Unit - III

Feedback Amplifiers & Oscillators

Feedback Amplifiers :-

Basic feedback Concepts

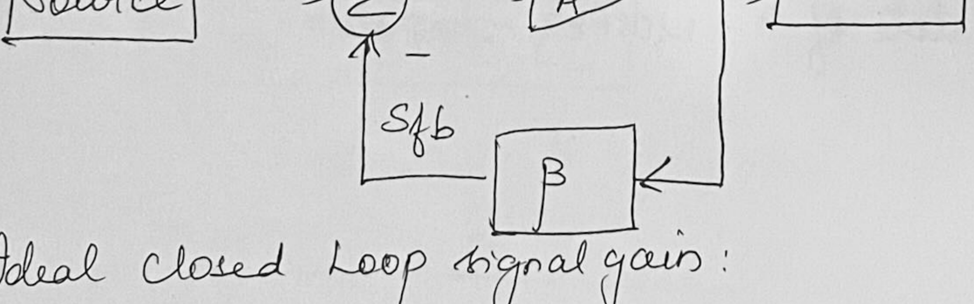
Need for feedback :-

Transistor circuit characteristics can be made essentially independant of the individual transistor parameters by using feedback.

General feedback theory

Negative feedback : a portion of the o/p signal is subtracted from the i/p signal (stability)

Positive feedback : a portion of o/p signal is added to the i/p signal.



Ideal closed Loop signal gain :

$S_i \rightarrow$ current /voltage

$A \rightarrow$ amplifier gain

$S_{fb} \rightarrow$ signal produced by the feedback circuit.

S_E = error produced when feedback signal is subtracted from the i/p signal. This error signal is i/p to amplifier & amplified to produce o/p

* The i/p signal is transmitted through amplifier whereas the o/p signal is transmitted through feedback circuit only.
* The feedback circuit does not load the amplifier. But actual conditions are not same as ideal.

$$S_o = AS_E \rightarrow (1)$$

where $A \rightarrow$ amplification factor

$S_{fb} = \beta S_o \rightarrow (2)$ where β = feedback factor

$$S_E = S_i - S_{fb} \rightarrow (3)$$

Sub (3) in (1)

(ie) $S_o = A(S_i - S_{fb})$

$$S_o = AS_i - AS_{fb}$$

$$S_o + AS_{fb} = AS_i \rightarrow (4)$$

Sub (2) in (4)

$$S_o + A\beta S_o = AS_i$$

$$S_o[1 + A\beta] = AS_i$$

$$\frac{S_o}{S_i} = \frac{A}{1+A\beta} = A_f = \frac{AF}{1+T} = \frac{1}{\beta}$$

where $T = A\beta \rightarrow$ loop gain

For negative feedback, the loop gain is positive

$$T = A\beta = \frac{S_{fb}}{S_E} \quad \left[\text{from } ① \; A = \frac{S_o}{S_E} \quad ② \; \beta = \frac{S_{fb}}{S_o} \right.$$

The error signal is small so the expected gain is large

if $A\beta >> 1$ then

$$A_f = \frac{A}{A\beta} = \frac{1}{\beta} \rightarrow \text{fn of fback n/w only}$$

gain with feedback

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

and the gain with feedback becomes a function of the feedback n/w only.

* The feedback circuit is composed of passive elements only (ie) the feedback amplifier gain is almost completely independant of transistor (basic amplifier) whose properties vary with temperature. But the feedback amplifier gain is constant.

for a large loop gain (ie)

$A\beta >> 1$

$$\frac{S_o}{S_i} = \frac{1}{\beta} \Rightarrow S_o = \frac{S_i}{\beta}$$

Sub in (3)

$$S_e = S_i - S_{fb}$$
$$= S_i - \beta S_o$$
$$= S_i - \frac{S_i}{\beta} \times \beta = 0.$$

For $A\beta >> 1$ the error value is zero.

Gain sensitivity :-

If $A\beta$ is very large, the overall gain of the feedback amplifier is a function of feedback network.

To quantify this :

Taking derivative of A_f w.r.t A

(ie) $$\frac{dA_f}{dA} = \frac{d}{dA}\left(\frac{A}{1+A\beta}\right)$$

$$= \frac{(1+A\beta)\cdot 1 - A(\beta)}{(1+A\beta)^2} = \frac{1+\cancel{A\beta}-\cancel{A\beta}}{(1+A\beta)^2}$$

$$dA_f = \frac{dA}{(1+A\beta)^2}.$$

$\div$ by A_f on both sides

$$\frac{dA_f}{A_f} = \frac{\frac{dA}{(1+A\beta)^2}}{\frac{A}{1+A\beta}} = \frac{dA}{A} \cdot \frac{\cancel{(1+A\beta)}}{(1+A\beta)^{\cancel{2}}}$$

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

Multiply & divide by A on RHS

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

$$\boxed{\frac{dA_f}{A_f} = \frac{dA}{A} \cdot \frac{A_f}{A}}$$

Percentage change in closed loop gain A_f is less than corresponding percentage change in open loop gain A by a factor $(1+A\beta)$

Bandwidth Extension

Frequency response of basic amplifier is characterized by a single pole.

$$A(s) = \frac{A_0}{1+\frac{s}{\omega_H}}$$

A_0 ← low frequency or mid band gain

ω_H ← upper 3dB/ corner frequency.

$$A_f(s) = \frac{A(s)}{1+\beta A(s)}$$

$$A_f(s) = \frac{\frac{A_0}{1+s/\omega_H}}{1+\beta\left[\frac{A_0}{1+s/\omega_H}\right]} = \frac{\frac{A_0}{\cancel{1+s/\omega_H}}}{\frac{1+\frac{s}{\omega_H}+\beta A_0}{\cancel{1+s/\omega_H}}}$$

$$A_f(s) = \frac{A_o}{1+\beta A_o + \frac{s}{\omega_H}}$$

Take out $1+\beta A_o$

$$A_f(s) = \frac{A_o}{(1+\beta A_o)\left[1 + \frac{s}{\omega_H(1+\beta A_o)}\right]}$$

The low frequency closed loop gain is smaller than the open loop gain by a factor $(1+\beta A_o)$

But the closed loop 3dB frequency is larger by $(1+A_o\beta)$.

Closed Loop BW

$$\omega_{fH} = \omega_H (1+A_o\beta)$$

Gain BW product:-

$A_o \omega_H$.

Noise sensitivity:-

Negative feedback may reduce the noise, but it increases the SNR.

It can reduce the noise generated in the amplifier but not the noise which is a part of the i/p signal.

$$(SNR)_i = \frac{S_i}{N_i} = \frac{V_i}{V_n}$$

$$(SNR)_o = \frac{S_o}{N_o} = \frac{AT_i\, S_i}{AT_n\, N_i}$$

$AT_i\, S_i$ ← O/P signal

$AT_n\, N_i$ ← O/P noise signal

A ↗ Amplification factor

<u>Examples:-</u>

(1) Calculate the feedback transfer function β, given A & A_f.

$A = 10^5$ & $A_f = 50$.

Solution:

$$A_f = \frac{A}{1+A\beta} \Rightarrow 50 = \frac{10^5}{1+\beta(10^5)}$$

$$\Rightarrow \boxed{\beta = 0.01999}$$

(2) Calculate the percentage change in the clo[se] loop gain A_f given a change in open lo[op] gain A.

$A = 10^5$; $A_f = 50$ & $\beta = 0.01999$. Assum[e] that the change in open loop gain is $dA = 10^4$ (a 10 % change)

Solution:

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

$$dA_f = \frac{50}{[(1+0.01999)(10^5)]} \quad \frac{10^4}{10^5}$$

$$dA_f = 2.5 \times 10^{-3}$$

$$\frac{dA_f}{A_f} = \frac{2.5 \times 10^{-3}}{50} = 5 \times 10^{-5} = 0.005\%$$

% change in the closed loop gain is less than % change in open loop gain.

(3) Determine the BW of a feedback amplifier with an open loop low frequency gain of $A_0 = 10^4$, an open loop BW $W_H = 2\pi(100)$ rad/sec & a closed loop low frequency gain $A_f(0) = 50$

Solution

$$BW = W_H(1+\beta A_0)$$

$$A_f(0) = \frac{A_0}{1+\beta A_0} \Rightarrow 50 = \frac{10^4}{1+\beta 10^4} \Rightarrow 1+\beta A_0 = \frac{10^4}{50} = 200.$$

$$BW \Rightarrow 2\pi \times 100 \times 200 = 2\pi \times 20 \times 10^3$$

The BW increases from 100 Hz to 20kHz as the gain decreases from 10^4 to 50.

Feedback Topologies

1) Series shunt
2) Shunt series
3) Series series
4) Shunt Shunt

The first term refers to connection at the amplifier input and the 2nd term refers to connection at the amplifier O/P.

Series shunt configuration

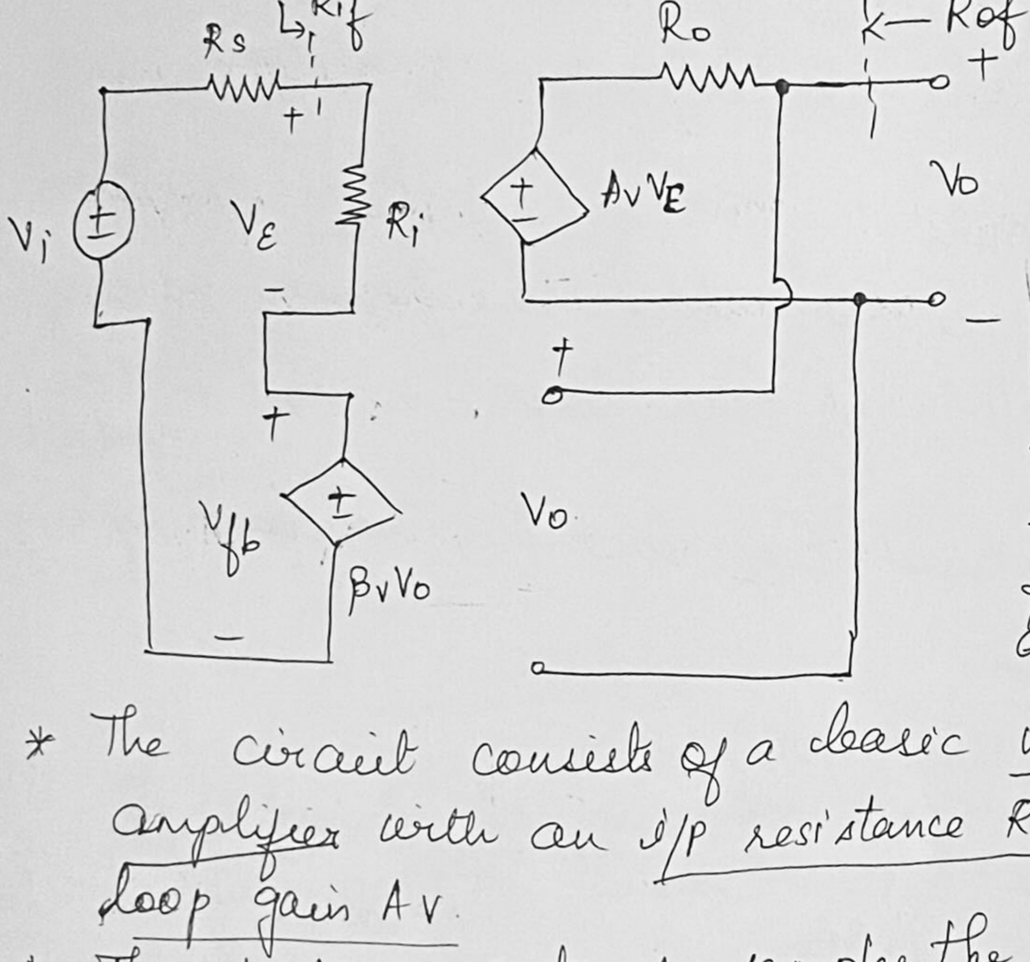


Fig shows the configuration of an ideal series shunt feedback amplifier.

* The circuit consists of a basic voltage amplifier with an i/p resistance R_i & open loop gain A_V.
* The feedback network samples the o/p voltage and produces V_{fb} which is in series with V_i.
* The i/p resistance to the feedback circuit is infinite, therefore there is no loading effect on the o/p of the amplifier due to feedback n/w.

The circuit is a voltage controlled voltage source and is an ideal voltage amplifier.

* An increase in O/P voltage increases the feedback voltage which in turn reduces the error voltage due to negative feedback.
* The smaller error voltage is amplified producing smaller O/P voltage. Thus the O/P voltage is stabilized.
* I/P ⇒ Series connection
  O/P ⇒ Shunt connection
* V_E = error voltage = difference b/w i/p & feedback.
* O/P of feedback n/w is open circuit.

$$A_{vf} = \frac{V_o}{V_i}$$

$$V_o = A_v V_E \Rightarrow V_E = \frac{V_o}{A_v}$$

$$V_i = V_E + V_{fb} = V_E + \beta_v V_o$$

feedback voltage transfer fn.

$$\therefore V_i = \frac{V_o}{A_v} + \beta_v V_o$$

$$V_i = V_o\left[\frac{1+A_v\beta_v}{A_v}\right]$$

$$\boxed{A_{vf} = \frac{V_o}{V_i} = \frac{A_v}{1+\beta_v A_v}} \rightarrow (1)$$

Eqn (1) is the closed loop gain of the feedback amplifier.

Although the magnitude of the closed loop gain is less than that of open loop gain, it is independant of individual transistor parameters.

To find the i/p resistance R_{if}

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

$$V_i = V_\varepsilon + V_{fb}$$

o/p side:

$$V_o = A_v V_\varepsilon$$

$$\cancel{V_\varepsilon} = \frac{\cancel{V_o}}{} \quad \therefore V_{fb} = \beta_v V_o = \beta_v A_v V_\varepsilon$$

Sub in V_i

$$V_i = V_\varepsilon + \beta_v A_v V_\varepsilon$$

$$V_i = V_\varepsilon(1+\beta_v A_v)$$

from i/p side

$$V_\varepsilon = I_i R_i$$

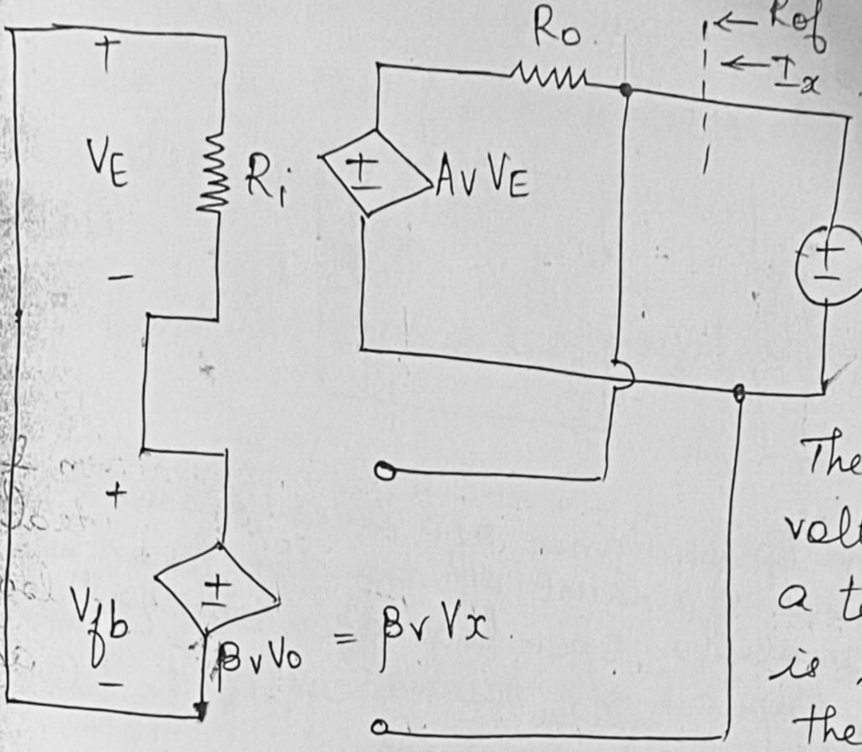
sub in the above eqn

$$V_i = I_i R_i(1+\beta_v A_v)$$

$$\boxed{\frac{V_i}{I_i} = R_{if} = R_i(1+\beta_v A_v)}$$

Series i/p connection results in an increased i/p resistance which is the desirable property of voltage amplifier.

Output Resistance R_{of}



$= \beta_V V_x$

The i/p signal voltage = 0 & a test voltage V_x is supplied to the o/p.

$$R_{of} = \frac{V_x}{I_x}$$

$$I_x = \frac{V_x - A_V V_E}{R_o}$$

From i/p since $V_i = 0$

$$V_E + V_{fb} = 0 \Rightarrow V_E = -V_{fb} = -\beta_V V_o = -\beta_V V_x$$

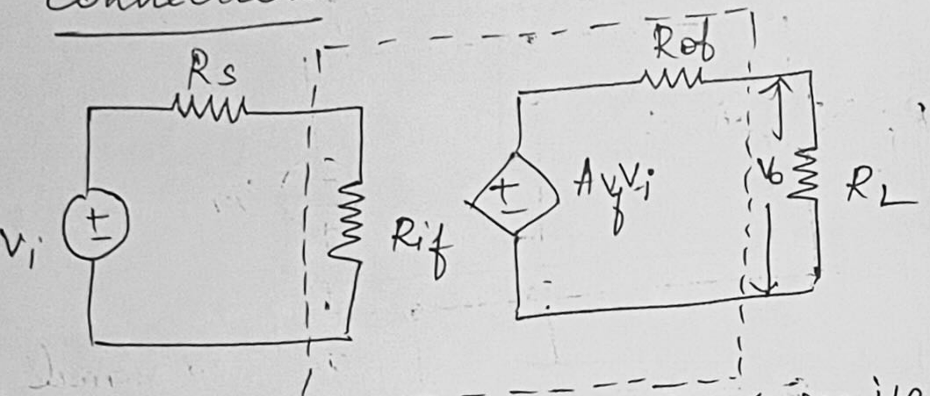
Sub in I_x

$$I_x = \frac{V_x + \beta_V V_x A_V}{R_o} = V_x \left(\frac{1+\beta_V A_V}{R_o} \right)$$

$$\boxed{R_{of} = \frac{V_x}{I_x} = \frac{R_o}{1+\beta_V A_V}}$$

Shunt output connection results in a decreased o/p resistance compared to that of basic voltage amplifier & this is desirable.

Equivalent circuit of series shunt feedback connection



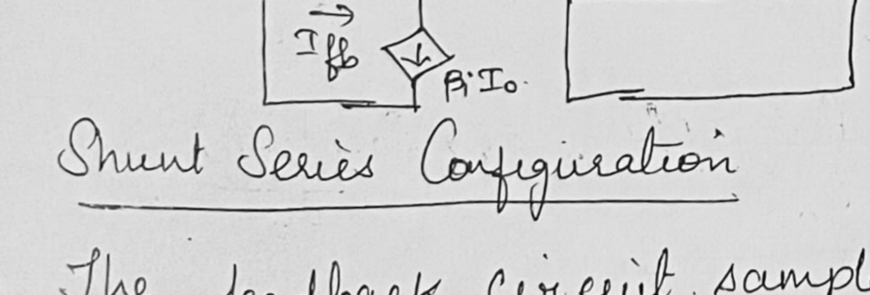
1) Determine the i/p resistance of a series i/p connection & the o/p resistance of a shunt o/p connection for an ideal feedback voltage amplifier. Open loop gain $=10^5$, closed loop gain $=50$. Input & o/p resistances of the basic ampr 10 kΩ & 20 kΩ respectively.

$A_{vf} = \frac{A_v}{1+\beta_v A_v} \Rightarrow (1+\beta_v A_v) = A_v / A_{vf} = \frac{10^5}{50} = 2\times10^3$.

$R_{if} = R_i(1+\beta_v A_v) = (10)(2\times10^3)\,k\Omega = 20M\Omega$

$R_{of} = \frac{R_o}{1+\beta_v A_v} = \frac{20}{2\times10^3}\,k\Omega = 10\Omega$.

Shunt Series configuration



current I_E amplified

Shunt Series Configuration

* The feedback circuit samples the o/p current and produces a feedback current I_{fb}, which is in shunt with i/p current I_i.

$I_E = I_i - I_{fb}$.

It is called current amplifier since I_E is amplified.

* Shunt connection on the i/p & series in o/p.
* An increase in the o/p current produces an increase in the feedback current, which in turn decreases the error current I_E. O/P is stable.

$I_o \uparrow$, $I_{fb} \uparrow$ $\therefore I_E \downarrow$ $\therefore$ stable.

A_{if} To find the closed loop gain (transfer fn.)

$$A_{if} = \frac{I_o}{I_i}$$

$$I_i = I_E + I_{fb}$$

$$I_o = A_i I_E \Rightarrow I_E = \frac{I_o}{A_i}$$

Sub in I_i

$$I_i = \frac{I_o}{A_i} + I_{fb} \qquad I_{fb} = \beta_i I_o.$$

$$I_i = \frac{I_o}{A_i} + \beta_i I_o = I_o\left(\frac{1}{A_i} + \beta_i\right) = \left(\frac{1 + A_i\beta_i}{A_i}\right) I_o$$

$$I_i = I_o \left(\frac{1 + A_i\beta_i}{A_i}\right)$$

$$\boxed{A_{if} = \frac{I_o}{I_i} = \frac{A_i}{1 + A_i\beta_i}}$$

Input resistance with feedback A_{iL} :-

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

β $\quad A_i I_E = I_o$

$$I_i = I_E + I_{fb}.$$

$$I_f = \beta_i I_o = \beta_i A_i I_E$$

$$I_i = I_E + \beta_i A_i I_E$$

$$I_i = I_E (1 + \beta_i A_i)$$

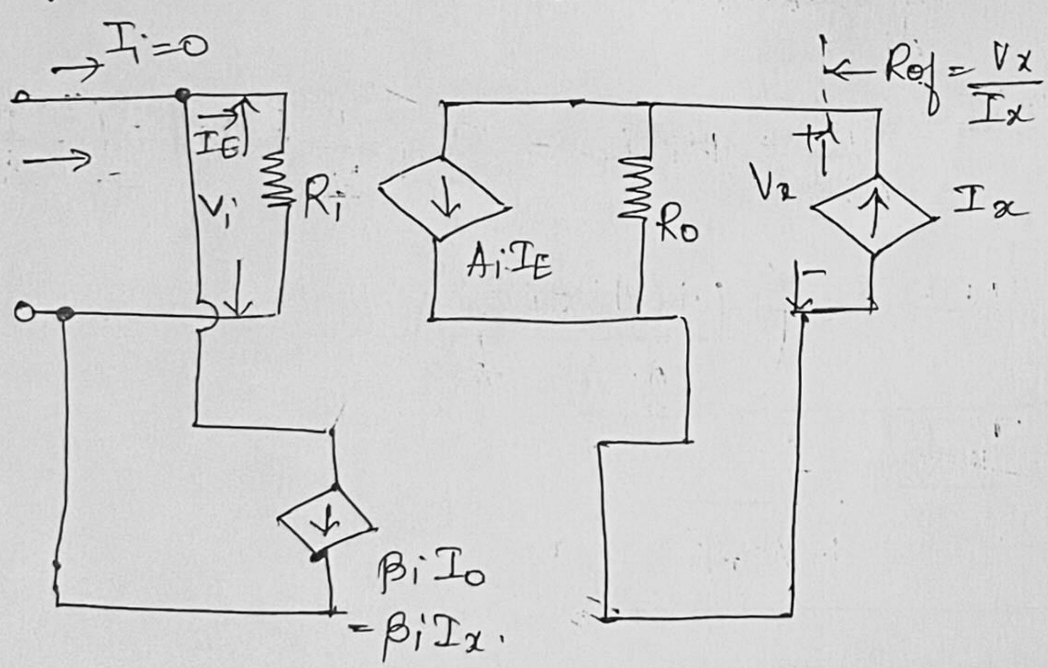
$$I_E = \frac{V_i}{R_i}$$

$$\therefore I_i = \frac{V_i}{R_i}(1 + \beta_i A_i)$$

$$\therefore \boxed{R_{if} = \frac{V_i}{I_i} = \frac{R_i}{1 + \beta_i A_i}}$$

Shunt input connection decreases the input resistance compared to that of basic amplifier, a desirable property of current amplifier

Output resistance R_{of} :-



The input current is set to zero and a test current of I_x is applied at the o/p.

$$R_{of} = \frac{V_x}{I_x} \qquad I_x = \frac{V_x}{R_o} + A_i I_E$$

From i/p

$I_E \pm I_{fb} = 0$

$I_E = -I_{fb} = -\beta_i I_x$

Sub in I_x

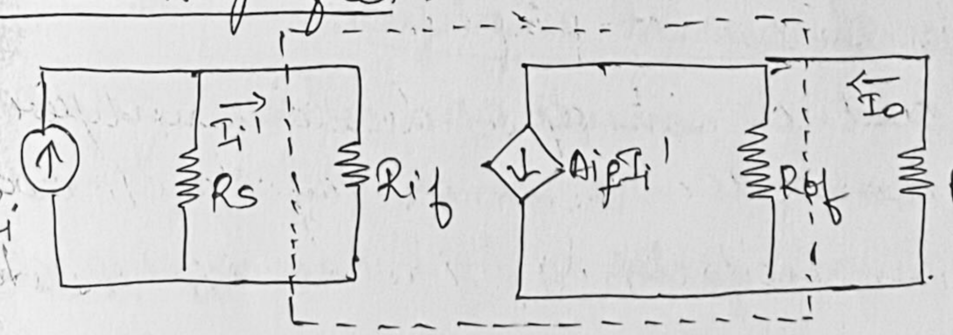
$$I_x = \frac{V_x}{R_o} - A_i \beta_i I_x$$

$$I_x(1 + A_i\beta_i) = \frac{V_x}{R_o}$$

$$\boxed{R_{of} = \frac{V_x}{I_x} = R_o(1+A_i\beta_i)}$$

Series o/p connection increases o/p resistance compared to that of basic amplifier.

Current Amplifier :-



Q) Determine the i/p resistance of shunt i/p connection & o/p resistance of a series o/p connection for a feedback current amplifier.

$A_i = 10^5$ $\quad A_f = 50$ $\quad R_i = 10k\Omega$ $\quad R_o = 20k\Omega$

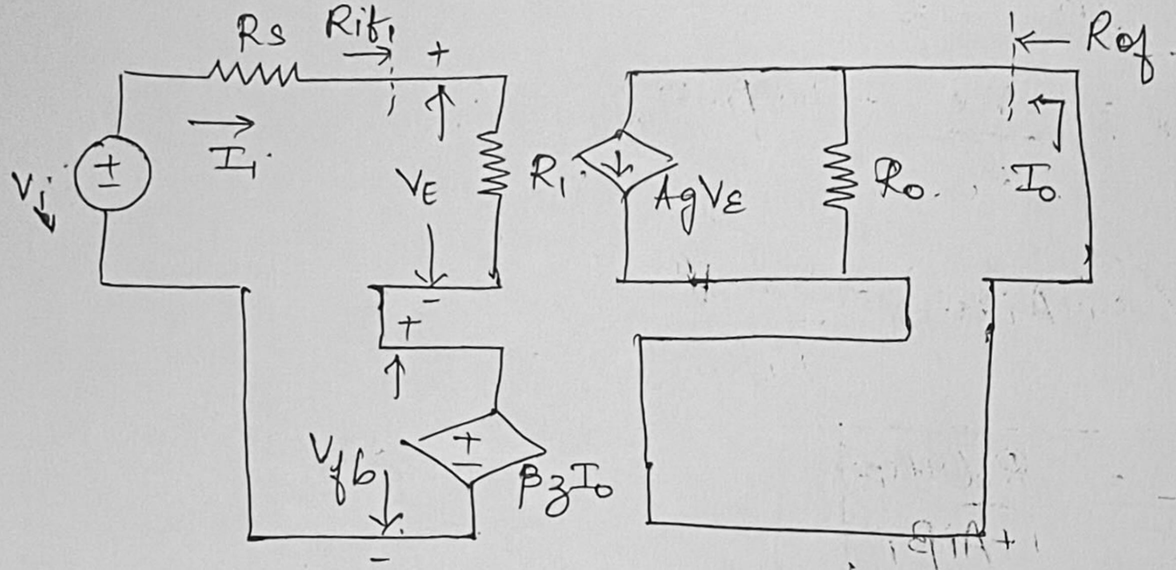
$$A_{if} = \frac{A_i}{1+\beta_i A_i} \Rightarrow 1+\beta_i A_i = \frac{A_{if}}{A_i}$$

$$1+\beta_i A_i = \frac{10^5}{50} = 2\times10^3$$

$$R_{if} = \frac{R_i}{1+\beta_i A_i} = \frac{10k\Omega}{2k\Omega} = 5\Omega$$

$$R_{of} = R_o(1+\beta_i A_i) = 20k(2k) = 40M\Omega$$

Series-Series Configuration



* The series-series feedback amplifier is shown.
* The feedback samples a portion of the o/p current & converts it to voltage.
* Voltage to current amplifier.
* The circuit consists of a basic amplifier that converts the error voltage to o/p current with a gain factor of Ag & has an i/p resistance R_i.
* The feedback circuit samples the o/p current & produces a feedback voltage V_{fb} which is in series with V_i

Current to voltage transfer ratio A_{gf}:

$$A_{gf} = \frac{I_o}{V_i}$$

$$I_o = A_g V_E \Rightarrow V_E = I_o / A_g$$

$$V_i = V_E + V_{fb}$$

$$V_i = \frac{I_o}{A_g} + \beta_z I_o = I_o\left(\frac{1}{A_g} + \beta_z\right)$$

$$V_i = \left(\frac{1 + A_g\beta_z}{A_g}\right) I_o$$

$$\boxed{g_f = \frac{I_o}{V_i} = \frac{A_g}{1 + A_g\beta_z}}$$ Transconductance amplifier.

R_{if} : Input resistance

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

$$V_i = V_E + V_{fb}.$$

$$V_{fb} = \beta_z I_o$$

$$I_o = A_g V_E$$

$$\therefore V_{fb} = \beta_z A_g V_E$$

Sub in V_i

$$V_i = V_E + \beta_z A_g V_E = V_E(1 + A_g\beta_z).$$

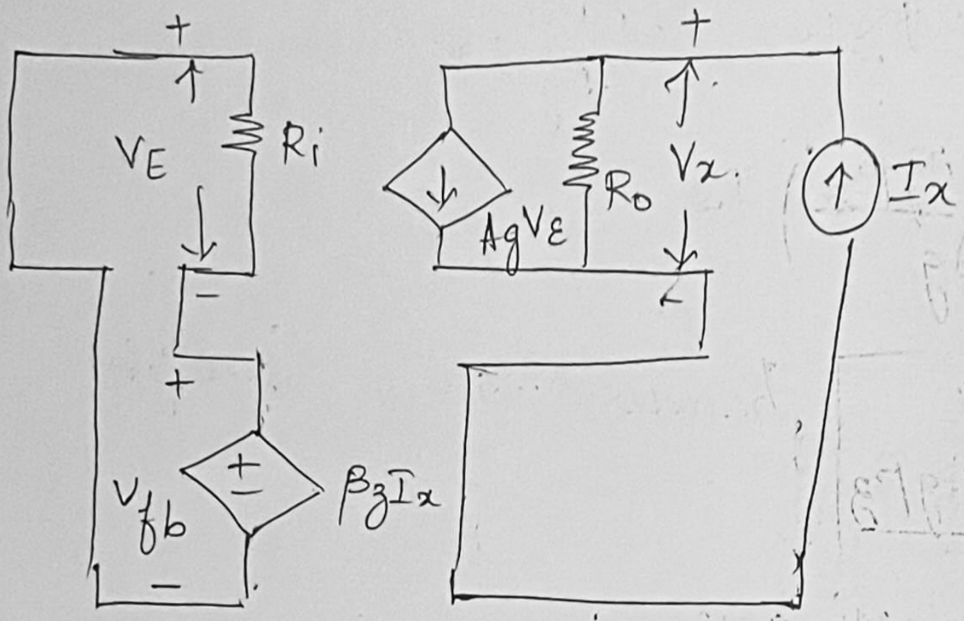
$$V_E = I_i R_i$$

$$\therefore V_i = I_i R_i (1 + A_g\beta_z).$$

$$\boxed{\frac{V_i}{I_i} = R_{if} = R_i(1 + A_g\beta_z)}$$

$\therefore$ Input resistance increases with this configuration

R_{of}: O/P resistance



The i/p $v_i = 0$

$$R_{of} = \frac{I_x}{V_x}$$

$$I_x = \frac{V_x}{R_o} + A_g V_E$$

from i/p

$$0 = V_E + V_{fb}$$

$$V_E = -V_{fb} = -\beta_z I_x$$

Sub in I_x

$$I_x = \frac{V_x}{R_o} + A_g(-\beta_z I_x)$$

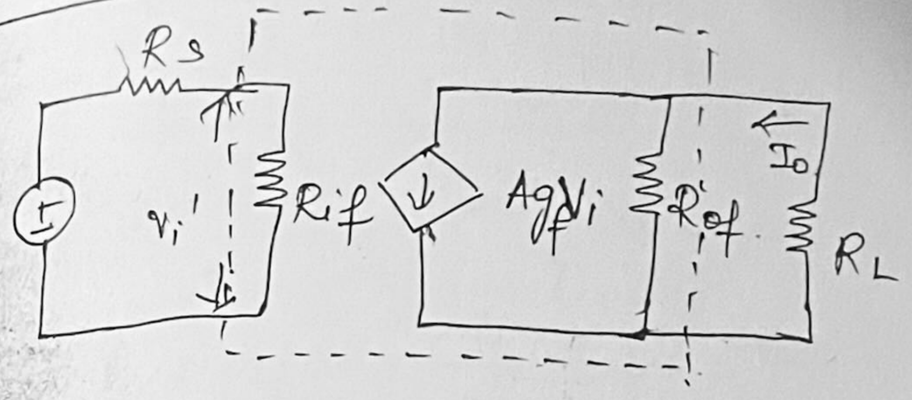
$$\Rightarrow I_x + A_g \beta_z I_x = \frac{V_x}{R_o}$$

$$I_x(1 + A_g\beta_z) = \frac{V_x}{R_o}$$

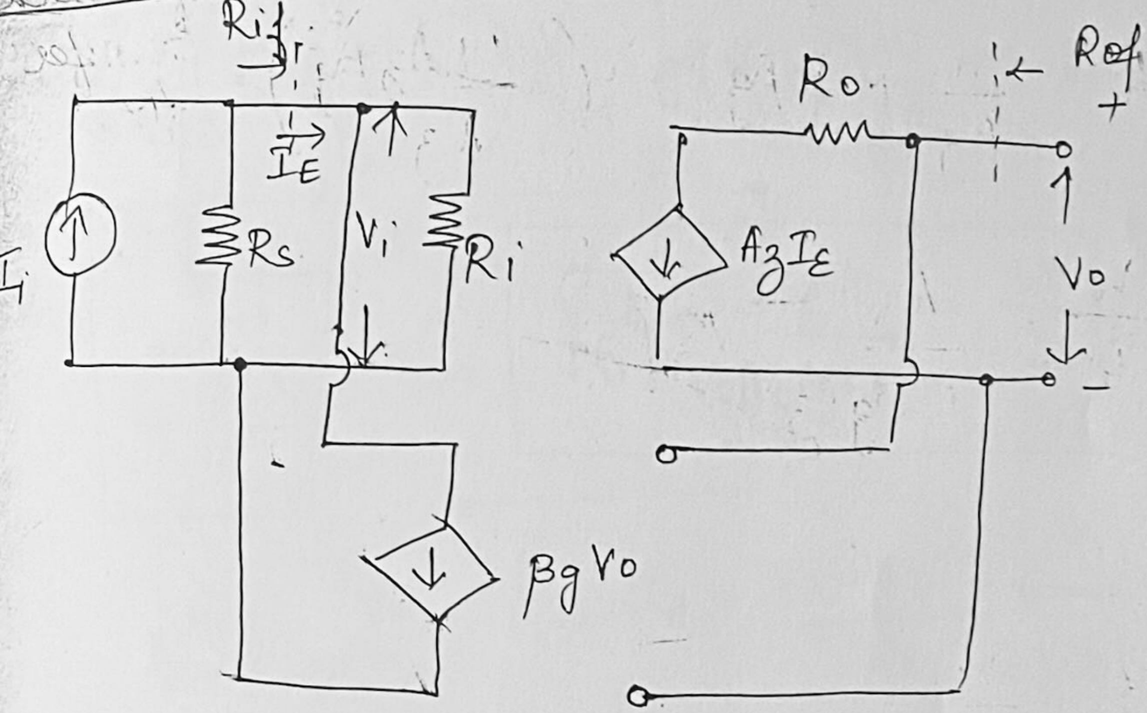
$$\boxed{\frac{V_x}{I_x} = R_o(1 + A_g\beta_z) = R_{of}}$$

O/P resistance increases as compared to basic amplifier

Transconductance Amplifier



Shunt-Shunt Configuration



* The feedback samples a portion of o/p voltage and converts it to current.
* Current to voltage amplifier → transresistor
* The circuit consists of basic amplifier that converts error current to o/p voltage with gain factor A_z.
* feedback circuit samples o/p voltage & produces feedback current I_{fb} which is in shunt with I_i.

$\underline{A_{zf}}$

$$A_{zf} = \frac{V_o}{I_i}$$

$$V_o = A_z I_\varepsilon \Rightarrow I_\varepsilon = \frac{V_o}{A_z}.$$

$$I_i = I_\varepsilon + I_{fb}$$

$$I_i = \frac{V_o}{A_z} + V_o\beta_g = V_o\left(\frac{1 + A_z\beta_g}{A_z}\right)$$

Conductance feedback transfer fn.

$$\boxed{\frac{V_o}{I_i} = \frac{A_z}{1+\beta_g A_z} = A_{zf}}$$

$\underline{R_{if}}$:

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

$$I_i = I_\varepsilon + I_{fb}$$

$$I_{fb} = \beta_g V_o \quad \& \quad V_o = A_z I_\varepsilon$$

$$\therefore I_{fb} = \beta_g A_z I_\varepsilon$$

Sub in I_i

$$I_i = I_\varepsilon + \beta_g A_z I_\varepsilon$$

$$I_i = I_\varepsilon(1+\beta_g A_z)$$

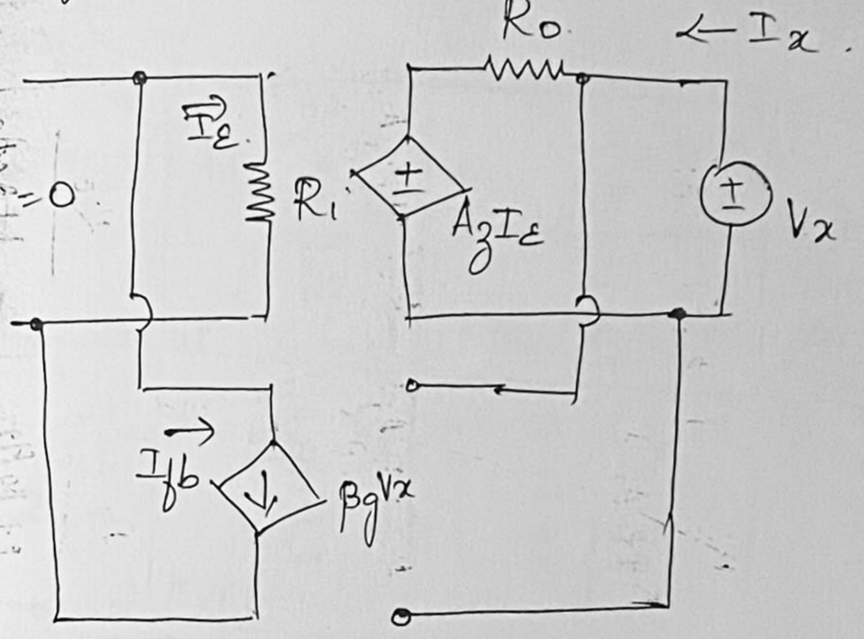
$$I_\varepsilon = \frac{V_i}{R_i} \quad \text{Sub in } I_i$$

$$I_i = \frac{V_i}{R_i}(1+\beta_g A_z)$$

$$\boxed{R_{if} = \frac{V_i}{I_i} = \frac{R_i}{1+\beta_g A_z}}$$

Input resistance decreases with this configuration.

__To find R_{of} :-__



$$R_{of} = \frac{V_x}{I_x} \qquad I_x = \frac{V_x - A_z I_\varepsilon}{R_o}$$

$$I_\varepsilon + I_{fb} = 0$$

$$I_\varepsilon = -I_{fb} = -\beta_g V_x$$

Sub in I_x.

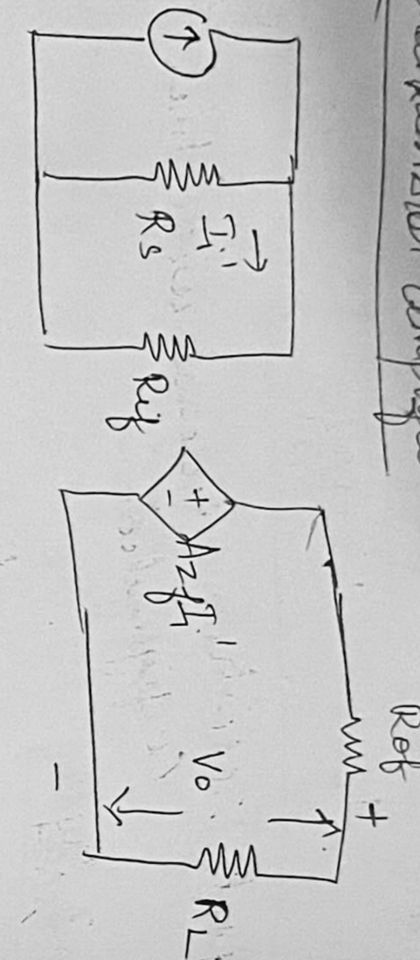
$$I_x = \frac{V_x + \beta_g V_x A_z}{R_o} = \frac{V_x(1+\beta_g A_z)}{R_o}$$

$$\boxed{\frac{V_x}{I_x} = R_{of} = \frac{R_o}{1+\beta_g A_z}}$$

O/P resistance is less than basic amplifier.

Feedback Amplifier	Signal source	O/P signal	Transfer function	I/P resistance	O/P resistance
1) Series shunt (voltage series) (voltage amplifier)	Voltage	Voltage	$A_{vf} = \frac{V_o}{V_i} = \frac{A_v}{1+\beta_v A_v}$	$R_i(1+\beta_v A_v)$	$\frac{R_o}{1+\beta_v A_v}$
2) Shunt series Current Amplifier current shunt.	Current	Current	$\frac{I_o}{I_i} = A_{if} = \frac{A_i}{1+\beta_i A_i}$	$\frac{R_i}{1+\beta_i A_i}$	$R_o(1+\beta_i A_i)$
3) Series - series transconductance amplifier current series	Voltage	Current	$A_{gf} = \frac{I_o}{V_i}$	$R_i(1+\beta_g A_g)$	$R_o(1+\beta_g A_g)$
4) Shunt-shunt transresistance amplifier voltage shunt	Current	voltage	$A_{zf} = \frac{V_o}{I_i} = \frac{A_z}{1+\beta_g A_z}$	$\frac{R_i}{1+\beta_g A_z}$	$\frac{R_o}{1+\beta_g A_z}$

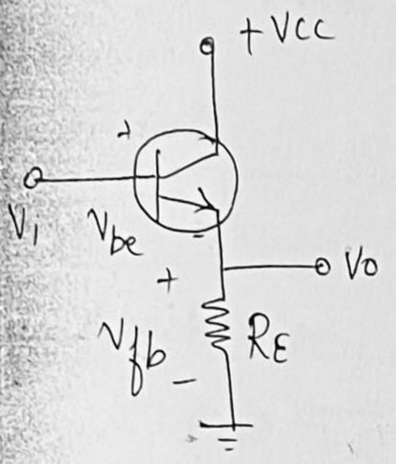
Transresistor amplifier

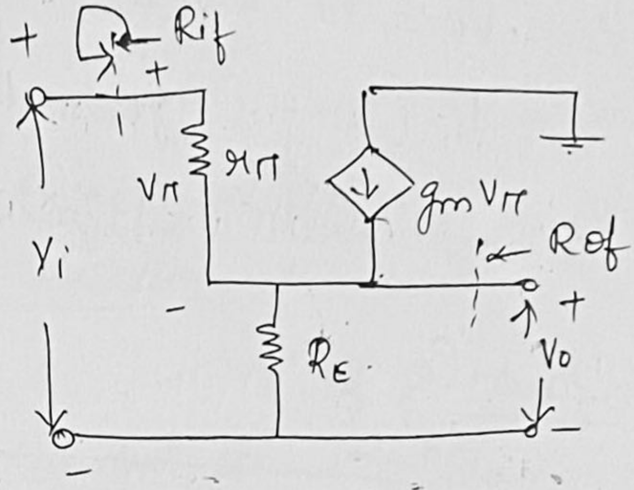


Practical Circuits :-

① Series Shunt Amplifiers

Emitter follower circuit





* The input signal is the voltage V_i, error signal is V_{be}, feedback voltage is equal to o/p voltage (ie)

$\beta_v = 1$

To find A_{vf} :-

$$A_{vf} = \frac{V_o}{V_i}$$

$$V_i = V_\pi + \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E = V_\pi \left[1 + \left(\frac{1}{r_\pi} + g_m\right) R_E\right]$$

$$V_o = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E = V_\pi \left[\frac{1}{r_\pi} + g_m\right] R_E$$

$$\frac{V_o}{V_i} = A_{vf} = \frac{\cancel{V_\pi}\left(1 + \left(\frac{1}{r_\pi} + g_m\right) R_E\right)}{\cancel{V_\pi}\left(\frac{1}{r_\pi} + g_m\right) R_E} = \frac{1 + \left(\frac{1}{r_\pi} + g_m\right) R_E}{\left(\frac{1}{r_\pi} + g_m\right) R_E}$$

Let $\frac{r_\pi}{1 + g_m} = r_e$ then $A_{vf} = \frac{R_E / r_e}{1 + R_E / r_e}$

$$\frac{\frac{r_\pi}{1 + g_m r_\pi} + R_E}{R_E}$$

Open loop gain is R_E / r_e.

$$\frac{r_e + R_E}{R_E} = r_e / R_E + 1$$

To find R_{if} :-

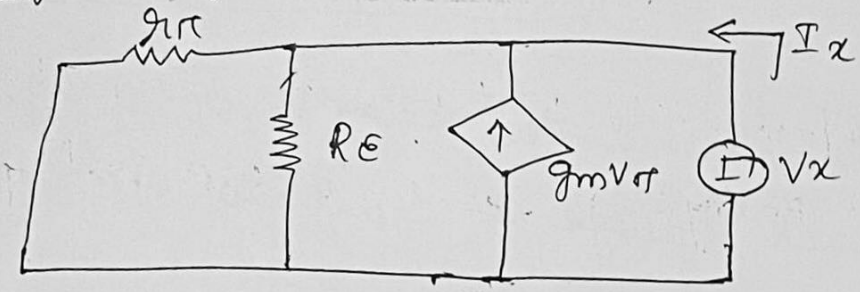
$$R_{if} = \frac{V_i}{I_i}$$

$$V_i = V_\pi + V_o = I_i r_\pi + (I_i + g_m I_i r_\pi) R_E$$

$$V_i = I_i \left[r_\pi + (1 + g_m r_\pi) R_E \right]$$

$$R_{if} = \frac{V_i}{I_i} = r_\pi + (1 + g_m r_\pi) R_E$$

To find R_{of} :



$$V_\pi + V_x = 0 \Rightarrow V_\pi = -V_x$$

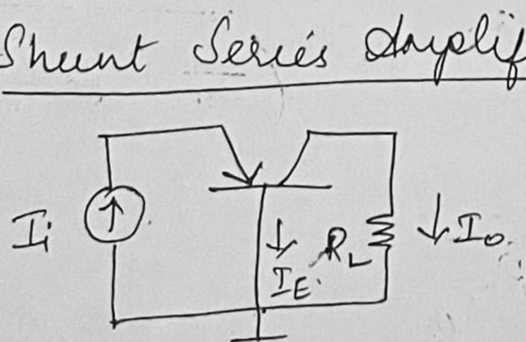
$$I_x + g_m V_\pi = \frac{V_x}{R_E} + \frac{V_x}{r_\pi} \Rightarrow I_x = \left[\frac{1}{R_E} + \frac{1}{r_\pi} + g_m \right] V_x$$

$$\frac{1}{R_o} = \frac{I_x}{V_x} = \frac{1}{R_E} + \left(\frac{1 + g_m r_\pi}{r_\pi} \right)$$

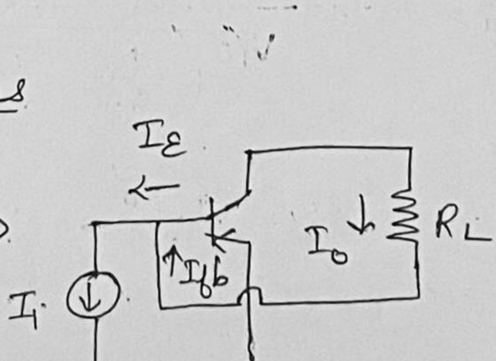
$$\frac{V_x}{I_x} = R_{of} = \frac{r_\pi}{(1+\beta)} \parallel R_E$$

The o/p resistance decreases with a shunt o/p connection.

Shunt Series Amplifiers



$\Rightarrow$



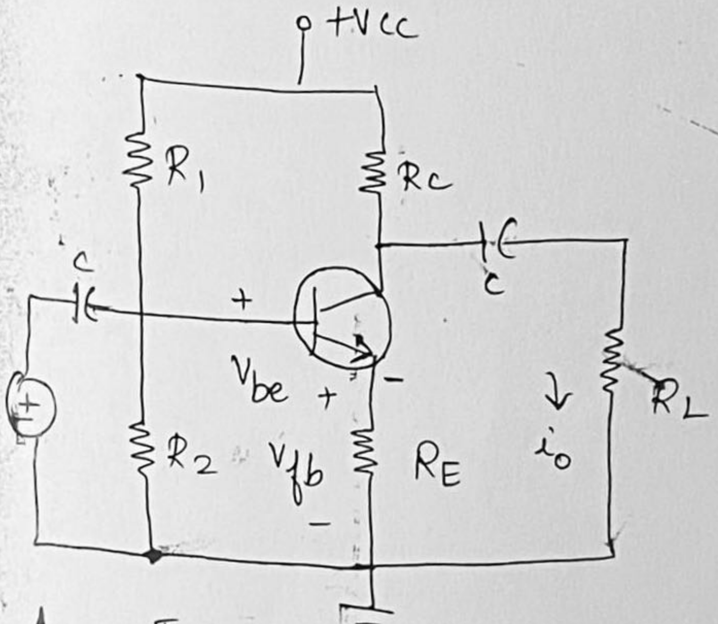
$$A_i = \frac{I_o}{I_E} = h_{fe}$$

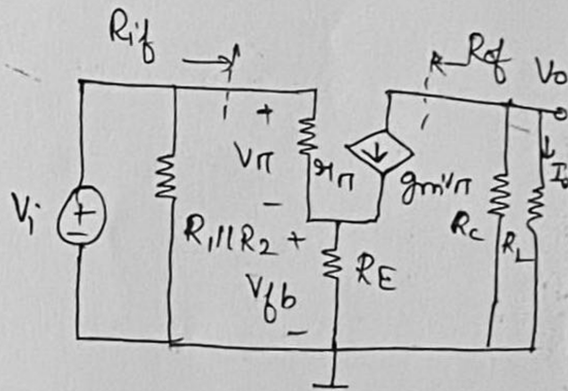
$$A_{if} = \frac{I_o}{I_i} = \frac{h_{fe}}{1+h_{fe}} = \frac{A_i}{1+A_i}$$

Transconductance (Series-Series) Amplifier

Discrete Circuit Representation

feedback voltage is a function of output current since the series output connection samples the output current.





$$A_g = \frac{I_o}{V_i}$$

$$I_o = \frac{-g_m V_\pi \times R_C}{R_L + R_C}$$

$$V_{fb} = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E$$

$$V_i = V_\pi + V_{fb} = V_\pi + \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E$$

$$V_i = V_\pi \left[1 + \left(\frac{1}{r_\pi} + g_m\right) R_E\right]$$

Substitute in A_g:

$$A_{gf} = \frac{I_o}{V_i} = \frac{-g_m\left(\frac{R_C}{R_C+R_L}\right)}{1+\left(\frac{1}{r_\pi}+g_m\right)R_E}.$$

Shunt - Shunt Feedback Practical ckt.