Course on

Electronic Circuit Analysis

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Unit-3: Feedback Amplifiers

1 Classification of Amplifiers

- The amplifiers are broadly classified into four categories:
  1. Voltage amplifiers
  2. Current amplifiers
  3. Transconductance amplifiers
  4. Transresistance amplifiers.
- The above classification is based on the magnitudes of i/p and o/p impedances of an amplifier relative to the source and load impedances, respectively.

(1) Voltage Amplifier:

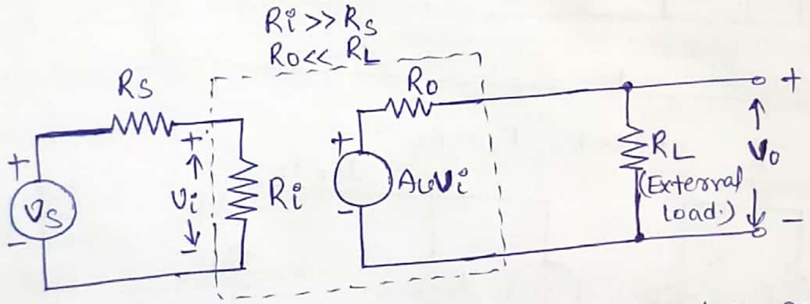


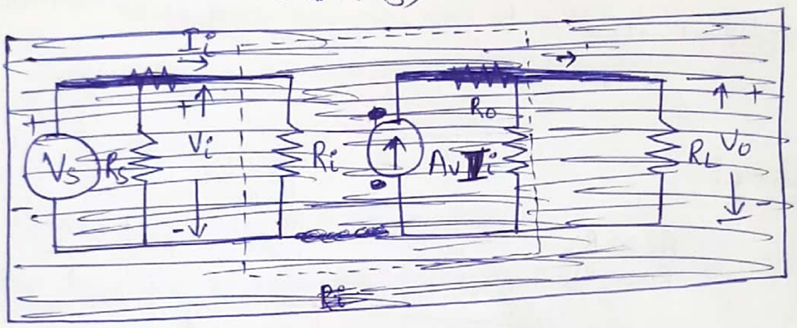
Fig. Thevenin's equivalent circuit of a two-port network (Amplifier)

- If the amplifier i/p resistance R_i is large compared with the source resistance R_s, then $V_i \approx V_s$.
- If the External load resistance R_L is large compared with the o/p resistance R_o of the amplifier, then $V_o \approx A_v V_i \approx A_v V_s$.
- This amplifier provides a voltage o/p proportional to the voltage i/p and the proportionality factor is independent of the magnitudes of the R_s and R_L. This is called voltage amplifier.
- An ideal voltage amplifier must have infinite input resistance ($R_i = \infty$) and zero o/p resistance ($R_o = 0$).
- The symbol A_v represents $\frac{V_o}{V_i}$ with $R_L = \infty$ and hence represents the open circuit voltage amplification or gain.

$$\boxed{A_v = \left.\frac{V_o}{V_i}\right|_{R_L = \infty}}$$

(2) Current Amplifier:

- An ideal current amplifier is defined as an amplifier which provides an output current proportional to the i/p signal current, and the proportionality factor is independent of R_S and R_L.
- An ideal current amplifier must have zero input resistance R_i ($R_i = 0$) and infinite output resistance R_o (i.e $R_o = \infty$). In practice, the amplifier has low R_i and very high R_o.
- It drives low-resistance load ($R_o \gg R_L$) and is driven by high resistance source ($R_i \ll R_S$).



$R_i \ll R_S$, $R_o \gg R_L$

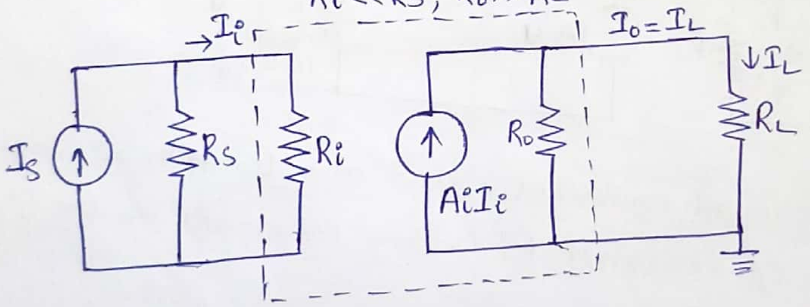


Fig: Norton's Equivalent circuit of Current Amplifier.

If $R_i \ll R_S$, $I_i = I_S$ and

$R_o \gg R_L$, $I_L \approx A_i I_i \approx A_i I_S$ ($\because I_S \approx I_i$)

$\therefore$ $\boxed{A_i = \frac{I_L}{I_i} \text{ with } R_L = 0}$ Short circuit current Gain.

(3) Transconductance amplifier:

- The ideal transconductance amplifier supplies an output current which is proportional to the signal voltage and is independent of R_S and R_L.
- This amplifier must have an infinite input resistance R_i (i.e $R_i = \infty$) and infinite output resistance R_o (i.e $R_o = \infty$).
- A practical transconductance amplifier has $R_i \gg R_S$ and $R_o \gg R_L$ so that drives a low-resistance load and driven by low-resistance source.

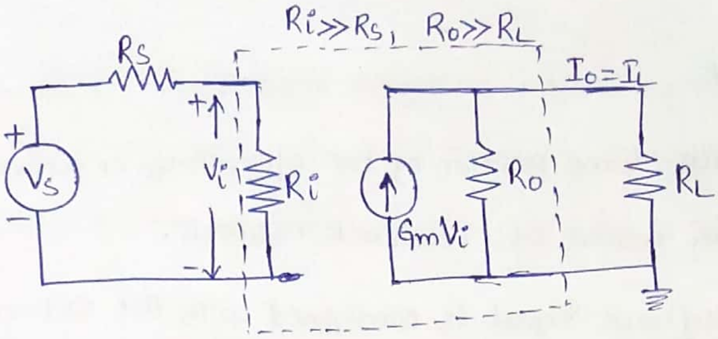


Fig. A transconductance Amplifier. (i/p-Thevenin's, o/p = Norton's ckt)

- If $R_i \gg R_s$, $V_i \simeq V_s$

$R_o \gg R_L$, $I_o \simeq I_L \simeq G_m V_i \simeq G_m V_s$.

$\therefore$ $\boxed{G_m = \frac{I_o}{V_i} = \text{Transconductance}}$

④. Transresistance Amplifier:

- A ideal transresistance amplifier supplies an output voltage V_o in proportion to the signal current I_s and which is independent of R_s and R_L.
- For practical transresistance amplifier, $R_i \ll R_s$ and $R_o \ll R_L$.

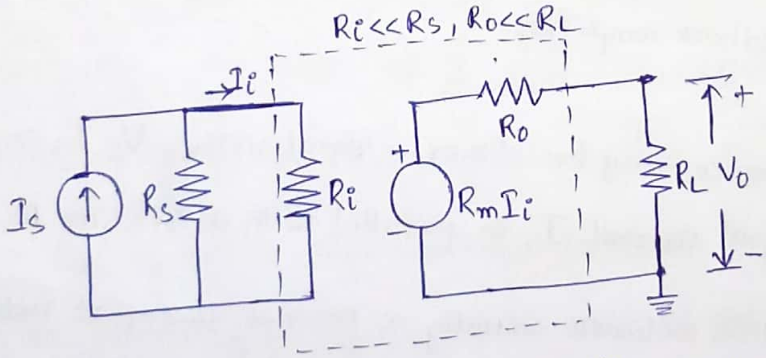


Fig. A transresistance amplifier (i/p - Norton's, o/p - Thevenins ckt)

- If $R_s \gg R_i$, $I_i \approx I_s$ and

$R_o \ll R_L$, $V_o \approx R_m I_i \approx R_m I_s$.

$\therefore$ $\boxed{R_m = \frac{V_o}{I_i}}$ with $R_L = \infty$.

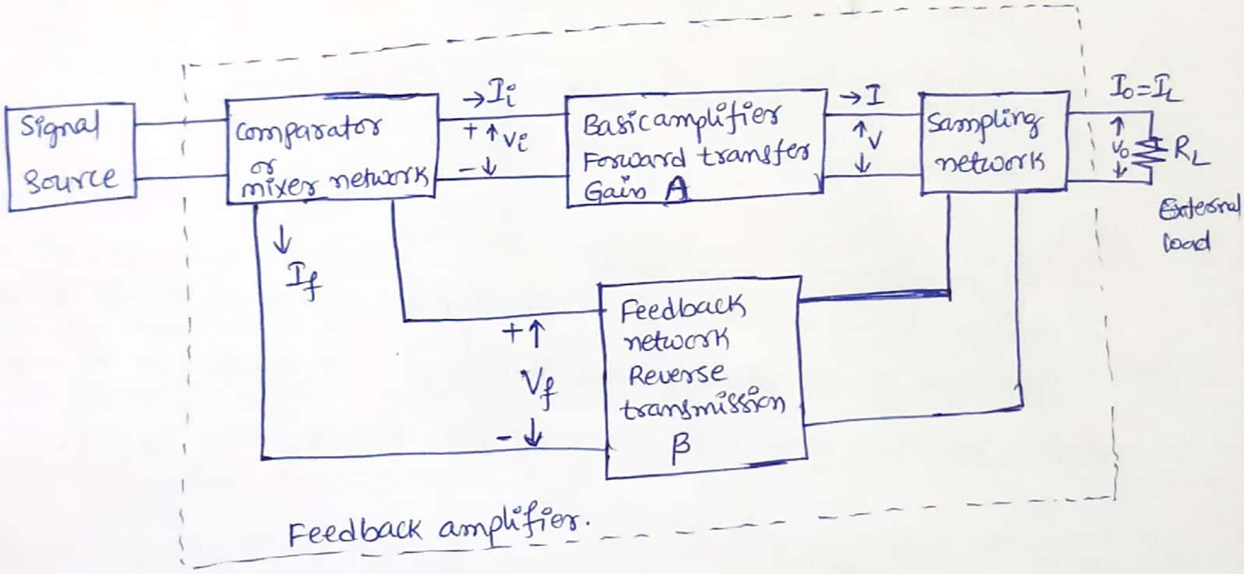
R_m = open-circuit mutual or transfer resistance.

Table: Ideal Amplifier Characteristics.

Parameter	Amplifier Type.			
	Voltage	Current	Transconductance	Transresistance.
R_i	∞	0	∞	0
R_o	0	∞	∞	0
Transfer characteristic	$V_o = A_v V_s$	$I_L = A_i I_s$	$I_L = G_m V_s$	$V_o = R_m I_s$.

② The Feedback Concept

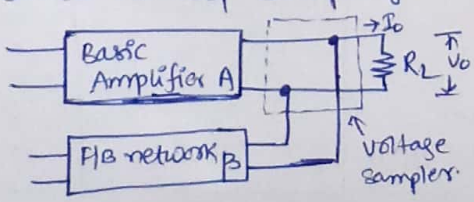
- In the feedback circuits, some portion of the o/p voltage or current is fedback to the i/p by means of feedback network.
- At the input the feedback signal is combined with the external or source signal through a mixer network and the resultant signal fed into the amplifier.

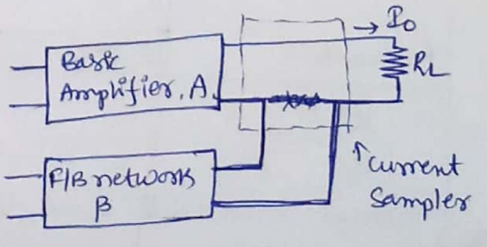


(i) Signal Source: This source may be either a signal voltage V_s in series with a R_s or a signal current I_s in parallel with a resistor R_s.

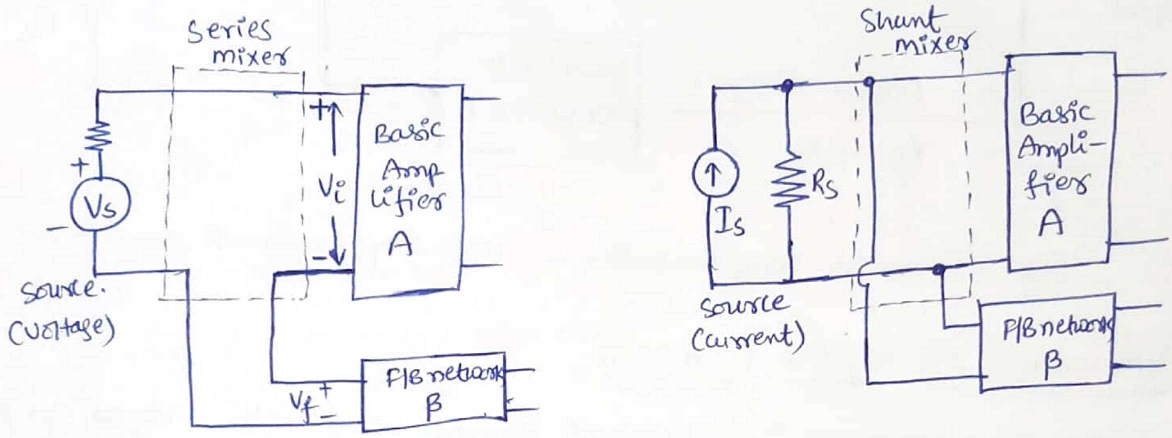
(ii) Feedback network: This network usually a passive two-port network which may contain resistors, capacitors, and inductors.

(iii) Sampling network: The sampling network may be voltage sampling or current sampling. In the voltage sampling network, the o/p voltage is sampled by connecting the feedback network in "shunt" across the o/p. The voltage sampling is also called as node sampling. In the current sampling network, the output current is sampled by connecting the feedback network in "series" with the output. This is also called as loop sampling.





(iv) Comparator (or) mixer network: The comparator or mixer network at the input may be series mixing (comparision) or shunt mixing. A differential amplifier is also used as a mixer.



(v) Transfer ratio (or) Gain of Basic amplifier: The ratio of the o/p signal to the input signal of the basic amplifier is called the gain A. The transfer ratio $\frac{V}{V_i}$ is the voltage amplification or voltage gain A_V. Similarly, the transfer ratio $\frac{I}{I_i}$ is the current amplification or current gain A_I. The ratio of $\frac{I}{V_i}$ is the transconductance G_M and the ratio of $\frac{V}{I_i}$ is the transresistance R_M. So "A" may be A_V, A_I, G_M or R_M of an amplifier without feedback.

- The symbol "A_f" represents the ratio of output signal to the input signal of the amplifier and is called the transfer gain of the amplifier with feedback.

A – Gain without feedback
A_f – Gain with feedback.

$$\boxed{\begin{aligned} A_f &= \frac{V_o}{V_s} = A_{Vf} \\ A_f &= \frac{I_o}{I_s} = A_{If} \\ A_f &= \frac{I_o}{V_s} = G_{Mf} \\ A_f &= \frac{V_o}{I_s} = R_{Mf} \end{aligned}} \qquad \boxed{\begin{aligned} A &= \frac{V}{V_i} = A_V \\ A &= \frac{I}{I_i} = A_I \\ A &= \frac{I}{V_i} = G_M \\ A &= \frac{V}{I_i} = R_M \end{aligned}}$$

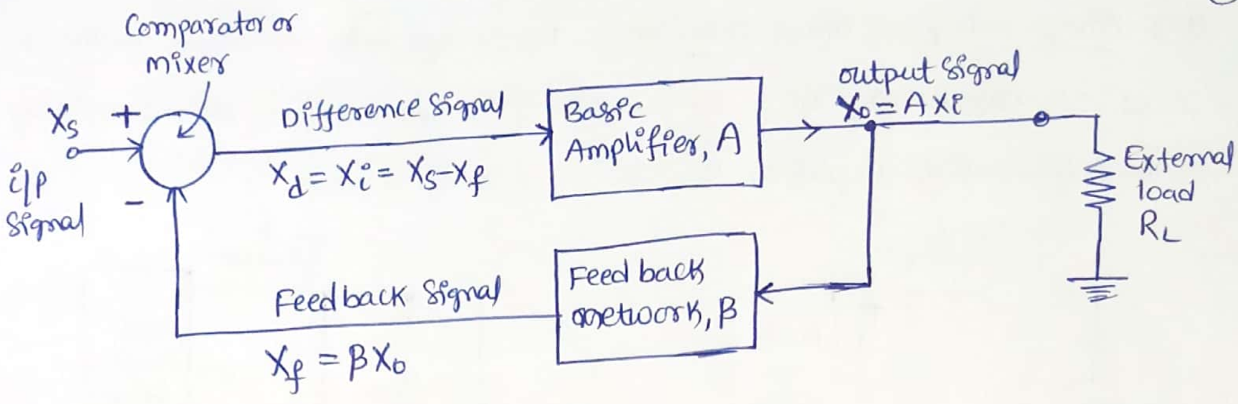


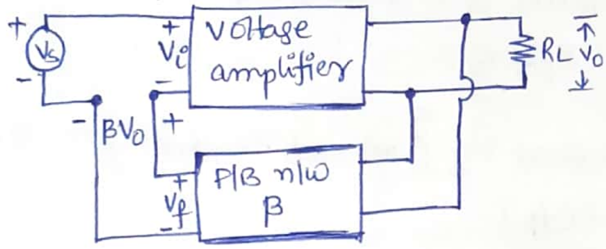
Fig. Schematic representation of single-loop feedback amplifier.

Advantages of negative feed back:

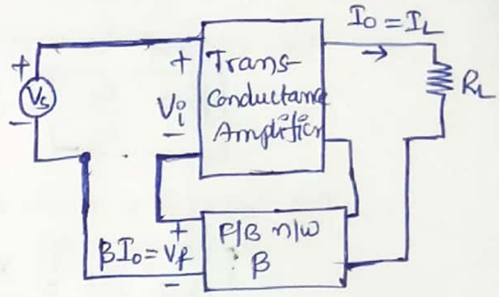
- When any increase in the output signal results in a feed back signal ($X_f = \beta X_o$) into the input to cause a decrease in the output signal, the amplifier is called to have negative feedback.
- In other words, when a part of the output is given back to the input so that the output decreases is called negative feed back.
- Advantages of negative feedback are:
  - i. I/P and o/p impedances can be modified as desired (increases or decreases)
  - (ii) The transfer gain A_f of the amplifier can be stabilized against variations in h- or hybrid π-parameters. (Stabilization of gain)
  - (iii) Improves the frequency response.
  - (iv) provides more linearity (high fidelity)
  - (v) It has less amplitude and phase distortion.
  - (vi) less harmonic distortion.
  - (vii) It can control the step response of an amplifier.
  - (viii) Increasing the bandwidth.
- Due to these reasons many amplifier and control systems uses negative feedback.
- Disadvantages are:
  - (i) The transfer gain A_f of the amplifier is reduced compared with the gain A (without feedback).

3. The transfer Gain with feedback :

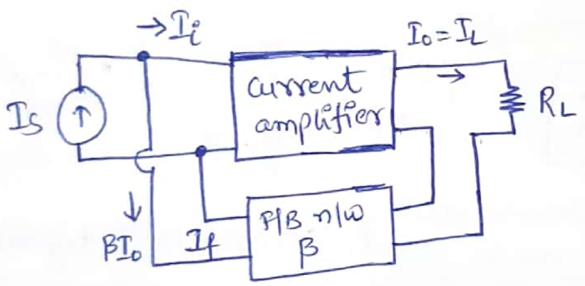
- The basic amplifier may be a voltage, transconductance, current or transresistance amplifiers connected in a feedback configuration.



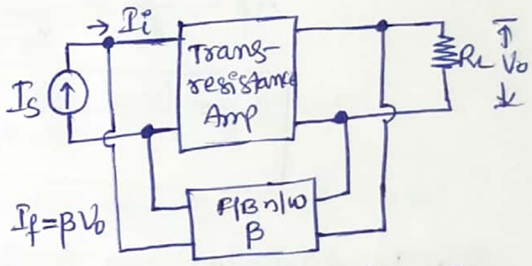
(a) Voltage amplifier with voltage-series feedback.



(b) Transconductance amplifier with current-series feedback.



(c) current amplifier with [redacted] current-shunt feedback.



(d) Transresistance amplifier with voltage-shunt feedback.

Table : Voltage and current signals in feedback amplifier.

Signal	Type of feedback			
	voltage-series	current series	current-shunt	voltage-shunt
output signal X_o	voltage V_o	current, $I_o=I_L$	current, $I_o=I_L$	voltage V_o.
X_s, X_f, X_d	voltage	voltage	current	current
A	A_V	G_M	A_I	R_M
β	V_f/V_o	V_f/I_o	I_f/I_o	I_f/V_o.

where X_s - input/source signal
X_o - output signal
X_f - Feedback signal
X_d - difference signal

- The difference signal X_d is given by:

$$\boxed{X_d = X_s - X_f = X_i} \quad \text{— (1)}$$

⇒ difference between the applied and feedback signal.

X_d is also called as error, comparison signal.

- The reverse transmission factor β is defined by

$$\boxed{\beta = \frac{X_f}{X_o}} \text{ — (2)} \quad (\because X_f = \beta X_o)$$

- The transfer gain A is defined by (without feedback)

$$\boxed{A = \frac{X_o}{X_i}} = \frac{X_o}{X_s - X_f} = \frac{(X_f/\beta)}{X_s - X_f}$$

- The gain with feedback is obtained as:

$$A_f = \frac{X_o}{X_s} = \frac{X_f/\beta}{X_d + X_f}$$

(or) $$\boxed{A_f = \frac{X_o}{X_s} = \frac{X_o}{X_i + X_f} = \frac{A}{1+\beta A}}$$

$$\left(\because \frac{A}{1+\beta A} = \frac{\left(\frac{X_o}{X_i}\right)}{1 + \frac{X_f}{\cancel{X_o}} \cdot \frac{\cancel{X_o}}{X_i}} = \frac{X_o}{\cancel{X_i}} \cdot \frac{\cancel{X_i}}{X_i + X_f} = \frac{X_o}{X_i + X_f}\right)$$

- If $|A_f| < |A|$, the feedback is known as negative feedback (or) degenerative F/B.
If $|A_f| > |A|$, the feedback is known as positive feedback or regenerative F/B

Loop gain: The product $(-A\beta)$ is called the loop gain, or return ratio.
The difference between unity and the loop gain is called the return difference $D = (1 + A\beta)$.
The amount of feedback introduced into an amplifier is expressed as:

$$N = 20 \log \left|\frac{A_f}{A}\right| = 20 \log \left|\frac{1}{1+A\beta}\right|$$

(4) General Characteristics of Negative feedback amplifiers:

(i) Desensitivity or Stabilization of gain: The stability of the amplifier transfer gain is effected by the variation due to aging (source replacement), temperature, replacement et.. of the circuit components.

- The fractional change in the amplification with feedback divided by the fractional change without feedback is called sensitivity of transfer gain.

we know that $A_f = \dfrac{A}{1+A\beta}$

$$\left|\frac{dA_f}{A_f}\right| = \frac{1}{|1+\beta A|}\left|\frac{dA}{A}\right|$$

Here, $\dfrac{1}{|1+A\beta|}$ is the sensitivity.

- The reciprocal of the sensitivity is called the desensitivity D, or

$$\boxed{D = (1+A\beta)}$$

The amount of feedback $N = -20\log D$.

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

- If $|A\beta| \gg 1$, then $A_f = \frac{\cancel{A}}{\cancel{A}\beta} = \frac{1}{\beta}$

- Feedback is used to improve stability of the amplifier by factor D.

(ii) Frequency distortion: If the feedback does not contain reactive elements, then the overall gain is not a function of frequency. So frequency and phase distortion is reduced.

(iii) Non linear Distortion:

- Suppose that a large amplitude signal is applied to an amplifier so that the operation of device extends slightly beyond its range of linear operation, then the o/p signal is slightly distorted.

- In negative feedback amplifier, if i/p is increased by some amount by the same amount gain is reduced, so that the output signal amplitude remains the same. So nonlinear distortion is reduced in negative feedback amplifiers.

If D is the distortion without feedback then

$D_f = \frac{D}{(1+A\beta)}$ is the distortion with feedback.

(iv) Reduction of noise:

- The noise introduced by the amplifier is divided by the $(1+A\beta)$ factor if feedback is employed.

- If $(1+A\beta)$ or D is much greater than unity, o/p noise is considerably reduced.

$N_f = \frac{N}{(1+A\beta)}$ noise with feedback. (N = Noise without feedback).

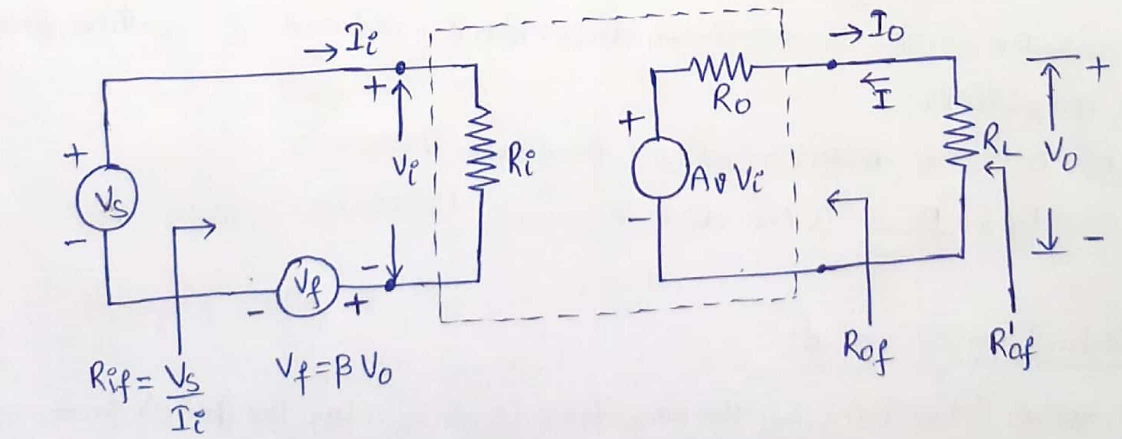
(5) Input resistance:

- For series mixing, the input resistance with feedback (R_{if}) is greater than the i/p resistance without feedback (R_i). ($R_{if} > R_i$) whereas for shunt mixing, $R_{if} < R_i$.

Table: Effect of Negative Feedback on amplifier Characteristics.

Parameter	Type of feedback			
	Voltage Series	Current series	Current-Shunt	Voltage-Shunt
R_{if}	Increases	Increases	Decreases	Decreases
R_{of}	Decreases	Increases	Increases	Decreases
Desensitizes	A_{vf}	G_{mf}	A_{If}	R_{mf}
Bandwidth	Increases	Increases	Increases	Increases
Non-linear distortion	Decreases	Decreases	Decreases	Decreases
Improves the performance of	Voltage amplifier	Trans conductance amplifier	Current amplifier	Transresistance amplifier

(a) Voltage-Series Feedback:



- The basic amplifier is replaced by its Thevenin's model.
- A_v represents the open circuit voltage gain by taking R_s into account. The R_s is considered as a part of the amplifier.
- From the above figure the input impedance with feedback is:

$$R_{if} = \frac{V_s}{I_i}.$$

$$V_s - I_i R_i - V_f = 0 \Rightarrow V_s = I_i R_i + V_f$$

$$V_s = I_i R_i + \beta V_o \quad \text{--- (1)}$$

and $V_o = \dfrac{A_v V_i \cdot R_L}{R_o + R_L} = A_V I_i R_i$ — ②

where $A_V = \dfrac{A_v R_L}{R_o + R_L} = \dfrac{V_o}{V_i}$ — ③

- From eq ① and ②

$$\boxed{R_{if} = \frac{V_s}{I_i} = R_i(1 + \beta A_V)} \quad — ④$$

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

$V_s = I_i \left[R_i (1 + \beta A_V) \right]$

$\dfrac{V_s}{I_i} = R_i \left[1 + \beta A_V \right] = R_{if}$

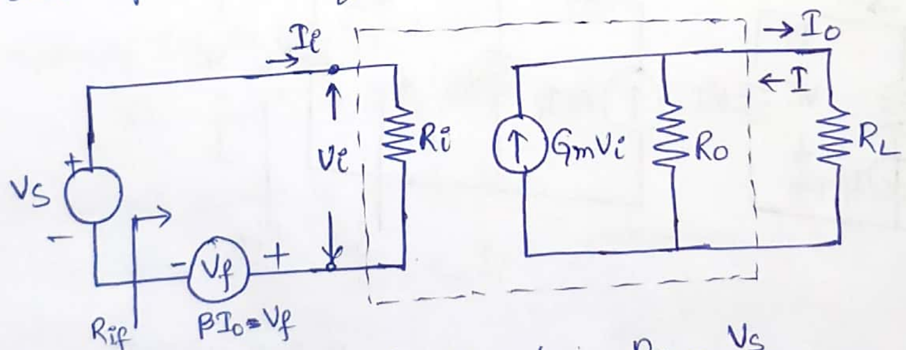
- whereas A_v – open circuit voltage gain without feedback.

A_V – voltage gain without feedback taking the R_L into account.

$$\therefore \boxed{A_v = \lim_{R_L \to \infty} A_V.} \quad — ⑤$$

(b) current – series feedback :

- The i/p circuit is represented by Thevenin's model and the output circuit by Norton's equivalent circuit.



- The input impedance is given by : $R_{if} = \dfrac{V_s}{I_i}$

- Applying KVL to the i/p side, we get

$$V_s - I_i R_i - V_f = 0$$

$$V_s = I_i R_i + V_f$$

$$= I_i R_i + \beta I_o \quad — ①$$

- The output current equation is written as

$$I_o = \frac{G_m V_i R_o}{R_o + R_L} = G_M V_i \quad — ②$$

where $G_M = \dfrac{G_m R_o}{R_o + R_L} = \dfrac{I_o}{V_i}$ — ③

- By substituting eq ② in ① we get

$$V_s = I_i R_i + \beta G_m V_i$$
$$= I_i R_i + \beta G_m I_i R_i$$
$$= I_i [R_i + \beta G_M R_i]$$

$$\boxed{R_{if} = \frac{V_s}{I_i} = R_i[1+\beta G_M]} \quad \text{—④}$$

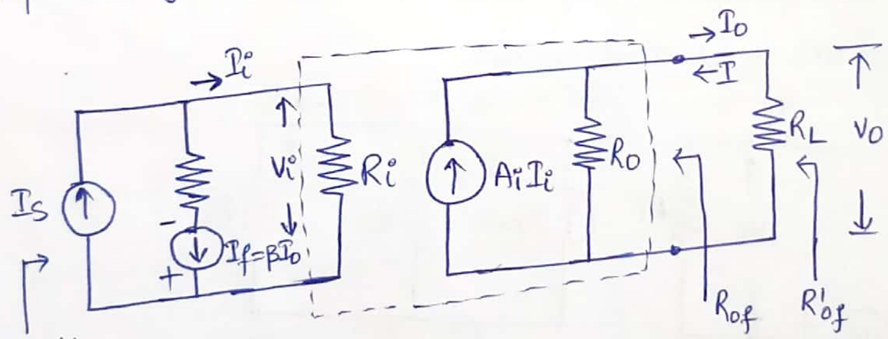
Here, $R_{if} > R_i$ for series mixing.

where G_m = Short circuit transconductance without feedback.

G_M = transconductance without feedback taking the R_L into account.

$$\therefore \boxed{G_m = \lim_{R_L \to 0} G_M} \quad \text{—⑤}$$

(c) current-shunt Feedback: The amplifier i/p and o/p circuits are replaced by its Norton's model.



$R_{if} = \frac{V_i}{I_s}$

- A_i - short circuit current gain by taking R_s into account.
- Applying KCL to the i/p side, we get

$$I_s - I_i - I_f = 0$$
$$I_s = I_i + I_f = I_i + \beta I_o \quad \text{—①}$$

$$\text{and } I_o = \frac{A_i I_i \cdot R_o}{R_o + R_L} = A_I I_i \quad \text{—②}$$

$$\text{where } A_I = \frac{A_i \cdot R_o}{R_o + R_L} = \frac{I_o}{I_i} \quad \text{—③}$$

- By substituting eq ② in ① we get

$$I_s = I_i + \beta A_I I_i$$
$$I_s = I_i(1+\beta A_I) \quad \text{—④}$$

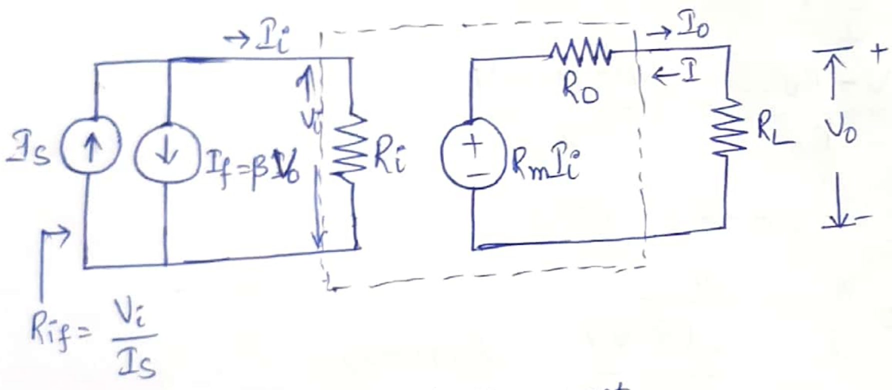
$$\boxed{R_{if} = \frac{V_i}{I_s} = \frac{V_i}{(1+\beta A_I) I_i} = \frac{R_i}{(1+\beta A_I)}} \quad (5) \qquad \left(\because \frac{V_i}{I_i} = R_i\right)$$

A_i = Short circuit current gain without feedback

A_I = current gain without feedback taking R_L into account.

$$\therefore \boxed{A_i = \lim_{R_L \to 0} A_I}$$

(d) Voltage-shunt feedback.



- Applying KCL to the input side, we get

$$I_s = I_i + I_f = I_i + \beta V_o \quad (1)$$

- The output voltage is written by:

$$V_o = \frac{R_m I_i \cdot R_L}{R_o + R_L} = R_M I_i \quad (2)$$

$$\text{where } R_M = \frac{R_m R_L}{R_o + R_L} = \frac{V_o}{I_i} \quad (3)$$

- substitute (2) in (1), we get

$$I_s = I_i + \beta R_M I_i$$

$$I_s = I_i (1 + \beta R_M) \quad (4)$$

- The input resistance with feedback is given as

$$R_{if} = \frac{V_i}{I_s} = \frac{V_i}{I_i(1+\beta R_M)} = \frac{R_i}{(1+\beta R_M)} \quad (5)$$

where R_m – open-circuit transresistance without feedback

R_M – transresistance without feedback by taking R_L into account

$$R_m = \lim_{R_L \to \infty} R_M \quad (6)$$

6 Output Resistance

- For Voltage Sampling $R_{of} < R_o$ and for current sampling $R_{of} > R_o$.

(a) Voltage-series feedback:

- The output resistance with feedback R_{of} is the resistance looking into the output terminals with R_L disconnected (or removed).
- To find R_{of} we must remove the external signal (set $V_s = 0$, (or) $I_s = 0$).
- Let $R_L = \infty$, impress a voltage V across the output terminals and calculate the current I delivered by V.
- Then $R_{of} = \frac{V}{I}$. we find with V_o replaced by V,

$$I = \frac{V - A_v V_i}{R_o} = \frac{V + \beta A_v V}{R_o} \quad \text{--- (1)}$$

where $V_i = -V_f = -\beta V$ ($\because V_o = V$), $V_s = 0$. Hence

$$R_{of} = \frac{V}{I} = \frac{V}{\frac{V + \beta A_v V}{R_o}} = \frac{R_o \cdot \cancel{V}}{\cancel{V}(1 + \beta A_v)} \quad \text{--- (2)}$$

o/P Resistance with f/B.
$$\boxed{R_{of} = \frac{R_o}{1 + \beta A_v}} \quad \text{--- (3)}$$

- The output resistance with feedback R'_{of} which includes R_L as a part of the amplifier is given by R_{of} in parallel with R_L.

$$R'_{of} = \frac{R_{of} R_L}{R_{of} + R_L} = \frac{\left(\frac{R_o R_L}{1 + \beta A_v}\right)}{\left(\frac{R_o}{1 + \beta A_v} + R_L\right)} = \frac{R_o R_L}{\cancel{1 + \beta A_v}} \times \frac{\cancel{1 + \beta A_v}}{R_o + R_L(1 + \beta A_v)}$$

$$= \frac{R_o R_L}{R_o + R_L(1 + \beta A_v)} = \frac{R_o R_L}{R_o + R_L + R_L \beta A_v} = \frac{R_o \cdot R_L / (R_o + R_L)}{1 + \frac{\beta A_v R_L}{(R_o + R_L)}}$$

$$\boxed{R'_{of} = \frac{R'_o}{1 + \beta A_V}} \quad \text{--- (4)}$$

where $R'_o = R_o \| R_L = \frac{R_o R_L}{R_o + R_L}$ $\Rightarrow$ output resistance without feedback but R_L taking into account

$$A_V = A_v \cdot \frac{R_L}{R_o + R_L}$$

(b) Voltage-shunt feedback:

$$I = \frac{V - R_m I_i}{R_o}$$

$$I_i = -I_f = -\beta V \quad (\text{with } I_s = 0)$$

$$I = \frac{V + R_m \beta V}{R_o} = \frac{V(1 + R_m \beta)}{R_o}$$

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

$$R'_{of} = R_{of} \| R_L = \frac{R_{of} \cdot R_L}{R_{of} + R_L} = \frac{\left(\frac{R_o}{1+\beta R_m}\right) R_L}{\frac{R_o}{1+\beta R_m} + R_L} = \frac{R_o R_L}{R_o + R_L + \beta R_m R_L}$$

$$= \frac{R_o R_L / (R_o + R_L)}{1 + \left[\beta R_m R_L / (R_o + R_L)\right]}$$

where $R'_o = \frac{R_o R_L}{R_o + R_L}$

$$R_m = \frac{R_m R_L}{R_o + R_L}$$

$$\boxed{R'_{of} = \frac{R'_o}{1 + \beta R_m}}$$

(c) Current-shunt feedback

- For finding R_{of}, R_L is disconnected (i.e $R_L = \infty$), the external signal source is made zero ($I_s = 0$) and V_o is replaced with V.

- Applying KCL to the o/p node, we get

$$I = \frac{V}{R_o} - A_i I_i \quad —(1)$$

- The input current is written as

$$I_s = I_i + I_f$$

$$0 = I_i + I_f \qquad (\because I_s = 0)$$

$$I_i = -I_f = -\beta I_o = \beta I \quad —(2) \quad (\because I = -I_o)$$

- Substituting I_i in eq (1) we get

$$I = \frac{V}{R_o} - \beta A_i I$$

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

$$I(1+\beta A_i) = \frac{V}{R_o} \quad —(3)$$

- The output resistance with feedback is given by

$$R_{of} = \frac{V}{I} = \frac{V}{\frac{V}{R_o(1+\beta A_i)}} = \frac{\cancel{V}}{\cancel{V}} \times \frac{R_o(1+\beta A_i)}{1}$$

$$\boxed{R_{of} = R_o(1+\beta A_i)} \quad —(4)$$

where A_i = short ckt current gain without ~~taking~~ taking the R_L into account.

- The o/p resistance with feedback R'_{of} including R_L as part of the amplifier is given by:

$$R'_{of} = R_{of} \| R_L.$$

$$= \frac{R_o(1+\beta A_i)R_L}{R_o(1+\beta A_i)+R_L}$$

$$= \frac{R_o R_L(1+\beta A_i)}{R_o + \beta A_i R_o + R_L} = \frac{R_o R_L(1+\beta A_i)}{R_o + R_L + \beta A_i R_o} = \frac{R_o R_L(1+\beta A_i)/R_o+R_L}{1 + \frac{\beta A_i R_o}{R_o + R_L}}$$

$$= \frac{R'_o(1+\beta A_i)}{1+\beta A_I} = R'_o \frac{(1+\beta A_i)}{(1+\beta A_I)} \quad —(5)$$

where $R_O' = \frac{R_O R_L}{R_O + R_L}$

and $A_I = \frac{A_i R_O}{R_O + R_L}$

(d) Current-series feedback:

- For finding R_{of}, R_L is disconnected (i.e, $R_L = \infty$), the external signal source is made zero (i.e, $V_s = 0$) and V_0 is replace with V.

- Applying KCL to the o/p node, we get

$$I = \frac{V}{R_O} - G_m V_i \quad -(1)$$

- The i/p voltage is written as

$$V_i = V_f = -\beta I_O = \beta I \quad (\text{with } V_s = 0,\ I = -I_O) \quad -(2)$$

- Substituting (2) in (1) we get

$$I = \frac{V}{R_O} - G_m \beta I$$

$$I + G_m \beta I = \frac{V}{R_O}$$

$$I(1 + \beta G_m) = \frac{V}{R_O} \quad -(3)$$

- The output resistance with feedback is given as:

$$R_{of} = \frac{V}{I} = \frac{V}{\frac{V}{R_O(1+\beta G_m)}} = \frac{V}{V} \times \frac{R_O(1+G_m\beta)}{1}$$

$$\boxed{R_{of} = R_O(1+\beta G_m)} \quad -(4)$$

where G_m: the short-circuit transconductance without taking R_L into account.

- The output resistance with feedback R_{of}' by including R_L as part of amplifier is given by

$$R_{of}' = R_{of} \| R_L$$

$$R'_{of} = \frac{R_o(1+\beta G_m)\cdot R_L}{R_o(1+\beta G_m)+R_L} = \frac{R_o R_L(1+\beta G_m)}{R_o+R_L+\beta G_m R_o}$$

$$= \frac{R_o R_L(1+\beta G_m) / R_o+R_L}{\frac{R_o+R_L+\beta G_m R_o}{R_o+R_L}}$$

$$= \frac{R'_o(1+\beta G_m)}{1+\frac{\beta G_m R_o}{R_o+R_L}}$$

$$= \frac{R'_o(1+\beta G_m)}{(1+\beta G_M)} \qquad \left(\because G_M = \frac{G_m R_o}{R_o+R_L}\right)$$

$$\boxed{R'_{of} = R'_o \frac{(1+\beta G_m)}{(1+\beta G_m)}} \quad — (5)$$

7) Method of Analysis of a feedback amplifier:

1. Identify the topology: X_f – voltage or current ?
   X_f is applied in series or shunt with source ?
   Sampled signal X_o is voltage or current ?

Set $V_o = 0$ for voltage sampling, $I_o = 0$ for current sampling, $V_i = 0$ shunt mixing, $I_i = 0$ series mixing.

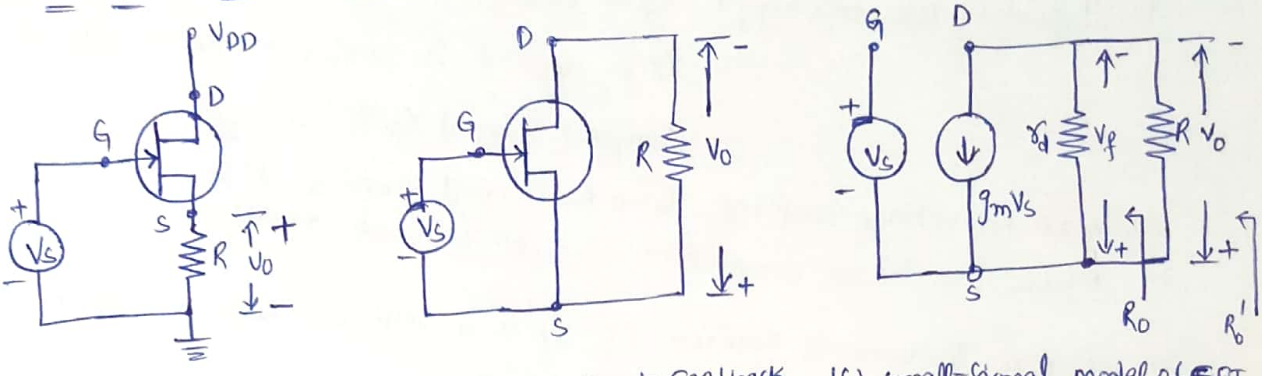
2. Draw the basic amplifier circuit without feedback.
3. Use a Thevenin's source if X_f is a voltage and use a Norton's source if X_f is a current.
4. Replace each active device by h-parameter or hybrid-π model.
5. Indicate X_f and X_o on the circuit obtained by carrying out steps 2, 3 and 4. Evaluate $\beta = \frac{X_f}{X_o}$
6. Evaluate A by applying KVL and KCL to the equivalent circuit obtained after step 4.
7. From A, β find D, A_f, R_{if}, R_{of} and R'_{of}.

Table. Feedback amplifier analysis.

Topology	Voltage series	Current-series	Current-shunt	Voltage-shunt
Feedback signal X_f	Voltage	Voltage	Current	Current
Sampled signal X_o	Voltage	Current	Current	Voltage
To find the i/p loop, set	$V_o = 0$	$I_o = 0$	$I_o = 0$	$V_o = 0$
To find o/p loop, set	$I_i = 0$	$I_i = 0$	$V_i = 0$	$V_i = 0$
Signal source	Thevenins	Thevenins	Norton	Norton
$\beta = X_f / X_o$	V_f / V_o	V_f / I_o	I_f / I_o	I_f / V_o
$A = X_o / X_i$	$A_V = V_o / V_i$	$G_M = I_o / V_i$	$A_I = I_o / I_i$	$R_m = \frac{V_o}{I_i}$
$D = 1 + \beta A$	$1 + \beta A_V$	$1 + \beta G_M$	$1 + \beta A_I$	$1 + \beta R_M$
A_f	A_V / D	G_m / D	A_I / D	R_m / D
R_{if}	$R_i \cdot D = R_i(1+\beta A_V)$	$R_i \cdot D$	R_i / D	R_i / D
R_{of}	$R_o / 1 + \beta A_V$	$R_o(1+\beta G_m)$	$R_o(1+\beta A_i)$	$R_o / (1+\beta R_m)$
$R'_{of} = R_{of} \| R_L$	$\frac{R'_o}{D} = \frac{R'_o}{(1+\beta A_V)}$	$R'_o \left(\frac{1+\beta G_m}{1+\beta G_M}\right)$	$R'_o \left(\frac{1+\beta A_i}{1+\beta A_I}\right)$	R'_o / D

(B) Voltage-Series Feedback: Two examples of this topology are considered.

(a) The FET source follower:



(a) source-follower (b) Amplifier without feedback. (c) small-signal model of FET.

- To find the input loop (circuit), set $V_o = 0$ so V_s appears directly between G and S.

  To find the output loop, set $I_i = 0$, and hence R appears only in the output loop. So, Fig (b) is the amplifier without feedback by applying the above rules.

- From the equivalent model of FET, $V_f = V_o$, and $\beta = \frac{V_f}{V_o} = 1$.

  So, this topology stabilizes the gain (voltage gain).

- Since without feedback $V_i = V_s$, then

$$A_V = \frac{V_o}{V_i} = \frac{V_o}{V_s} = \frac{g_m \cancel{V_s} \cdot (r_d R)}{\cancel{V_s}\; r_d + R} = \frac{g_m r_d R}{r_d + R} = \frac{\mu R}{r_d + R} \quad -(1)$$

where $\mu = g_m r_d$.

$$D = 1 + \beta A_V = 1 + \beta\left[\frac{\mu R}{r_d + R}\right] = \frac{r_d + R + \beta \mu R}{r_d + R} \quad (\because \beta = 1)$$

$$= \frac{r_d + R + \mu R}{r_d + R} = \frac{r_d + (1+\mu)R}{r_d + R} \quad -(2)$$

$$A_{Vf} = \frac{A_V}{D} = \frac{\mu R}{\cancel{r_d + R}} \times \frac{\cancel{r_d + R}}{r_d + (1+\mu)R} = \frac{\mu R}{r_d + (1+\mu)R} \quad -(3)$$

The input impedance of an FET is infinite, $R_i = \infty$, and hence

$$R_{if} = R_i \cdot D = \infty. \quad -(4)$$

The output resistance is computed by looking into the FET source, S.

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

From the Figure (c), $R_o = r_d$

$\beta = 1$

$A_v = \lim_{R\to\infty} A_V = \mu$ $\qquad \because A_v = \frac{\mu \cdot \cancel{R}}{\cancel{R}(\frac{r_d}{R}+1)} = \frac{\mu}{0+1} = \underline{\underline{\mu}}$

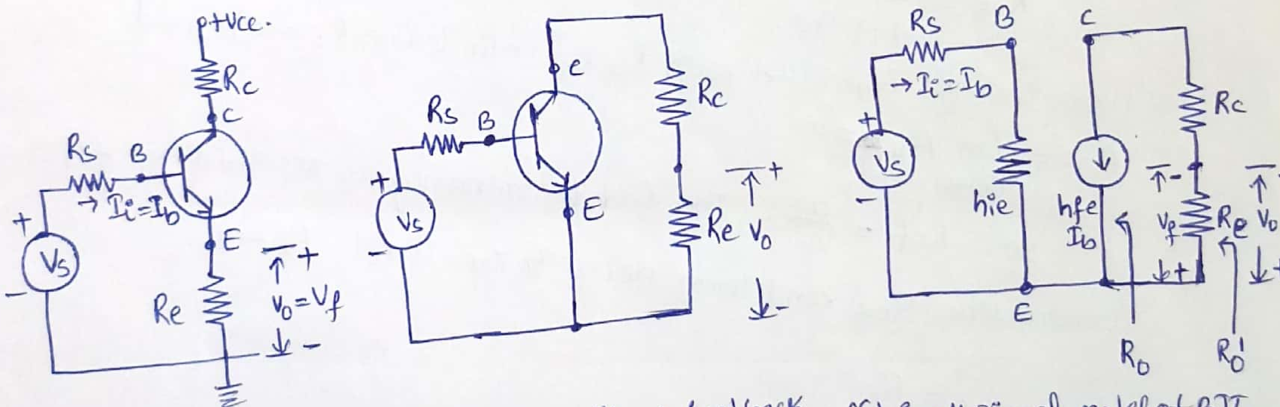
$$\therefore R_{of} = \frac{R_o}{1+A_v} = \frac{r_d}{1+\mu} \quad \text{—(5)}$$

$$R'_{of} = \frac{R'_o}{D} = \frac{R \cdot r_d}{\cancel{R+r_d}} \cdot \frac{\cancel{r_d+R}}{r_d+(1+\mu)R}$$

$$R'_{of} = \frac{R \cdot r_d}{r_d+(1+\mu)R} \quad \text{—(6)}$$

Note that $R_{of} = \lim_{R\to\infty} R'_{of} = \frac{r_d}{1+\mu}$

b) <u>The Emitter follower</u>:



(a) An Emitter follower (b) Amplifier without feedback (C) Small signal model of BJT.

- The feedback signal is the voltage V_f across Re and the sampled signal is V_o across Re. So this is a voltage series - feedback.
- To find the input circuit, set $V_o=0$ and to find the output circuit set $I_i=0$. So by setting $V_o=0$, V_s in series with R_s appears between B and E. and by $I_i=0$, Re appears only in the o/p loop. (Fig (b)).
- From Fig(c), $V_f = V_o$ and $\beta = \frac{V_f}{V_o} = 1$. This topology stabilizes voltage gain.
- Since Rs is considered as part of the amplifier, then $V_i = V_s$, and

$$A_V = \frac{V_o}{V_i} = \frac{V_o}{V_s} = \frac{h_{fe} I_b R_e}{V_s} = \frac{h_{fe}\cancel{I_b} \cdot R_e}{(R_s+h_{ie})\cancel{I_b}} = \frac{h_{fe} R_e}{R_s+h_{ie}} \quad \text{—(1)}$$

- $D = 1 + \beta A_V = 1 + (1) \cdot \frac{h_{fe} R_e}{R_s + h_{ie}} = \frac{R_s + h_{ie} + h_{fe} R_e}{R_s + h_{ie}}$ —(2)

$$A_{vf} = \frac{A_V}{D} = \frac{h_{fe} R_e}{\cancel{R_s + h_{ie}}} \times \frac{\cancel{R_s + h_{ie}}}{R_s + h_{ie} + h_{fe} R_e} = \frac{h_{fe} R_e}{R_s + h_{ie} + h_{fe} R_e} \quad \text{—(3)}$$

For $h_{fe} R_e \gg R_s + h_{ie}$, $A_V \approx \frac{h_{fe} R_e}{h_{fe} R_e} \approx \underline{1}$

- The input resistance without feedback is:

$R_i = R_s + h_{ie}$

$$R_{if} = R_i \cdot D = (\cancel{R_s + h_{ie}}) \frac{R_s + h_{ie} + h_{fe} R_e}{(\cancel{R_s + h_{ie}})} = R_s + h_{ie} + h_{fe} R_e \quad \text{—(4)}$$

- The resistance seen looking into the emitter is R_{of}. Hence R_e is considered as an external load.

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

Here the R_o in parallel with I_s is infinite (i.e $R_o = \infty$). and

$$A_v = \lim_{R_e \to \infty} A_v = \infty.$$

so. $R_{of} = \frac{\infty}{\infty}$: The indeterminancy is resolved by first evaluating R_{of}' and then going to the limit $R_e \to \infty$.

- since $R_o' = R_e$,

$$R_{of}' = \frac{R_o'}{D} = \frac{R_e (R_s + h_{ie})}{R_s + h_{ie} + h_{fe} R_e}$$

and $$R_{of} = \lim_{R_e \to \infty} R_{of}' = \lim_{R_e \to \infty} \frac{\cancel{R_e}(R_s + h_{ie})}{\cancel{R_e}\left[\frac{R_s + h_{ie}}{R_e} + h_{fe}\right]}$$

$$= \frac{R_s + h_{ie}}{0 + h_{fe}}$$

$$R_{of} = \frac{R_s + h_{ie}}{h_{fe}} \quad \text{—(5).}$$