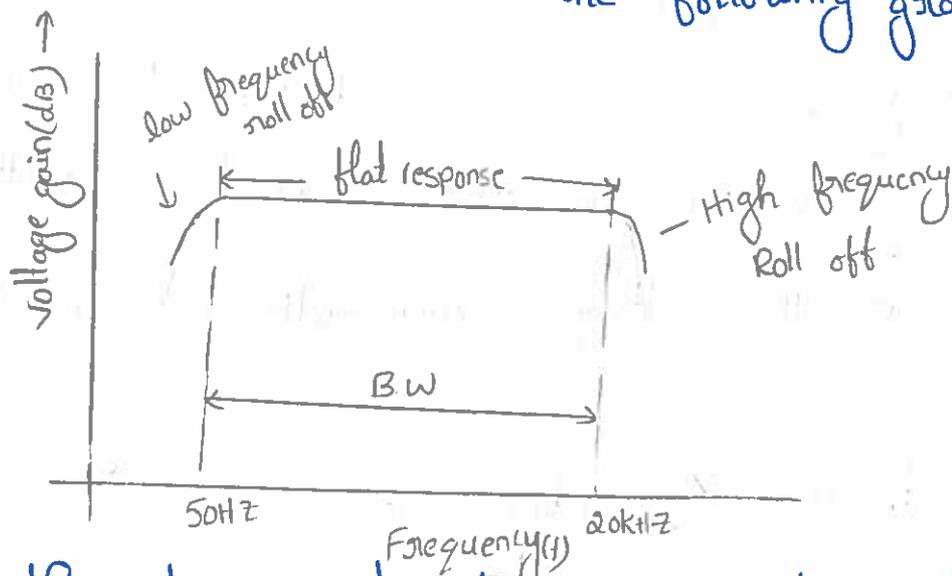
When an AC input signal is applied to the base of the first transistor, it gets amplified and appears across the collector load R_L which is then passed through the coupling capacitor C_C to the next stage. This becomes the input of the next stage, whose amplified output again appears across its collector load. Thus the signal is amplified in stage by stage action.

The important point that has to be noted here is that the total gain is less than the product of the gains of individual stages. This is because when a second stage is made to follow the

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first stage, the effective load resistance of the first stage is reduced due to the shunting effect of the input resistance of the second stage. Hence, in a multistage amplifier, only the gain of the last stage remains unchanged. As we consider a two stage amplifier here, the output phase is same as input. Because the phase reversal is done two times by the two stage CE configured amplifier circuit.

Frequency Response of RC coupled amplifier:-

Frequency response curve is a graph that indicates the relationship between voltage gain and function of frequency. The frequency response of RC coupled amplifier is as shown in the following graph.



From the above graph, it is understood that the frequency rolls off or decreases for the frequencies below 50 Hz and for frequencies above 20 kHz.

Whereas the voltage gain for the range of frequencies between 50Hz and 20kHz is constant. we know that,

$$X_c = \frac{1}{2\pi f c}$$

It means that the capacitive reactance is inversely proportional to the frequency.

At low frequencies (i.e. below 50Hz) :-

The capacitive reactance is inversely proportional to the frequency. At low frequencies, the reactance is quite high. The reactance of input capacitor C_{in} and the coupling capacitor C_c are so high that only small part of input signal is allowed. The reactance of the emitter by pass capacitor C_e is also very high during low frequencies. Hence it cannot shunt the emitter resistance effectively. With all these factors, the voltage gain rolls off at low frequencies.

At High frequencies (i.e. above 20kHz)

Again considering the same point, we know that the capacitive reactance is low at high frequencies. So, a capacitor behaves as a short circuit, at high frequencies. As a result of this, the loading

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effect of the next stage increases, which reduces the voltage gain. Along with this, as the capacitance of emitter diode decreases, it increases the base current of the transistor due to which the current gain (β) reduces. Hence voltage gain rolls off at high frequencies.

At Mid-frequencies (i.e. 50Hz to 20kHz) :-

The voltage gain of the capacitors is maintained constant in this range of frequencies, as shown in figure. If the frequency increases, the reactance of the capacitor C_c decreases which tends to increase the gain. But this lower capacitance reactive increases the loading effect of the next stage by which there is a reduction in gain. Due to these two factors, the gain is maintained constant.

Advantages of RC Coupled Amplifier :-

The following are the advantages of RC coupled amplifier.

The frequency response of RC amplifier provides constant gain over a wide frequency range, hence most suitable for audio applications.

The circuit is simple and has lower cost because it employs resistors and capacitors which is

cheap.

It becomes more compact with the upgrading technology.

Disadvantages of RC coupled amplifier:-

The following are the disadvantages of RC coupled amplifier.

The voltage and power gain are low because of the effective load resistance.

They become noisy with age.

Due to poor impedance matching, power transfer will be low.

Applications of RC coupled Amplifier:-

The following are the applications of RC coupled amplifier.

* They have excellent audio fidelity over a wide range of frequency.

* widely used as voltage amplifiers.

* Due to poor impedance matching RC coupling is rarely used in final stages.

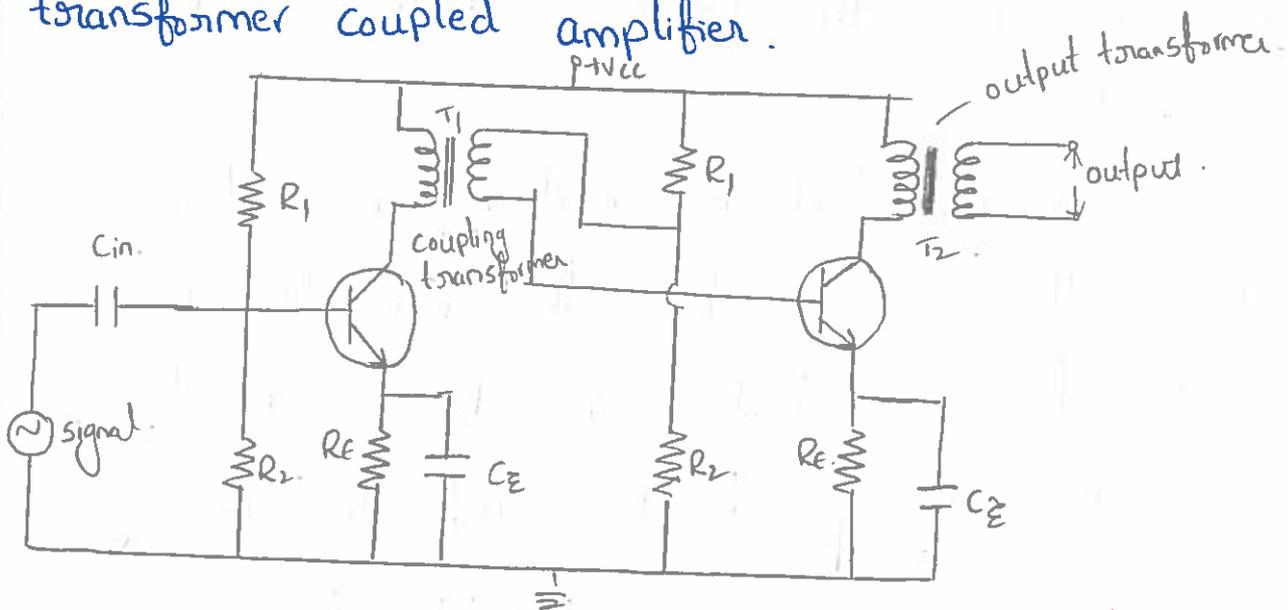
Construction of Transformer Coupled Amplifier

The amplifier circuit in which, the previous stage is connected to the next stage using coupling transformer, is called as transformer coupled amplifier.

The coupling transformer T_1 is used to feed the output of 1st stage to the input of 2nd stage. The collector load is replaced by the primary winding of the transformer. The secondary winding is connected between potential divider and the base of 2nd stage, which provides the input to the 2nd stage.

Instead of coupling capacitor like in RC coupled amplifier, a transformer is used for coupling any two stages, in the transformer coupled amplifier circuit.

The figure below shows the circuit diagram of transformer coupled amplifier.



The potential divider network R_1 and R_2 and the resistor R_e , together form the biasing and stabilization network. The emitter by-pass capacitor C_e offers a low reactance path to the signal. The resistor R_L is used as a load impedance. The input capacitor C_{in} present at the initial stage of the amplifier couples AC signal to the base of the transistor. The capacitor C_c is the coupling capacitor that connects two stages and prevents DC interference between the stages and controls the shift of operating point.

Operation of Transformer Coupled Amplifier...

When an AC signal is applied to the input of the base of the first transistor then it gets amplified by the transistor and appears at the collector to which the primary of the transformer is connected.

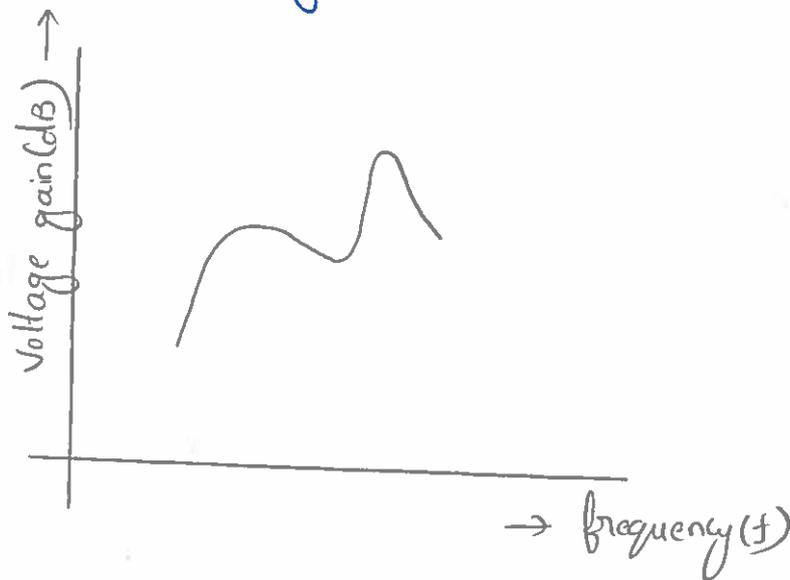
The transformer which is used as a coupling device in this circuit has the property of impedance changing, which means the low resistance of a stage (or) load can be reflected as a

high load resistance to the previous stage. Hence the voltage at the primary is transferred according to the turns ratio of the secondary winding of the transformer.

This transformer coupling provides good impedance matching between the stages of amplifier. The transformer coupled amplifier is generally used for power amplification.

Frequency Response of Transformer Coupled amplifier

The figure below shows the frequency response of a transformer coupled amplifier. The gain of the amplifier is constant only for a small range of frequencies. The output voltage is equal to the collector current multiplied by the reactance of primary.



At low frequencies, the reactance of primary begins to fall, resulting in decreased gain. At high frequencies, the capacitance between turns of windings

acts as a bypass Condenser to reduce the output voltage and hence gain.

So, the amplification of audio signals will not be proportionate and some distortion will also get introduced, which is called as "frequency Distortion."

Advantages of transformer coupled Amplifier

The following are the advantages of a transformer Coupled amplifier -

- * An excellent impedance matching is provided.
- * Gain achieved is higher.
- * There will be no power loss in collector and base resistors.
- * Efficient in operation.

Disadvantages of transformer coupled amplifier

The following are the disadvantages of a transformer Coupled amplifier.

- * Through the gain is high, it varies considerably with frequency. Hence a poor frequency response.
- * Frequency distortion is higher.
- * Transformer tend to produce hum noise.
- * Transformer are bulky and costly.

Applications:-

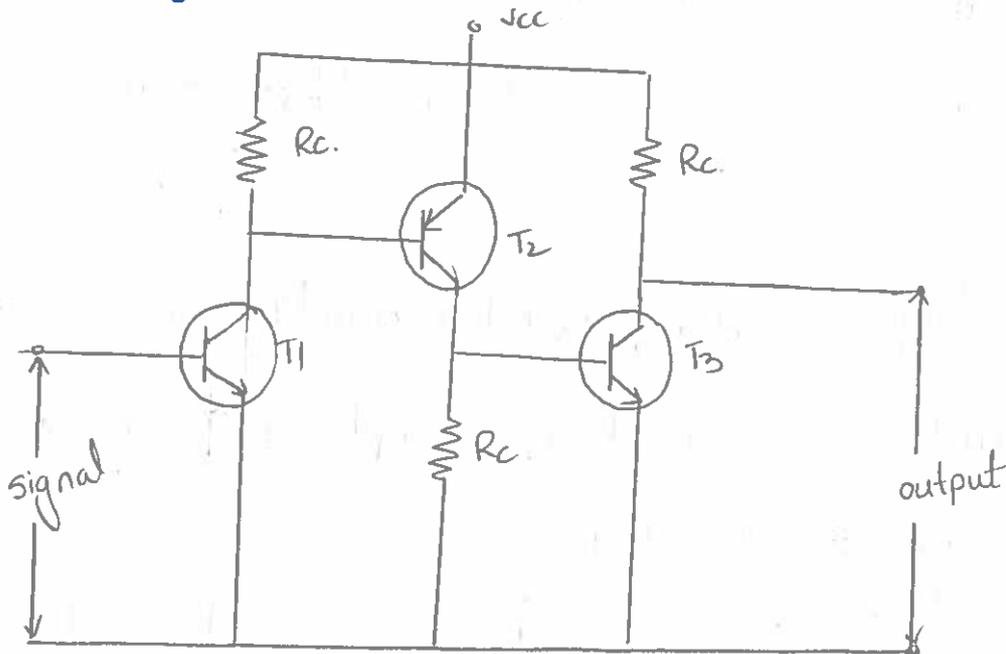
- * Mostly used for impedance matching purposes.
- * Used for power amplification.
- * Used in applications where maximum power transfer is needed.

Direct coupled Amplifier:-

As no coupling devices are used, the coupling of the amplifier stages is done directly and hence called as "Direct coupled amplifier".

Construction:-

The figure below indicates the three stage direct coupled transistor amplifier. The output of first stage transistor T_1 is connected to the input of second stage transistor T_2 .



The transistor in the first stage will be an NPN transistor, while the transistor in the next stage will be a PNP transistor and so on. This is because, the variations in one transistor tend to cancel the variations in the other. The rise in the collector current and the variation in β of one transistor get cancelled by the decrease in the other.

Operation:-

The input signal when applied at the base of transistor T_1 , it gets amplified due to the transistor action and the amplified output appears at the collector resistor R_c of transistor T_1 . This output is applied to the base of transistor T_2 which further amplifies the signal. In this way, a signal is amplified in a direct coupled amplifier circuit.

Advantages:-

The advantages of direct coupled amplifier are as follows

- * The circuit arrangement is simple because of minimum use of resistors.
- * The circuit is low cost because of the absence of expensive coupling devices.

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Disadvantages:-

- * It cannot be used for amplifying high frequencies.
- * The operating point is shifted due to temperature variations.

Applications:-

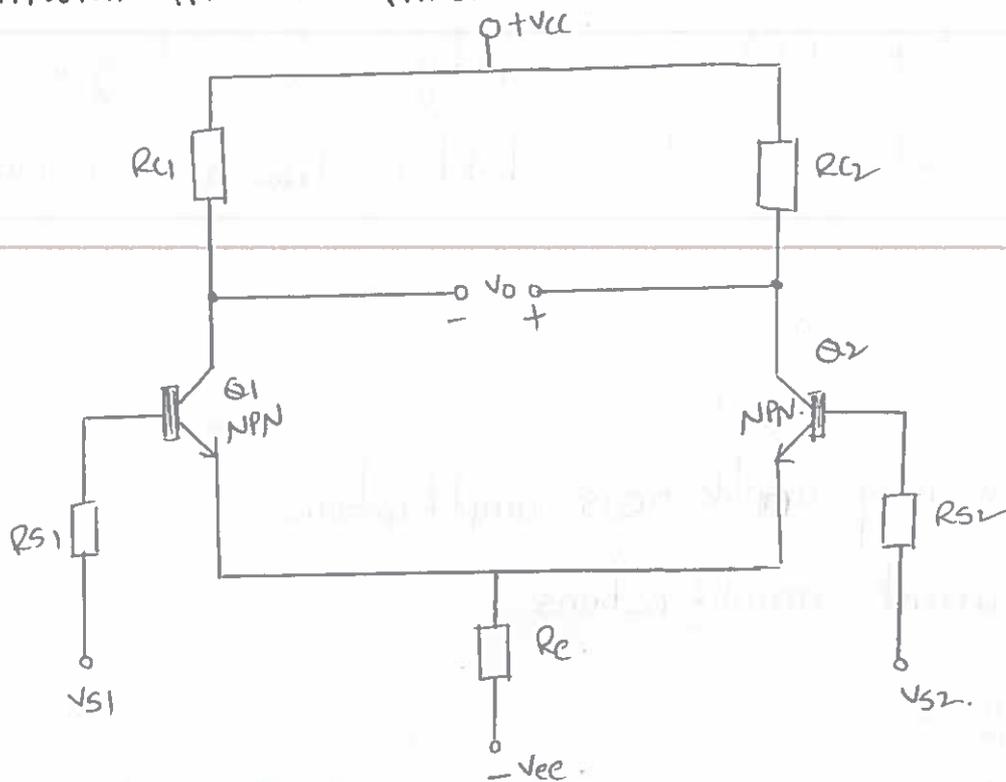
- * Low frequency ~~amplifications~~ amplifications.
- * Low current amplifications.

Comparisons...

Let us try to compare the characteristics of different types of coupling methods discussed till now.

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

Differential amplifier circuit:-



Input 1 of differential amplifier is connected to the base of transistor Q_1 , and input 2 of the differential is connected to the base of another transistor. V_{cc} and V_{ee} are the two supplies for differential amplifier. The circuit works proper even with a single supply voltage. If you want to run the differential amplifier with a single supply then connect V_{cc} to supply voltage and V_{ee} to ground.

Working of Differential Amplifier:-

If input signal is applied to the base of transistor Q_1 , then there is voltage drop across collector resistor R_{c1} so the output of the transistor Q_1 is low. When there is no input voltage to the

transistor Q_1 , the voltage drop across resistor R_{e1} is very less as a result output transistor Q_1 is high. 13

When transistor Q_1 is turned on, the current through the emitter resistor R_e increases as emitter current I_e is almost equal to the collector current I_c . As a result voltage drop across resistor R_e increases and make emitter of both transistors positive. In this condition transistor Q_2 does not conduct as there is no base voltage. As a result collector voltage of transistor Q_2 is high. Hence it is clear that the output is produced at the collector of transistor Q_2 when an input is applied to the base of Q_1 .

Transistors Q_1 & Q_2 have the exactly same characteristics. The two collector resistors are equal while the two emitter resistances R_{e1} & R_{e2} are also equal.

$$R_{c1} = R_{c2} \text{ and } R_{e1} = R_{e2}.$$

The magnitudes of supply voltages $+V_{cc}$ and $-V_{ee}$ also same. If the input voltages V_{s1} and V_{s2} .

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are equal then emitter currents I_{e1} & I_{e2} are also equal.

If $V_{s1} = V_{s2}$ then $I_{e1} = I_{e2}$.

Total emitter current is given as

$$\Rightarrow I_e = I_{e1} + I_{e2}$$

$$\Rightarrow V_e = V_b - V_{be}$$

$V_{c1} = V_{c2} = V_{cc} - I_c R_c$ assuming collector resistances
 $R_{c1} = R_{c2} = R_c$.

Differential Amplifier Applications:-

- * Differential amplifier used as voltage comparator.
- * It is used in voltage subtractors.
- * Used in operational amplifiers to amplify the input signal.
- * Differential amplifier is used as a voltage follower.

Hybrid π equivalent circuits of BJTs:-

At low frequencies, we can analyze the transistor using h-parameters. But for high frequency, analysis of h-parameter model is not suitable for following reasons.

- * The values of h-parameters are not constant at high frequencies. So it is necessary to analyse

transistor at each and every frequency which is impractical.

At high frequency h-parameters become complex in nature.

Due to the above reasons, modified T model and hybrid π models are used for high frequency analysis of the transistor. These models give a reasonable compromise between accuracy and simplicity to do high frequency analysis of the transistor.

Hybrid- π Common emitter transistor model...

Common emitter circuit is most important practical configuration and this is useful for the analysis of transistor using hybrid- π model. The following figure shows the hybrid- π model for a transistor in CE configuration. For this model, all parameters are assumed to be independent of frequency. But they may vary with the quiescent operating point.

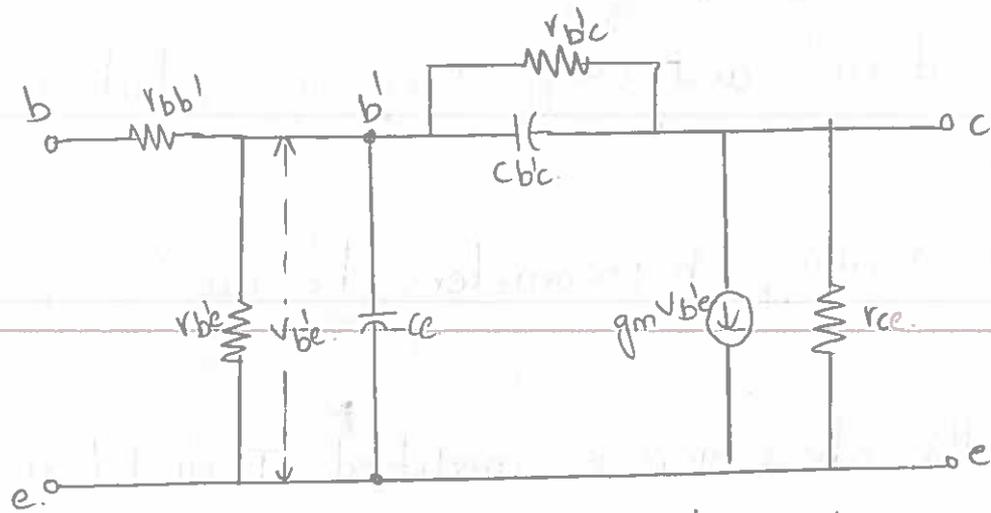


Fig: Hybrid- π model for a transistor in CE configuration

Elements in hybrid- π model:-

$C_{b'e}$ and $C_{b'c}$: Forward biased PN junction exhibits a capacitive effect called diffusion capacitance. This capacitive effect of normally forward biased base-emitter junction of the transistor is represented by $C_{b'e}$ or C_e . The diffusion capacitance is connected between b' and e represents the excess minority carrier storage in the base.

The reverse bias PN junction exhibits a capacitive effect called "transition capacitance." This capacitive effect is normally reverse biased collector base junction of the transistor is represented by $C_{b'c}$ or C_c .

$r_{bb'}$: The internal node " b " is physically not accessible bulk node b represents external base terminal.

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 r_{be} : It is the portion of the base emitter which may be thought of as being in series with the collector junction. This establishes a virtual base b' for junction capacitances to be connected instead of b .

r_{bc} : Due to early effect, varying voltages across collector to emitter junction results in base-width modulation. A change in the effective base-width causes the emitter current to change. This feedback effect between output and input is taken into account by connecting g_{bc} or r_{bc} between b' and c .

g_m : Due to small changes in voltage V_{be} across emitter junction, there is excess minority carrier concentration injected into the base which is proportional to V_{be} . So resulting small signal collector current with collector shorted to the emitter is also proportional to V_{be} .

g_m is also called a transconductance and it is given by

$$g_m = \frac{\Delta I_c}{\Delta V_{be}} \text{ at a constant } V_{ce}$$

r_{ce} : It is the output resistance. It is also the result of early effect.

Hybrid- π parameter values:-

The following table shows the typical values for hybrid- π parameters at room temperature and for $I_c = 1.3\text{mA}$.

| parameter | Meaning | value. |
|------------------------|--|---------------------------------------|
| g_m | Mutual conductance | 50 mA/V |
| $r_{bb'}$ | Base spreading resistance | 100 Ω |
| $r_{b'e}$ or $g_{b'e}$ | Resistance between b' and e conductance between b' and e | 1k Ω 1m mho |
| $r_{b'c}$ or $g_{b'c}$ | Resistance of reverse biased PN junction between base and collector conductance of reverse biased PN junction between base and collector. | 4M Ω . $0.25 * 10^{-6}$ mho |
| r_{ce} or g_{ce} | output resistance between c & e conductance resistance between b & c | 80k Ω $12.5 * 10^{-6}$ mho |
| C_e | junction capacitance between b & e | 100pF |
| C_c | Junction capacitance between base and collector. | 3pF |

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Transistor Transconductance g_m :

Let us consider a p-n-p transistor in CE configuration with V_{CC} bias in the collector circuit as shown in the above figure.

Transconductance g_m is given as,

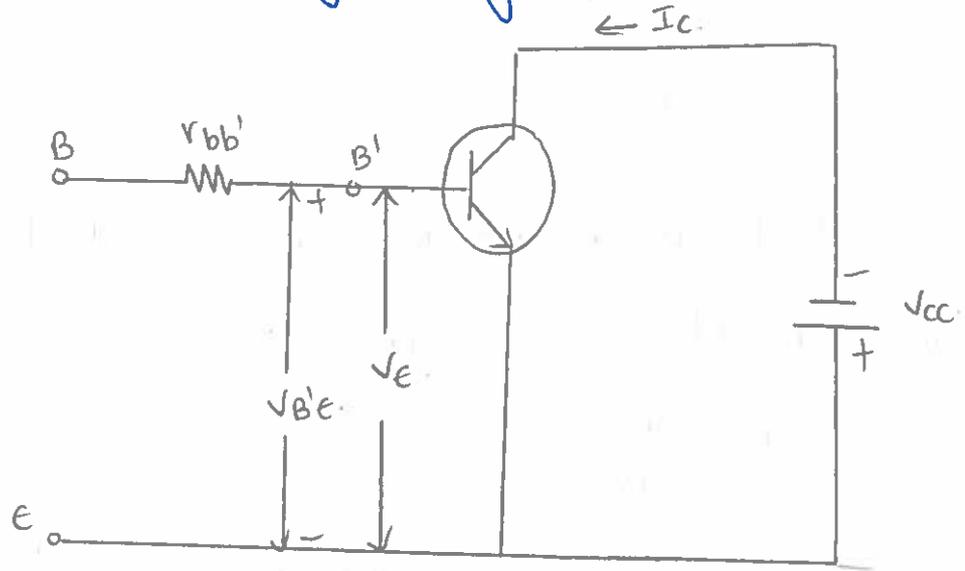


Fig: pertaining to the derivation of g_m

The collector current in active region is given as,

$$g_m = \left. \frac{\partial I_c}{\partial V_{B'E}} \right|_{V_{CE}}$$

The collector current in active region is given as

$$I_c = I_{C0} - \alpha I_E$$

$$\partial I_c = \alpha \partial I_E \quad \because I_{C0} = \text{constant}$$

substituting value of ∂I_c

$$g_m = \alpha \frac{\partial I_E}{\partial V_{BE}} = \alpha \frac{\partial I_E}{\partial V_E} \quad \because V_E = V_{B'E}$$

unit - 1/ohm

The emitter diode resistance, r_e is given as,

$$r_e = \frac{\partial V_E}{\partial I_E}$$

$$\frac{1}{r_e} = \frac{\partial V_E}{\partial I_E}$$

Substituting r_e in place of $\partial I_E / \partial V_E$ we get,

Substituting r_e in place of $\partial I_E / \partial V_E$ we get,

$$g_m = \frac{\alpha}{r_e}$$

The emitter diode is a forward biased diode and its dynamic resistance is given as

$$r_e = \frac{V_T}{I_E}$$

The emitter diode is a forward biased and its dynamic resistance is given as,

$$r_e = \frac{V_T}{I_E}$$

where V_T is the "voltage equivalent of temperature", defined by

$$V_T = \frac{kT}{q}$$

where k is the Boltzmann constant in joules per degree kelvin ($1.38 \times 10^{-23} \text{ J/K}$) is the electronic charge ($1.6 \times 10^{-19} \text{ C}$)

Substituting value of v_e in equation (3) we get,

$$g_m = \frac{\alpha I_e}{V_T} = \frac{I_{C0} - I_C}{V_T} \quad \therefore I_C = I_{C0} - \alpha I_e$$

For p-n-p transistor I_C is negative. For an n-p-n transistor I_C is positive, but the foregoing analysis (with $v_e = +v_{be}$) leads to $g_m = (I_C - I_{C0})/V_T$.

Hence, for either type of transistor, g_m is positive

$$g_m = \frac{I_C - I_{C0}}{V_T} \quad \therefore I_C \gg I_{C0}$$

For $I_C = 1.3 \text{ mA}$, $g_m = 0.05 \text{ mho}$ or 50 mA/V . For $I_C = 7.8 \text{ mA}$, $g_m = 0.3 \text{ mho}$ or 300 mA/V . These values are much larger than the transconductances obtained with FETs.

Input conductance $g_{b'e}$

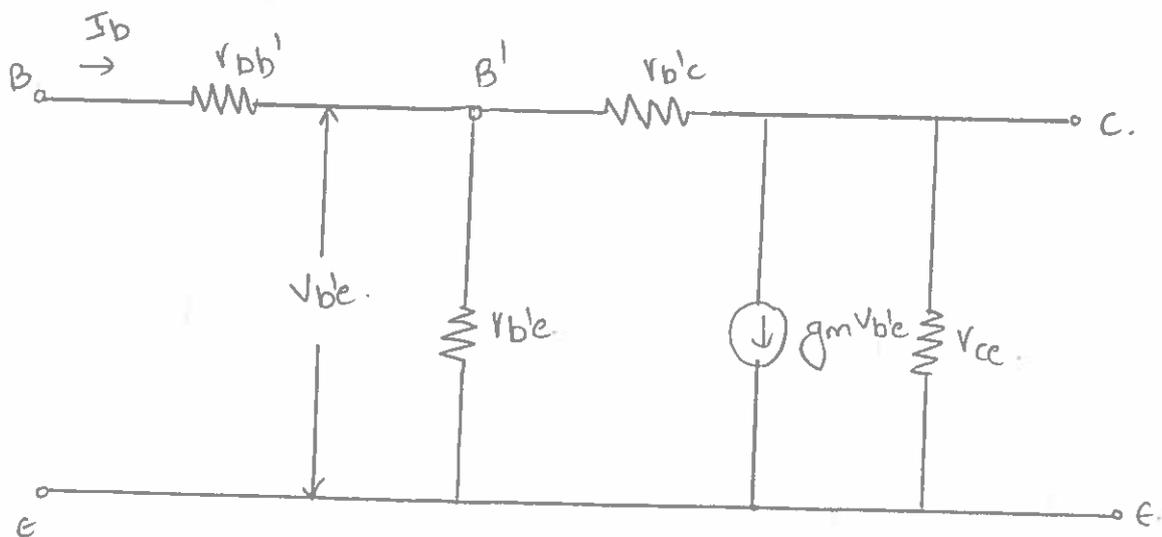


fig. - Hybrid- π model for CE configuration at low frequency

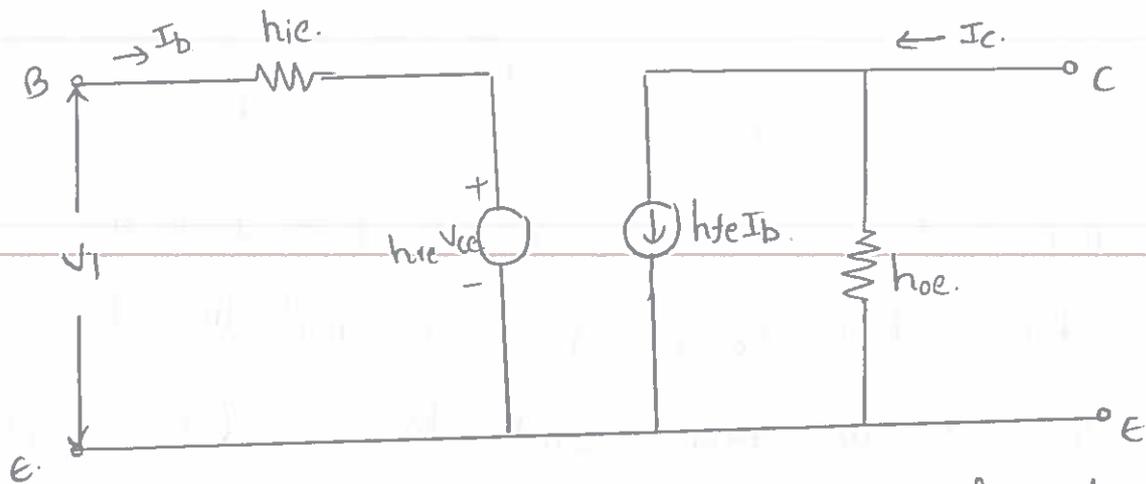


fig-11 - parameter model for CE configuration
at low frequency

First consider h-parameter model for CE configuration.
Applying KCL to output circuit.

$$I_c = h_{fe} I_b + h_{oe} v_{ce}$$

Making $v_{ce} = 0$, the short circuit current gain h_{fe} is defined as

$$h_{fe} = \frac{I_c}{I_b}$$

$$I_c = g_m v_{b'e}$$

$$= g_m I_b r_{b'e}$$

$$\frac{I_c}{I_b} = g_m r_{b'e}$$

$$\therefore v_{b'e} = I_b r_{b'e}$$

Substituting the value of I_c/I_b ,

$$h_{fe} = g_m r_{b'e}$$

or

$$r_{b'e} = \frac{h_{fe}}{g_m} \quad \text{or} \quad g_{b'e} = g_m / h_{fe} \quad \text{unit}^{-1}, 34/67$$

$$g_m = I_c / V_T$$

$$\therefore r_{b'e} = \frac{h_{fe} V_T}{|I_c|}$$

$$\text{or } \beta_{b'e} = \frac{|I_c|}{V_T h_{fe}}$$

Feedback conductance $g_{b'c}$:

Let us consider h-parameter model for CE configuration with input open circuit ($I_b = 0$), v_i is given as

$$v_i = h_{re} v_{ce}$$

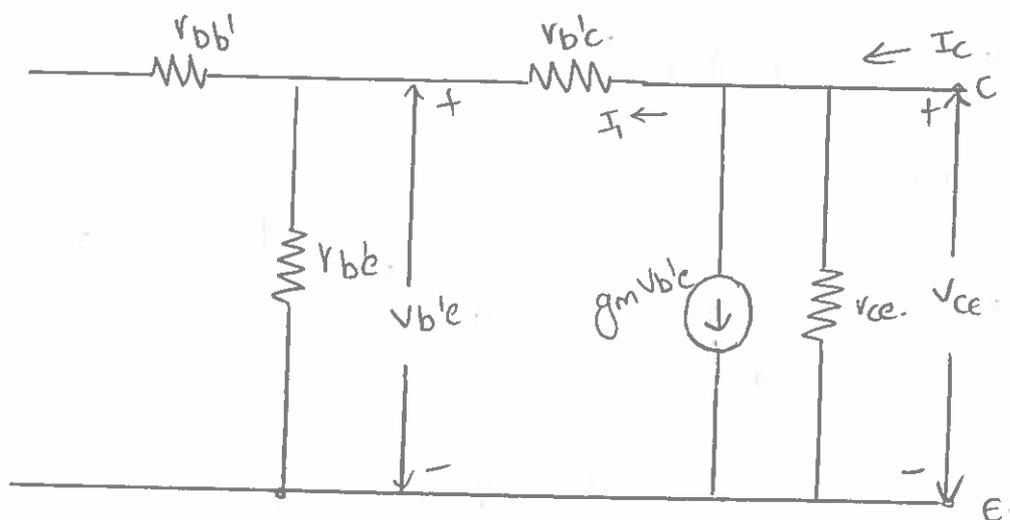


Fig: Hybrid- π model for CE configuration

with $I_b = 0$, v_{ce} is given as,

$$v_{ce} = I_1 (r_{b'c} + r_{b'e})$$

$$I_1 = \frac{v_{ce}}{r_{b'c} + r_{b'e}}$$

voltage between b' and e , $v_{b'e}$ can be given as,
 unit - 1, 25/162

$$V_{b'e} = I_b r_{b'e}$$

$$= r_{b'e} \frac{V_{ce}}{r_{b'c} + r_{b'e}}$$

with $I_b = 0$

$$v_i = V_{b'e}$$

$$= \frac{r_{b'e} V_{ce}}{r_{b'c} + r_{b'e}}$$

substituting the value of v_i ,

$$\frac{r_{b'e} V_{ce}}{r_{b'c} + r_{b'e}}$$

$$h_{re} V_{ce} =$$

$$= \frac{r_{b'e}}{r_{b'c} + r_{b'e}}$$

$$= h_{re} r_{b'c} + h_{re} r_{b'e}$$

$$\left(\frac{1 - h_{re}}{h_{re}} \right) r_{b'e}$$

$$r_{b'c} =$$

$$= \frac{r_{b'e}}{h_{re}} \quad \because 1 - h_{re} \cong 1$$

$$g_{b'c} = \frac{h_{re}}{r_{b'e}} = h_{re} g_{b'e}$$

Substituting the value of $r_{b'e}$,

$$r_{b'c} = \frac{h_{fe} V_T}{|I_c| h_{re}}$$

$$g_{b'c} = \frac{|I_c| h_{re}}{h_{fe} V_T}$$

Base spreading resistance $r_{bb'}$:

$$h_{ie} = r_{bb'} + r_{b'e}$$

$$r_{bb'} = h_{ie} - r_{b'e}$$

Substituting the value of $r_{b'e}$,

$$r_{bb'} = h_{ie} - \frac{h_{fe} V_T}{I_c}$$

Output resistance g_{ce} :

Using h-parameters output conductance is given as,

$$h_{oe} = \frac{I_c}{V_{ce}}$$

Applying KCL to the output circuit,

$$I_c = \frac{V_{ce}}{r_{ce}} + g_m V_{b'e} + I_1$$

$$1/r_{ce} = g_{ce} = h_{oe} - g_{b'c} h_{fe}$$

Unit-1, 37/67

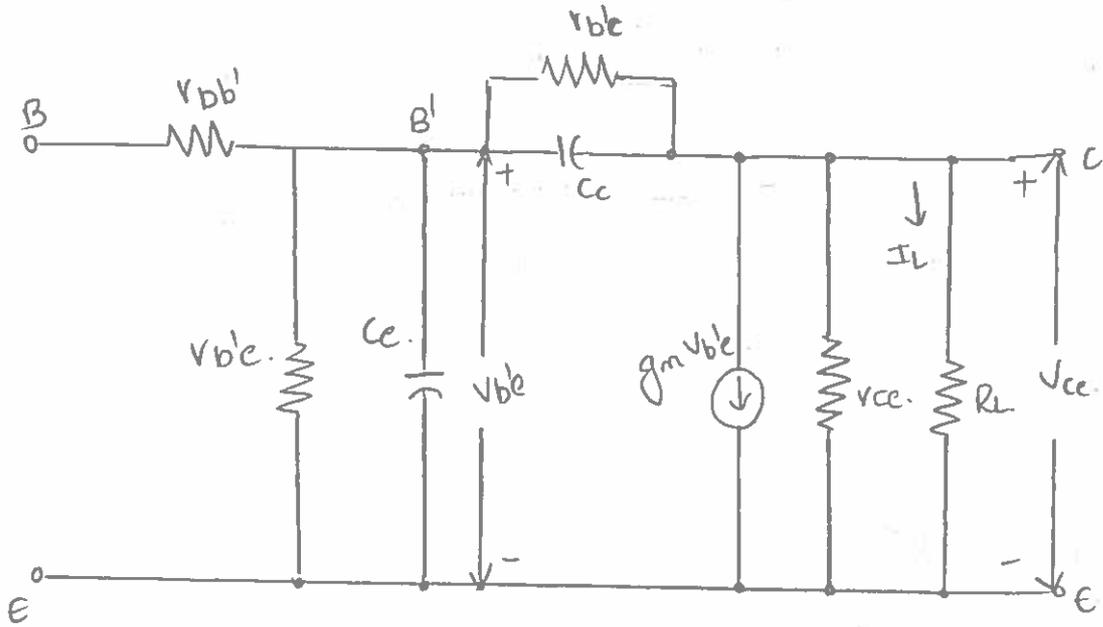
Relation between hybrid- π and h-parameters.

| S.No | parameter relation |
|------|---|
| 1. | $g_m = \frac{I_c}{V_T}$ |
| 2. | $r_{b'e} = \frac{h_{fe}}{g_m}$ |
| 3. | $r_{bb'} = h_{ie} - r_{b'e}$ |
| 4. | $r_{b'c} = \frac{r_{b'e}}{h_{re}}$ |
| 5. | $g_{ce} = \frac{1}{r_{ce}} = h_{oe} - g_{b'c} h_{fe}$ |

Hybrid π Capacitances

$$C_e = C_{De} + C_{Te} \approx C_{De}$$

$$C_e = \frac{g_m}{2\pi f_t}$$



Miller capacitance is $C_M = C_{b'e} (1 + g_m R_L)$

Here $R_L = 0$.

$$\therefore C_M = C_{b'e} (C_c)$$

parallel combination of $r_{b'e}$, and $(C_e + C_c)$ is given as

$$Z = \frac{r_{b'e} \times \frac{1}{j\omega(C_e + C_c)}}{r_{b'e} + \frac{1}{j\omega(C_e + C_c)}}$$

$$= \frac{r_{b'e}}{1 + j\omega r_{b'e} (C_e + C_c)}$$

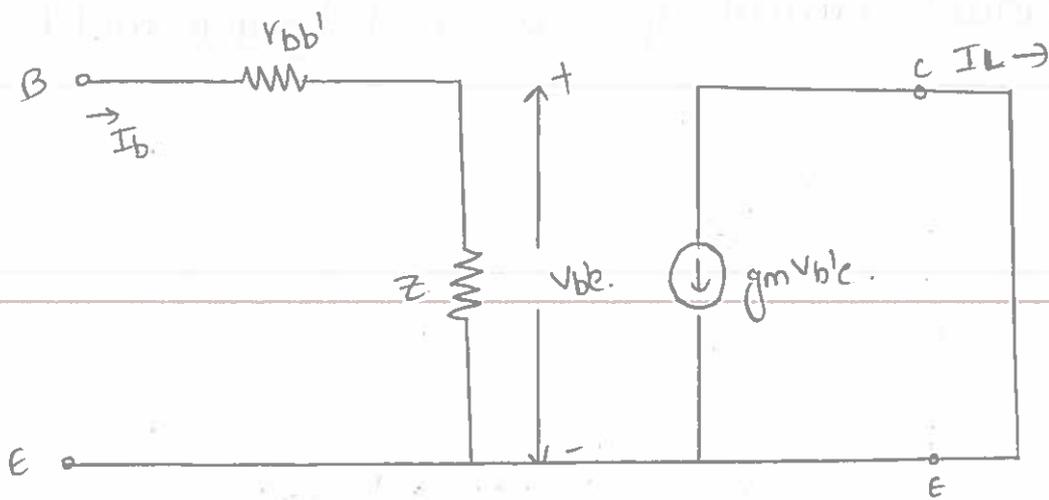


fig- Further simplified hybrid- π model

$$v_{b'e} = I_b Z$$

$$Z = \frac{v_{b'e}}{I_b}$$

The current gain for the circuit is,

$$A_i = \frac{I_L}{I_b} = \frac{-g_m v_{b'e}}{I_b} \quad \because I_L = -g_m v_{b'e}$$

$$A_i = -g_m Z$$

$$= \frac{-g_m r_{b'e}}{1 + j\omega r_{b'e} (C_e + C_c)}$$

$$A_i = \frac{-h_{fe}}{1 + j\omega r_{b'e} (C_e + C_c)}$$

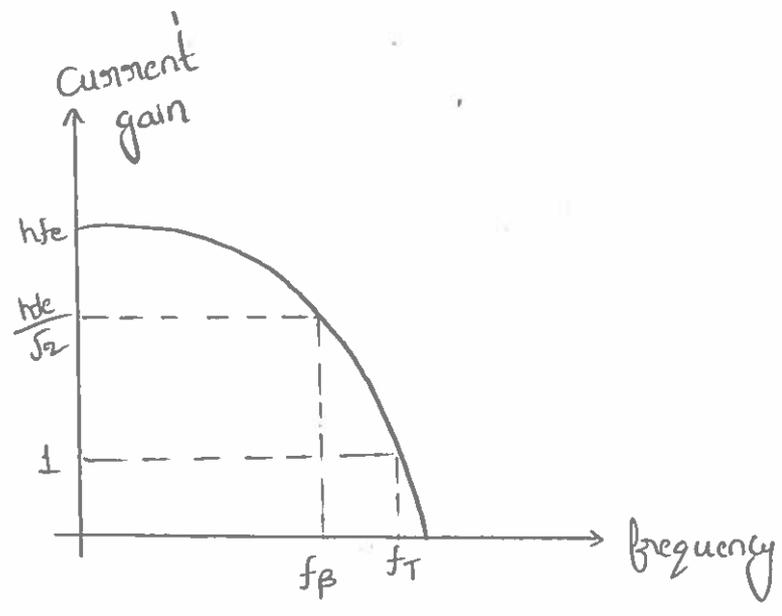


Fig: Frequency vs Current gain.

$$f_{\beta} = \frac{1}{2\pi r_{b'e} (C_c + C_e)}$$

$$A_i = \frac{-h_{fe}}{1 + j \frac{f}{f_{\beta}}}$$

$$|A_i| = \frac{h_{fe}}{\sqrt{1 + \left(\frac{f}{f_{\beta}}\right)^2}}$$

f_{β} (Cutoff frequency):

It is the frequency at which the transistor short circuit CE current gain drops by 3dB or $1/\sqrt{2}$ times from its value at low frequency. It is given as,

$$f_{\beta} = \frac{1}{2\pi r_{b'e} (C_c + C_e)}$$

or

$$= \frac{g_{b'e}}{2\pi(C_e + C_c)}$$

f_c (cut-off frequency):

It is the frequency at which the transistor short circuit CB current gain drops by 3dB or $1/\sqrt{2}$ times from its value at low frequency.

The current gain for CB configuration is given as.

$$A_i = \frac{-h_{fb}}{1 + j \frac{f}{f_c}}$$

where

$$f_c = \frac{1}{2\pi r_{b'e} (1 + h_{fb}) C_e}$$

$$= \frac{1 + h_{fe}}{2\pi r_{b'e} C_e} \approx \frac{h_{fe}}{2\pi r_{b'e} C_e}$$

$$|A_i| = \frac{h_{fb}}{\sqrt{\left(1 + \left(\frac{f}{f_c}\right)^2\right)^2}}$$

At

$$f = f_c$$

$$|A_i| = \frac{h_{fb}}{\sqrt{2}}$$

Parameter f_T :-
mm o mm m

It is the frequency at which short circuit CE current gain becomes unity.

$$\text{At } f = f_T.$$

$$1 = \frac{h_{fe}}{\sqrt{1 + \left(\frac{f_T}{f_B}\right)^2}}$$

The ratio of f_T/f_B is quite large compared to 1.

$$f_T = g_m / 2\pi C_{ce}.$$

Problem :-
mm o mm

Short circuit CE current gain of transistor is 25 at a frequency of 2MHz if $f_B = 200\text{kHz}$. Calculate

i) f_T ii) h_{fe} iii) Find $|A_i|$ at a frequency of 10MHz and 100MHz.

$$\begin{aligned} \text{i) } f_T &= |A_i| \times f = 25 \times 2 \times 10^6 \\ &= 50\text{MHz}. \end{aligned}$$

$$\text{ii) } h_{fe} = \frac{f_T}{f_B} = \frac{50\text{MHz}}{200\text{kHz}} = 250\text{kHz}$$

$$\text{iii) } |A_i| = \frac{h_{fe}}{\sqrt{1 + \left(\frac{f}{f_B}\right)^2}}$$

At $f = 100 \text{ MHz}$

$$|A_i| = \frac{250}{\sqrt{1 + \left(\frac{100 \times 10^6}{200 \times 10^3}\right)^2}} = 0.5$$

Current gain with resistive load

$$C_{eq} = C_e + C_c (1 + g_m R_L)$$

For further simplification,

At output circuit value of C_c can be calculated as,

$$\frac{\frac{1}{j\omega C_c}}{\frac{k-1}{k}} \approx \frac{1}{j\omega C_c} \quad \because k = -100$$

$$\therefore C_c \left(\frac{k}{k-1} \right) \approx C_c$$

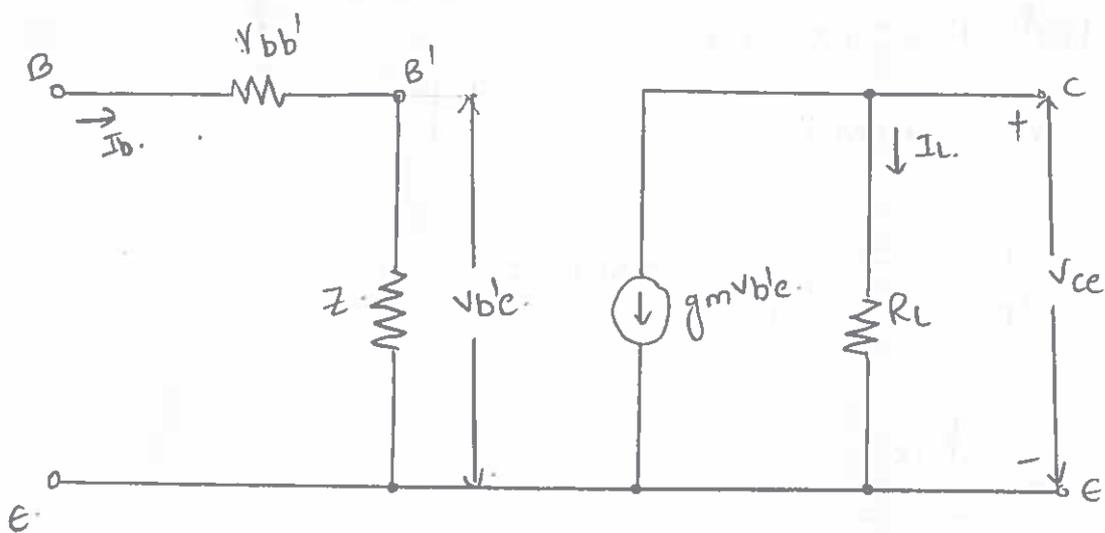


Fig:- simplified hybrid-π model for CE with RL

$$Z = \frac{V_{be}}{I_b}$$

$$A_i = \frac{-h_{fe}}{1 + j\left(\frac{f}{f_H}\right)}$$

$$|A_i| = \frac{h_{fe}}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}}$$

At $f = f_H$

$$A_i = \frac{h_{fe}}{\sqrt{2}}$$

f_H is the frequency at which the transistor gain drops by 3dB or $\frac{1}{\sqrt{2}}$ times from its value at low frequency.

It is given as

$$f_H = \frac{1}{2\pi r_{be} C_{eq}}$$

$$= \frac{1}{2\pi r_{be} [C_e + C_c (1 + g_m R_L)]}$$

At $R_L = 0$

$$f_H = \frac{1}{2\pi r_{be} [C_e + C_c]} = f_{\beta}$$

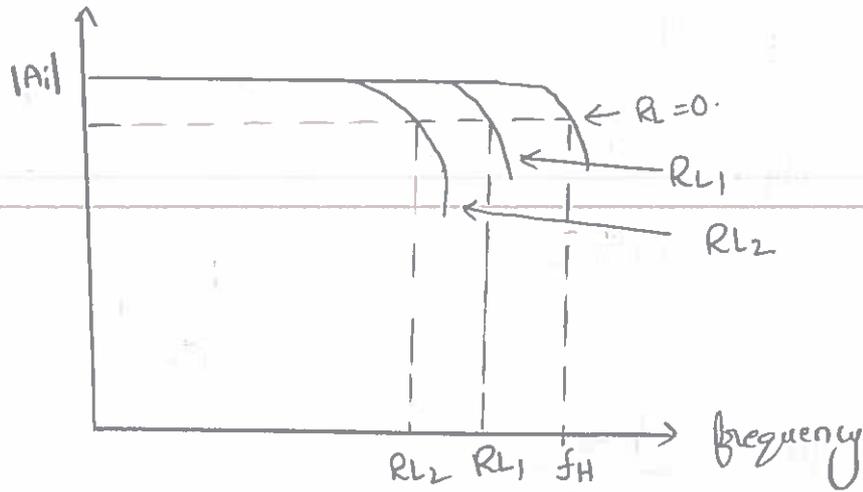


fig: variation f_H with R_L

Current gain including source resistance:

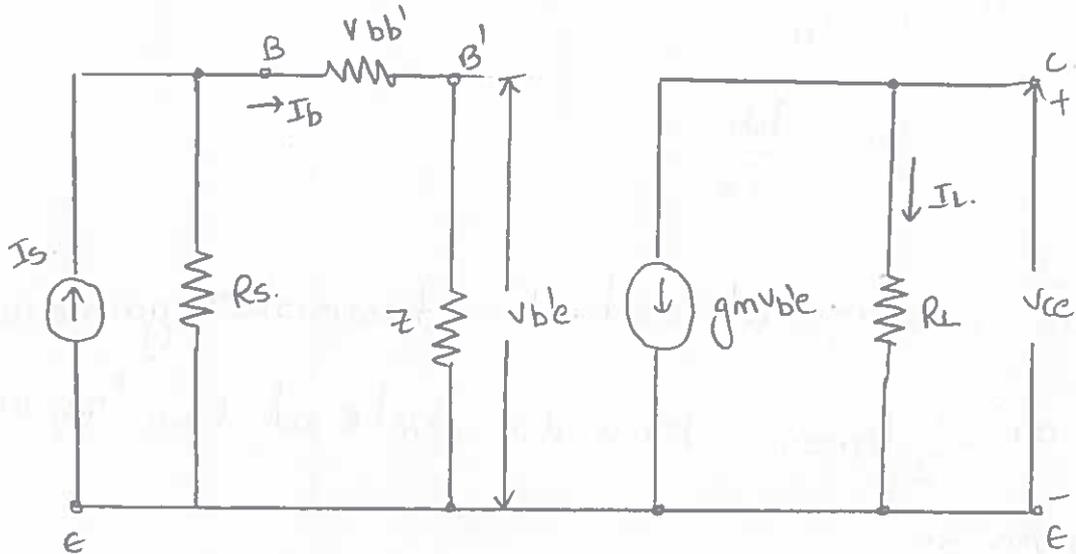


fig: Equivalent circuit assuming current source.

$$\frac{I_L}{I_s} = \frac{-g_m r_{be} R_s}{R_s + r_{bb'} + r_{be}}$$

A_{i_s} at low frequency =

$$= \frac{-h_{fe} R_s}{R_s + h_{ie}}$$

unit $\rightarrow 1$, $46/62$

Voltage gain including source resistance:

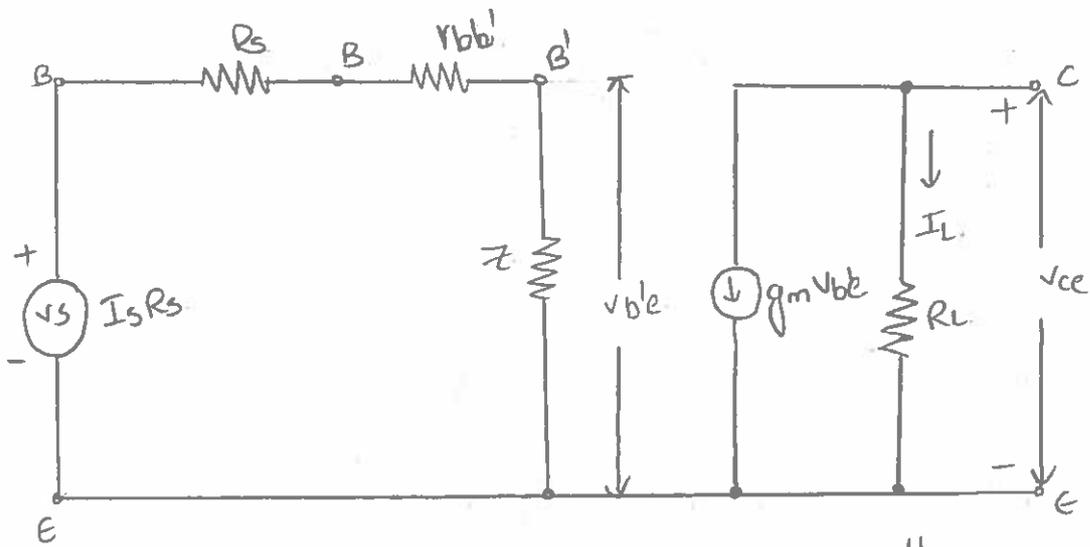


Fig:- Equivalent circuit assuming voltage source

$$A_{Vs} = \frac{V_o}{V_s} = \frac{I_L}{I_s} \frac{R_L}{R_s} = \frac{-g_m Z R_s}{R_s + r_{bb'} + Z} \times \frac{R_L}{R_s}$$

$$= \frac{-g_m Z R_L}{R_s + r_{bb'} + Z}$$

$$A_{Vs \text{ low}} = \frac{I_L}{I_s} \frac{R_L}{R_s} = \frac{-h_{fe} R_s}{R_s + h_{ie}} \times \frac{R_L}{R_s}$$

$$= \frac{-h_{fe} R_L}{R_s + h_{ie}}$$

Cut-off frequency including source resistance

$$A_{is \text{ high}} = \frac{A_{is}}{1 + j \left(\frac{f}{f_H} \right)}$$

$$A_{vs \text{ high}} = \frac{A_{vs}}{1 + j\left(\frac{f}{f_H}\right)}$$

$$\text{where, } f_H = \frac{1}{2\pi R_{eq} C_{eq}}$$

$$\text{where } R_{eq} = r_{be} \parallel (r_{bb'} + R_s)$$

$$\text{and } C_{eq} = C_e + C_c (1 + g_m R_L)$$

For $R_L = 0$.

$$f_H = \frac{1}{2\pi R (C_e + C_c)}$$

$$= \frac{f_T}{g_m R} \quad \therefore f_T = \frac{g_m}{2\pi (C_e + C_c)}$$

$$= \frac{h_{fe} f_\beta}{g_m R} \quad \therefore f_T = h_{fe} f_\beta$$

$$= \frac{f_\beta}{g_{be} R} \quad \therefore g_{be} = \frac{g_m}{h_{fe}}$$

Gain bandwidth product:-

* Gain Bandwidth product for voltage.

$$|A_{vs \text{ low } f_H}| = |A_{vs0} f_H| = \frac{-h_{fe} R_L}{R_s + h_{ie}} \times \frac{1}{2\pi R_{eq} C_{eq}}$$

$$= \frac{R_L}{R_s + r_{bb'}} * \frac{f_T}{1 + 2\pi f_T C_c R_L}$$

mit-1, 48/62

* Gain bandwidth product for current

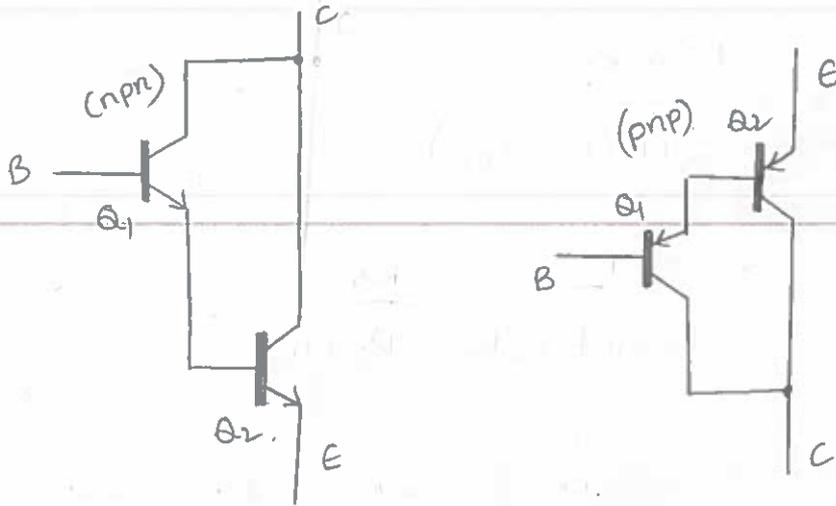
$$|A_{iso} \times f_H| = \frac{g_m R_s}{2\pi C (R_s + r_{bb'})}$$
$$= \frac{f_T}{1 + 2\pi f_T C_C R_L} \cdot \frac{R_s}{R_s + r_{bb'}}$$

Darlington pair:-

This transistor is also called as Darlington pair, contains of two BJTs, that are connected to deliver a high current gain from a low base current. In this transistor, the emitter of the i/p transistor is connected to the o/p of the base of the transistor and the collectors of the transistors are wired together. So, the i/p transistor amplifies the current even further amplifies by the o/p transistor.

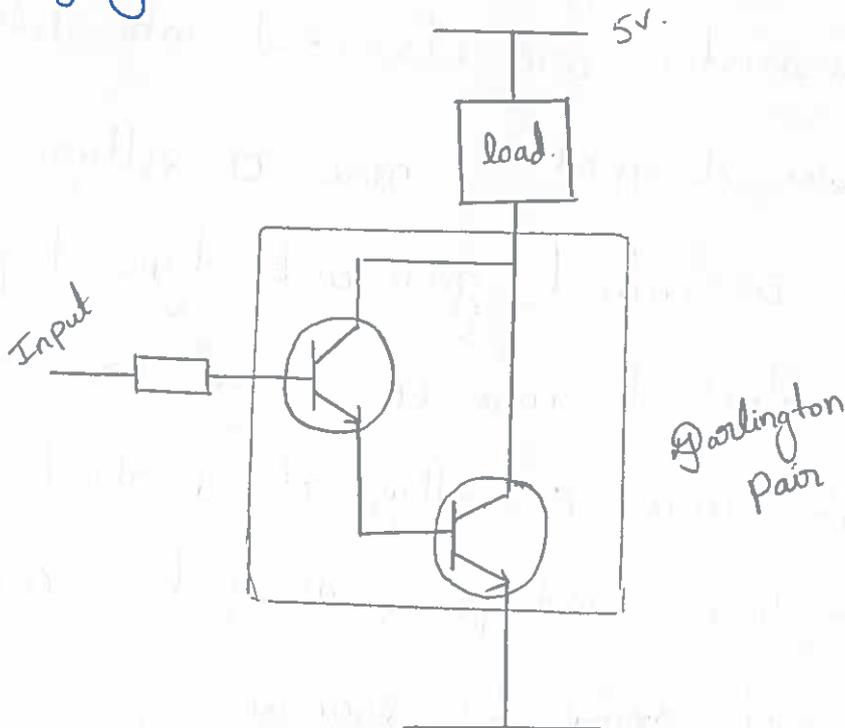
Darlington transistors are classified into different types by power dissipation, max CE voltage, polarity, Min DC current gain and type of packaging. The common values of max CE voltage are 30V, 60V, 80V & 100V, The max CE voltage of Darlington transistor is 450V and power dissipation can be in the range of 200mw to 250mw.

PNP and NPN Darlington transistors



Working of a Darlington transistor:-

A darlington transistor acts as a single transistor with high current gain, it means that a small amount of current is used from the microcontroller or a sensor to run a larger load. For instance, the following circuit is explained below. The below Darlington circuit is built with two transistors shown in the circuit diagram.



working of a Darlington pair transistor unit-1, 50/67

What is current gain?

Current gain is the most important characteristic of a transistor and it is indicated with h_{fe} . When the Darlington transistor is switched ON, then the current supplies through the load to the circuit.

$$\text{Load current} = \text{i/p current} \times \text{transistor gain.}$$

The current gain of every transistor varies. For a normal transistor the current gain would be normally around 100. So the current available to drive the load is 100 times greater than the i/p of the transistor.

The amount of i/p current to switch on a transistor is low in certain applications. So, a particular transistor cannot supply ample current to the load. So, the load current is equal to the i/p current and gain of the transistor. If the input current increase is not possible, then the gain of the transistor will need to be increased. This process can be done by using a darlington pair.

A Darlington transistor contains two transistors, but it acts as a single transistor with a current gain that equals. The total current gain is equal to

Current gains of the transistor 1 and transistor 2.
For instance, if you have two transistors with a similar current gain i.e. 100.

We know that, total current gain (h_{FE}) = Current gain of transistor 1 (h_{FE1}) \times current gain of transistor 2 (h_{FE2})

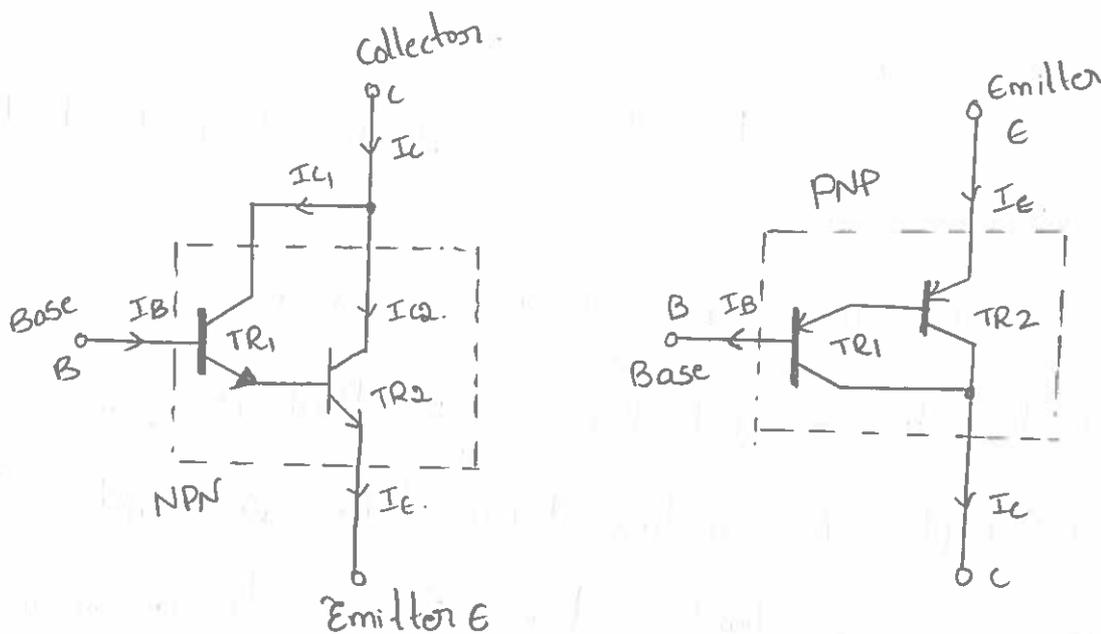
$$100 \times 100 = 10,000.$$

You can observe in the above, it gives a vastly increased current gain compared with a single transistor. So, this will permit a low i/p current to switch a huge load current.

Generally, to turn on the transistor the base i/p voltage of the transistor must be greater ~~than~~ (\rightarrow) than 0.7 volts. In a darlington transistors, two transistors are used. So, the base voltage will be doubled $0.7 \times 2 = 1.4V$. When the darlington transistor is turned on, then the voltage drop across the emitter & collector will be around 0.9V. So, if the supply voltage is 5V, the voltage across the load will be $(5V - 0.9V = 4.1V)$.

Structure of Darlington transistor:-

The structure of darlington transistor is shown below. For instance, here we have used NPN pair transistor. The collectors of the two transistors are connected together, and the emitter of the transistor TR₁ energises the base terminal of the TR₂ transistor. The structure attains β multiplication because for a base and collector current (I_B and $\beta \cdot I_B$), where the current gain is greater than unity that is defined as



Structure of Darlington transistors

$$I_C = I_{C1} + I_{C2}$$

$$I_C = \beta_1 \cdot I_B + \beta_2 \cdot I_B$$

But the base current of the transistor TR₁ is equal to I_{E1} (emitter current), and emitter of the TR₁ transistor is connected to the base terminal of the

transistor TR₂.

$$I_{B2} = I_{E1}$$

$$= I_{C1} + I_B$$

$$= \beta_1 \cdot I_B + I_B$$

$$= I_B(\beta_1 + 1)$$

Substitute this I_{B2} value in the above equation.

$$I_C = \beta_1 \cdot I_B + \beta_2 \cdot I_B(\beta_1 + 1)$$

$$I_C = \beta_1 \cdot I_B + \beta_2 \cdot I_B \beta_1 + \beta_2 \cdot I_B$$

$$= (\beta_1 + (\beta_2 \cdot \beta_1) + \beta_2) \cdot I_B$$

In the above equations, β_1 & β_2 are gains of individual transistors.

Here, the overall current gain of the first transistor is multiplied by the second transistor that is specified by β , & a couple of bipolar transistors are combined to form a single Darlington transistor with a very high input resistance and value of β .

Darlington transistor Applications

This transistor is used in various applications where a high gain is required at a low frequency.

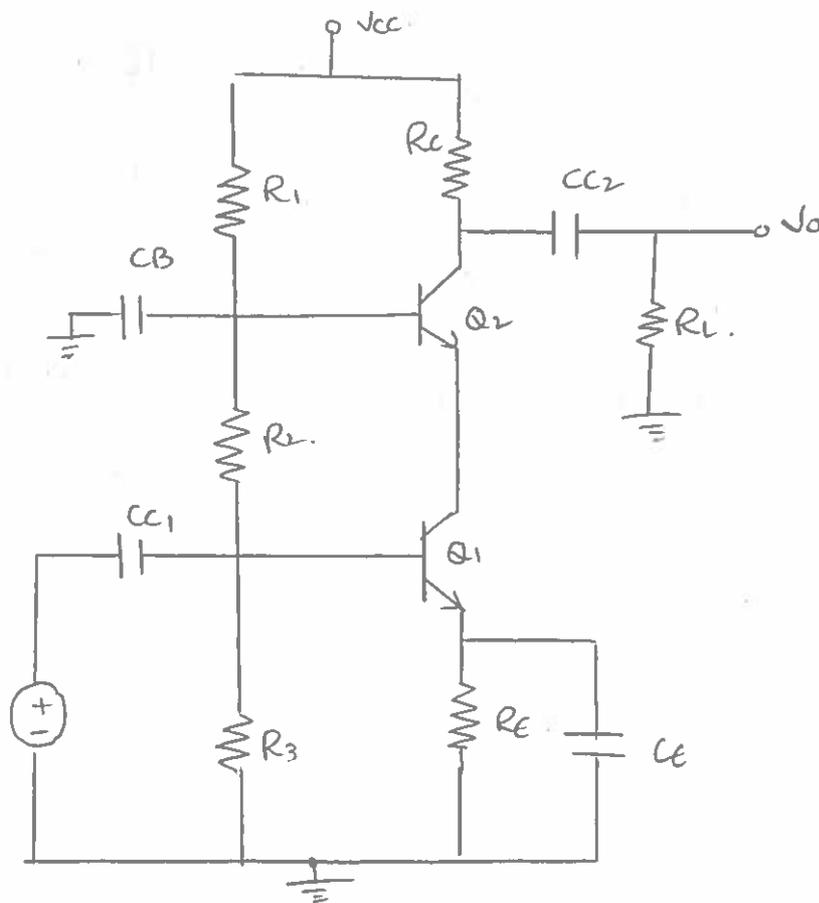
Some applications are.

- * Power regulators.
- * Audio amplifier o/p stages.
- * controlling of motors.
- * Display drivers.
- * Controlling of Solenoid.
- * Light and touch sensors.

Cascode amplifier using BJT:-

The cascode amplifier is the two stage amplifier in which common emitter stage is connected to common base stage.

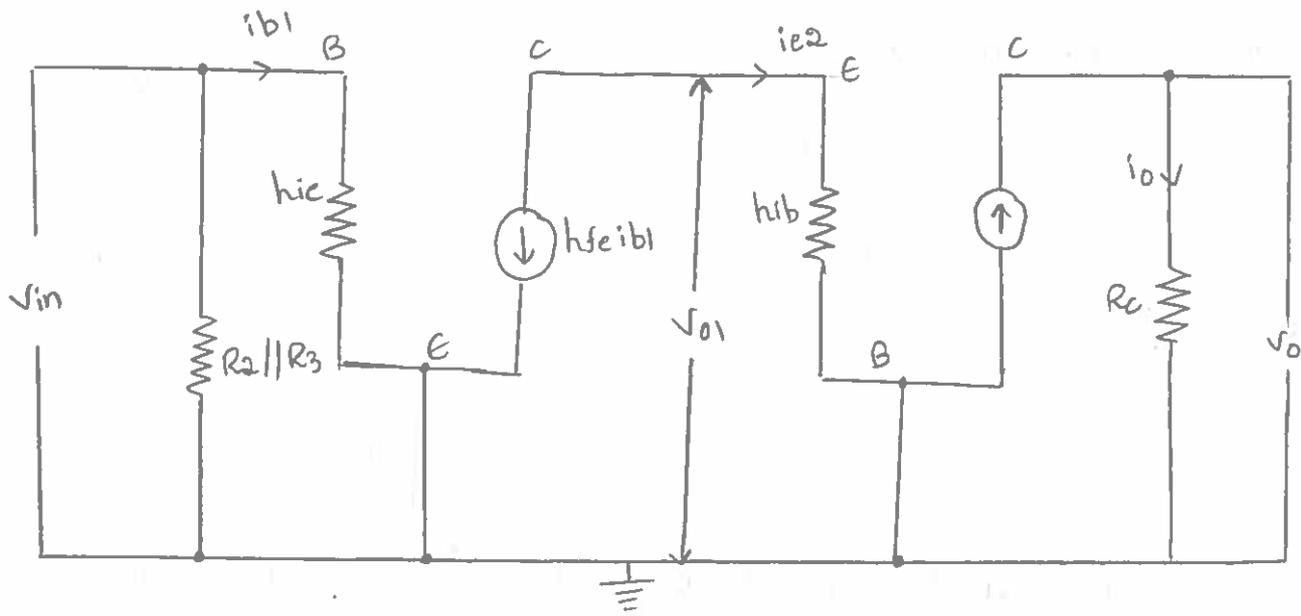
The CE-CB cascode connection is as shown in figure.



The input signal is applied at Q_1 , i.e. at common emitter stage and output is obtained at Q_2 . V_{CC} , R_1, R_2, R_3 , R_C are used to bias transistor Q_1 & Q_2 in active region. R_C is used to make Q-point stable against temperature variation. AC output voltage is obtained at R_C . Collector coupling capacitors are used to block dc signal pass a signals.

AC signal is applied at base of Q_1 which amplifies it with unity gain, and voltage v_{o1} appears across capacitor of Q_1 . v_{o1} acts as input to Q_2 which further amplifies the signal and voltage v_o appears across collector of CB configuration. To perform small signal analysis we need to draw ac equivalent circuit of the given amplifier. To draw the ac equivalent circuit all capacitors must be replaced by short circuit and the DC sources connected to ground.

The AC equivalent circuit is as shown in figure.



The overall voltage gain is the product of first stage gain to second stage gain.

$$A_{VT} = A_{V2} * A_{V1}$$

$$A_{VT} = (v_o/v_i) * (v_i/v_{in})$$

from the above figure we can see that $v_o = I_o * R_c$ → ①

The output current $I_o = h_{fb} i_{e2}$.

hence substituting in equation 1 we get $v_o = h_{fb} i_{e2} * R_c$ → ②

Now to determine v_{o1} we need to apply KVL to the input side of common base connection.

and we get $v_{o1} = i_{e2} * h_{ib}$ → ③

Divide equation "2" by "3" we get

$$v_o/v_i = (h_{fe} i_{e2} * R_c) / (i_{e2} * h_{ib})$$

$$A_{v2} = (h_{fb} * R_c) / (h_{ib}) \rightarrow \textcircled{4}$$

Now determine the gain for first stage.

$$A_{v1} = v_{o1}/v_{in}$$

From the above figure $v_{o1} = i_{e2} * h_{ib} \rightarrow \textcircled{5}$

Since i_{e2} and $h_{fe} i_{b1}$ are opposite in direction,

we can write $i_{e2} = -h_{fe} * i_{b1}$.

Substituting in above equation 5.

$$v_{o1} = -h_{fe} i_{b1} * h_{ib} \rightarrow \textcircled{6}$$

To determine v_{in} we need to apply KVL at the input side.

$$v_{in} - h_{ie} i_{b1} = 0$$

$$v_{in} = h_{ie} i_{b1} \rightarrow \textcircled{7}$$

Now divide (6) and (7)

$$A_{v1} = v_{o1}/v_{in} = (-h_{fe} * i_{b1}) * (h_{ib} * h_{ie} * i_{b1})$$

$$A_{v1} = -h_{fe} * (h_{ib} * h_{ie}) \rightarrow \textcircled{8}$$

But we know

$$h_{ib} = h_{ie} / (1 + h_{fe})$$

Substitute in equation (8)

$$A_{V1} = (-h_{fe}/h_{ie}) \times (h_{ie}/(1+h_{fe}))$$

$$A_{V1} = -h_{fe}/(1+h_{fe})$$

$$A_{V1} \approx -1 \rightarrow (9)$$

Multiply A_{V1} and A_{V2} to obtain A_{VT}

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

$$A_{VT} = (-h_{fb} * R_c) / (h_{ib}).$$

The negative sign indicates the 180 degree phase shift provided by CE stage.

Input impedance:- The input impedance is parallel combination of resistors at input side

$$R_{in} = R_2 \parallel R_3 \parallel h_{ie} \rightarrow (10)$$

Output Impedance:- The output impedance is given by the output resistance of the second stage

$$R_o = R_c \rightarrow (11)$$

In broadband amplifiers cascode configuration is used.

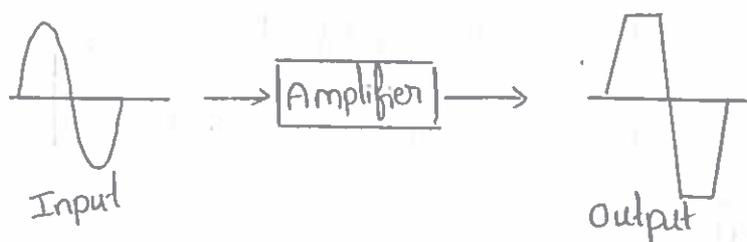
Distortion in Amplifier

Definition:- Distortion in amplifier basically implies the variation in the waveform received at the

output with respect to the applied input. The unwanted alterations generated during amplification is known as distortion.

A pure signal always has a single frequency component where voltage varies positive and negative by an equal amount. If this variation is less than full 360° cycle, then it is called signal is distorted.

When we talk about an ideal amplifier, the amplified output must be exact replica of the input. But practically such an ideal amplifier doesn't exist. The undesired changes in the signal at the amplifier's output are basically termed as distortion in amplifier.



Distorted output of an amplifier

For a distortion less output signal, dc biasing is required at the base or gate terminal. When dc biasing is employed, the signal is amplified over its entire cycle. The bias "Q-point" must fall at the

middle of the loadline. Thus, with such a "Q point" setting, type A amplification can be achieved. To have a detailed explanation about class A amplifiers refer to our previous article power amplifier.

Reasons for signal distortion:-

* Due to incorrect biasing when the signal is not amplified for the entire cycle of the input signal then distortion occurs.

* It also occurs in the case when the applied input signal is very large.

* Distortion in amplifier sometimes results when the amplification is not linear over the complete frequency range.

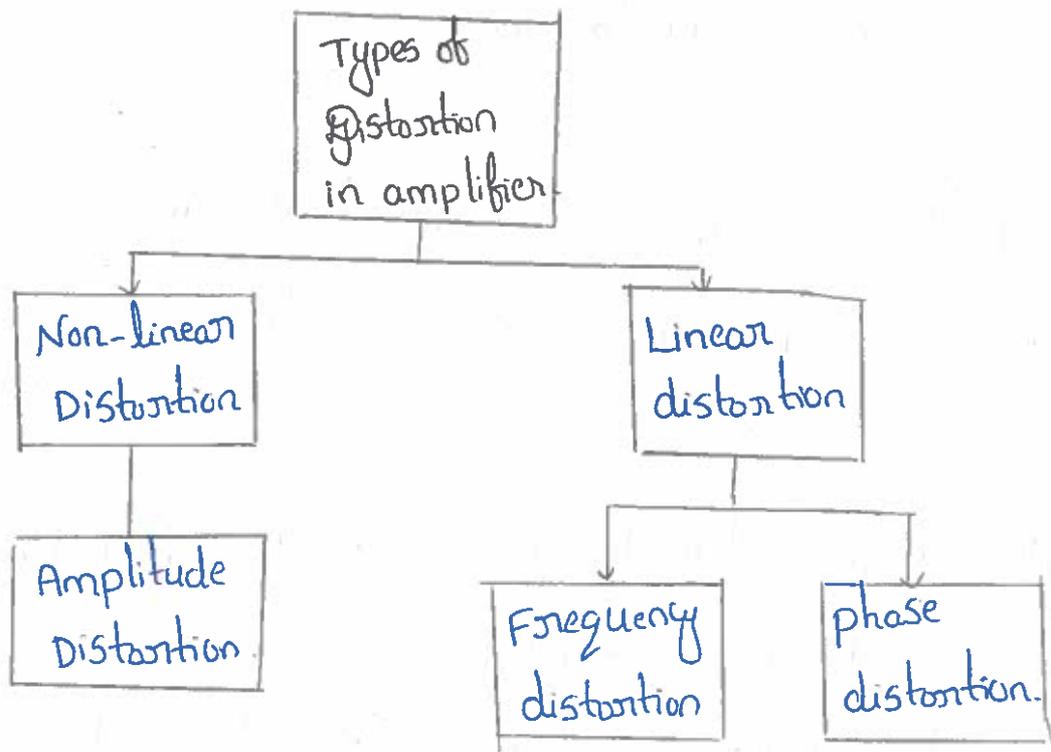
As we are already aware of the fact that the amplifier basically amplify small voltage signal in order to provide a larger signal at the output. After amplification, the output signal is the value obtained by the multiplication of amplifier's gain with that of the input signal.

This is the reason why we get an amplified signal at the output of an amplifier. But the

gain of amplifier. i.e. β is different for the even similar type of transistor. This causing variation of "Q-point" from a transistor to other.

Types of Distortion in amplifier:-

The type of distortion merely depends on the region of characteristics that are used by transistor, the reactance of the device and the associated circuit.



* Non-linear Distortion:-

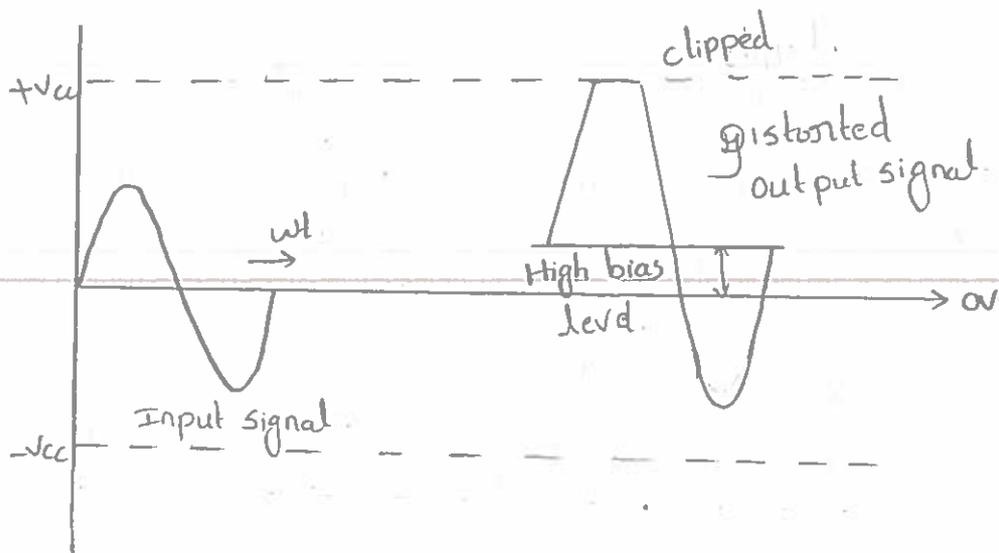
This type of distortion occurs in an amplifier when the signal input is large and the active device is driven into a non-linear region of its characteristics.

* Amplitude Distortion

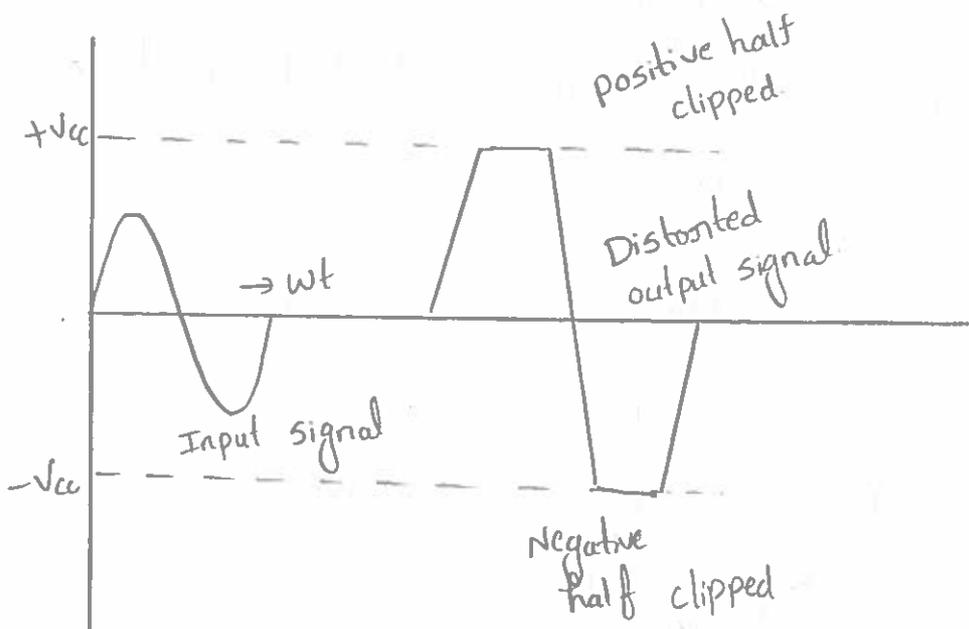
This type of distortion occurs due to attenuation in the peak value of the waveform. The shift in "Q-point" and amplification for less than 360° of the input signal leads to amplitude distortion. It occurs mainly due to "incorrect biasing and clipping". As we know that if the biasing point of the transistor is correct, one can have output is the exact replica of input in the amplified form. Let us understand it with the help of the following three cases.

* Case-1:- Suppose insufficient biasing is provided, the "Q-point" will lie near the lower half of the loadline. In such condition, negative half of ~~input~~ input is clipped and we get distorted at the output of the amplifier.

* Case 2:- Suppose an extra bias potential is provided, the "Q-point" will now be at the upper half of the load line. This condition gives an output that is cut-off at positive half of the waveform.



Case 3:- Sometimes correct biasing also leads to distortion in the output in case of the large input signal. This is so because the large input signal is amplified by the gain of the amplifier. In this case, both "positive and negative" half of the waveform gets "clipped" at some position.



* This is also known as clipping distortion. The efficiency of the circuit extremely decreases due to amplitude distortion.

Linear Distortion:- This type of distortion occurs when small input signal drives the device and it operates in the linear region of its characteristics.

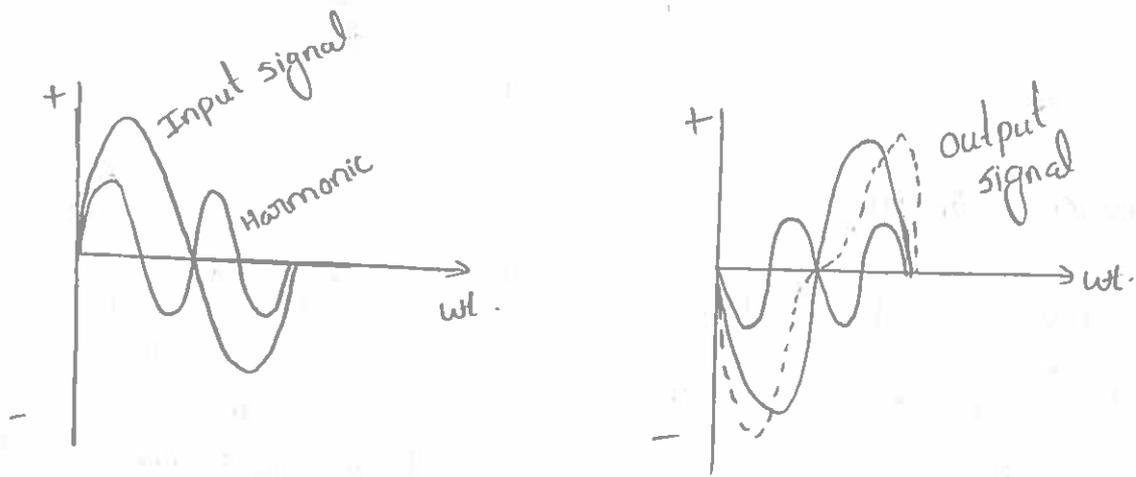
The mainly occurs due to frequency dependent characteristics of the active devices.

* Frequency Distortion:-

In frequency distortion, the level of amplification varies with respect to frequency. In a practical amplifier, during amplification input signal consist of fundamental frequency along with different frequency components. The different frequency along with is known as "harmonics". After amplification, the amplitude of harmonics is somewhat a fraction of fundamental amplitude. Resultantly causing no any severe effect at the output waveform. But if the amplitude of harmonics after amplification goes to higher value then its effect cannot be avoided as will be noticeable at the output. The diagram shown below will help you to understand frequency distortion clearly - here input consists of fundamental frequency along with harmonics. The combination of the two on amplification will give a distorted signal at the output.

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It occurs either due to presence of reactive elements or by the electrode capacitances of the amplifier circuits.



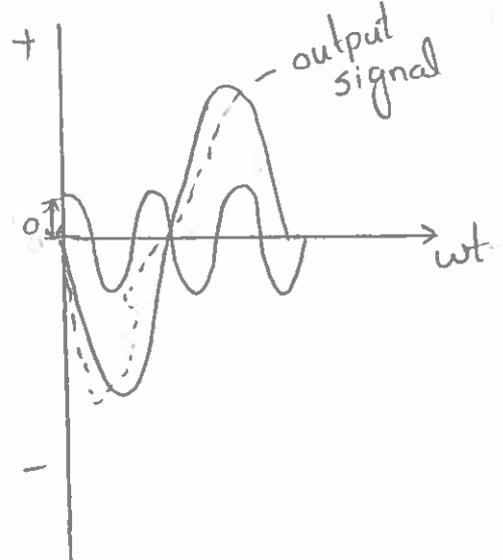
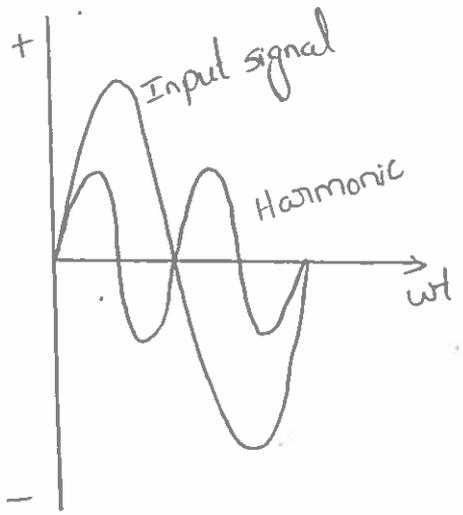
Frequency distortion due to Harmonics

* Phase Distortion:-

Phase distortion in the amplifier is also known as delay distortion. As the name indicates whenever there is a time delay between input and occurrence of the signal at the output. It is said to be phase distorted signal. It occurs mainly due to electrical reactance. As we have discussed that a signal consists of different frequency components. So, when different frequency suffers different phase shift, phase distortion takes place. Phase distortion has no

practical significance in audio amplifiers as the human ear is insensitive to phase shift. The type and amount of distortion that is tolerable or intolerable depend on the application of amplifier.

Generally, the system working gets affected only when the amplifier causes excessive distortion.



phase distortion due to delay

