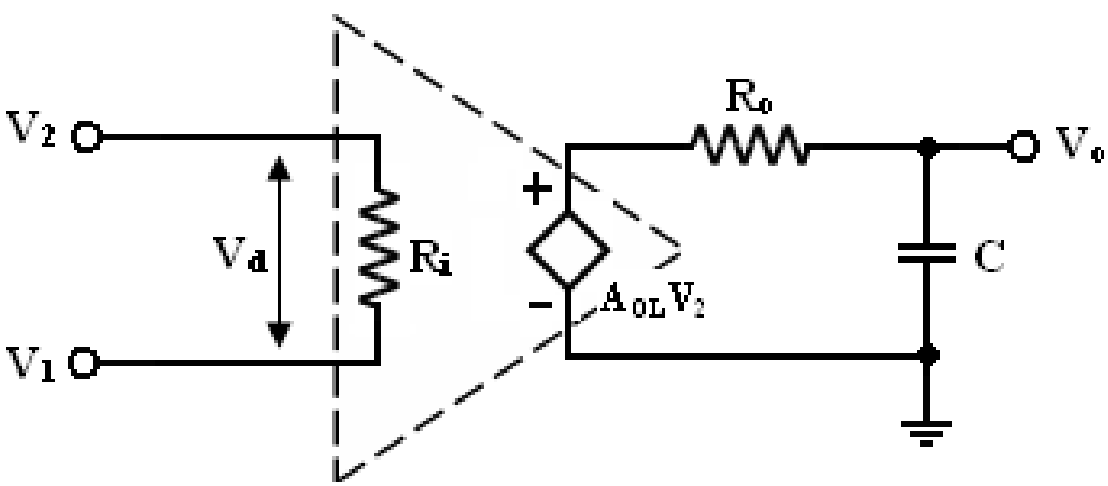
AC Characteristics:

For small signal sinusoidal (AC) application one has to know the ac characteristics such as frequency response and slew-rate.

Frequency Response:

The variation in operating frequency will cause variations in gain magnitude and its phase angle. The manner in which the gain of the op-amp responds to different frequencies is called the frequency response. Op-amp should have an infinite bandwidth Bw =∞ (i.e) if its open loop gain in 90dB with dc signal its gain should remain the same 90 dB through audio and onto high radio frequency. The op-amp gain decreases (roll-off) at higher frequency what reasons to decrease gain after a certain frequency reached. There must be a capacitive component in the equivalent circuit of the op-amp. For an op-amp with only one break (corner) frequency all the capacitors effects can be represented by a single capacitor C. Below fig is a modified variation of the low frequency model with capacitor C at the o/p.

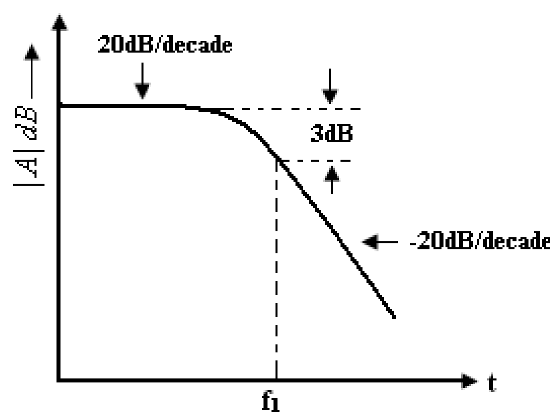


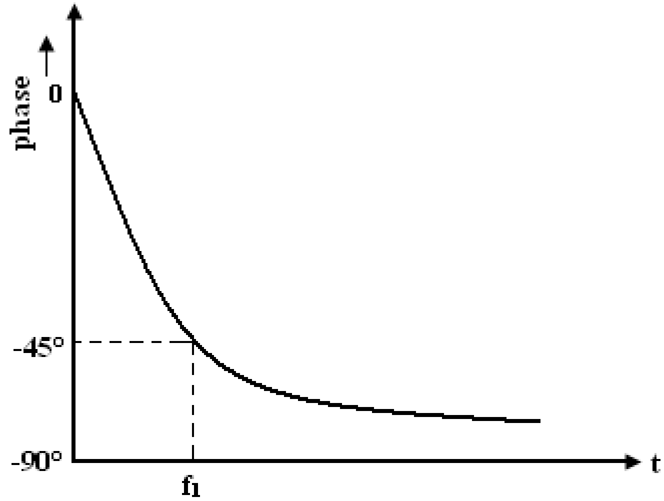
There is one pole due to R_0 C and one -20dB/decade. The open loop voltage gain of an op-amp with only one corner frequency is obtained from above fig.

f1 is the corner frequency or the upper 3 dB frequency of the op-amp. The magnitude and phase angle of the open loop volt gain are fu of frequency can be written as,

The magnitude and phase angle characteristics from eqn (29) and (30)

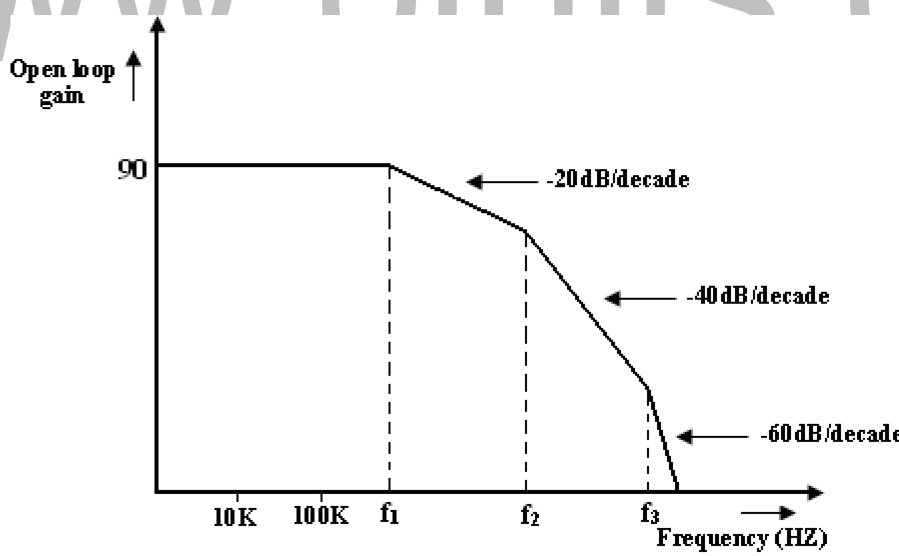
1. For frequency f<< f_1 the magnitude of the gain is 20 log A_{OL} in dB.
2. At frequency f = f_1 the gain in 3 dB down from the dc value of A_{OL} in dB. This frequency f_1 is called corner frequency.
3. For f>> f_1 the fain roll-off at the rate off -20dB/decade or-6dB/decade.





From the phase characteristics that the phase angle is zero at frequency f =0.

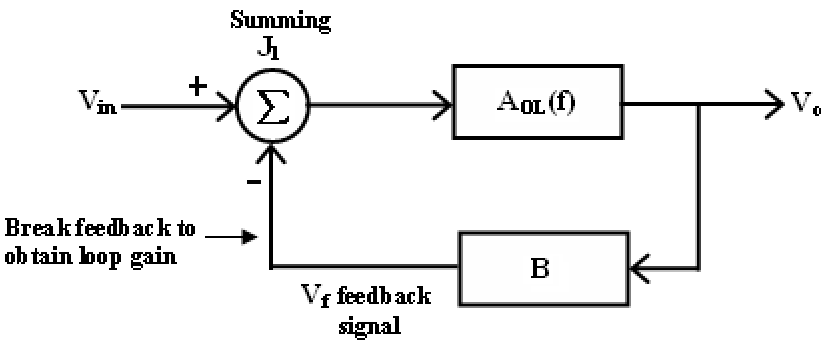
At the corner frequency f_1 the phase angle is -45^0 (lagging and a infinite frequency the phase angle is -90^0 . It shows that a maximum of 90^0 phase change can occur in an op-amp with a single capacitor C. Zero frequency is taken as te decade below the corner frequency and infinite frequency is one decade above the corner frequency.



Circuit Stability:

A circuit or a group of circuit connected together as a system is said to be stable, if its o/p reaches a fixed value in a finite time. (or) A system is said to be unstable, if its o/p increases with time instead of achieving a fixed value. In fact the o/p of an unstable sys keeps on inc reasing until the system break down. The unstable system are impractical and need be made stable. The criterian gn for stability is used when the system is to be tested practically. In theoretically, always used to test system for stability , ex: Bode plots.

Bode plots are compared of magnitude Vs Frequency and phase angle Vs frequency. Any system whose stability is to be determined can represented by the block diagram.



The block between the output and input is referred to as forward block and the block between the output signal and f/b signal is referred to as feedback block. The content of each block is referred –Transfer frequency' From fig we represented it by A_{OL} (f) which is given by

A_{OL} (f) = V_0 /Vin if V_f= 0 ------(1)

where A_{OL} (f) = open loop volt gain. The closed loop gain A_f is given by

$A_F = V_0$ /Vin

$A_F = A_{OL} / (1+(A_{OL})(B)$ ------(2)

B = gain of feedback circuit.

B is a constant if the feedback circuit uses only resistive components. Once the magnitude Vs frequency and phase angle Vs frequency plots are drawn, system stability may be determined as follows

1. Method:1:

Determine the phase angle when the magnitude of (A_{OL}) (B) is 0dB (or) 1. If phase angle is > .-180^0 , the system is stable. However, the some systems the magnitude may never be 0, in that cases method 2, must be used.

2. Method 2:

Determine the phase angle when the magnitude of (A_{OL}) (B) is 0dB (or) 1. If phase angle is > .-180^0 , If the magnitude is –ve decibels then the system is stable. However, the some systems the phase angle of a system may reach -180^0 , under such conditions method 1 must be used to determine the system stability.

Slew Rate:

Another important frequency related parameter of an op-amp is the slew rate. (Slew rate is the maximum rate of change of output voltage with respect to time. Specified in V/µs).

Reason for Slew rate:

There is usually a capacitor within 0, outside an op-amp oscillation. It is this capacitor which prevents the o/p voltage from fast changing input. The rate at which the volt across the capacitor increases is given by

dVc/dt = I/C ----------------- (1)

I -> Maximum amount furnished by the op-amp to capacitor C. Op-amp should have the either a higher current or small compensating capacitors.

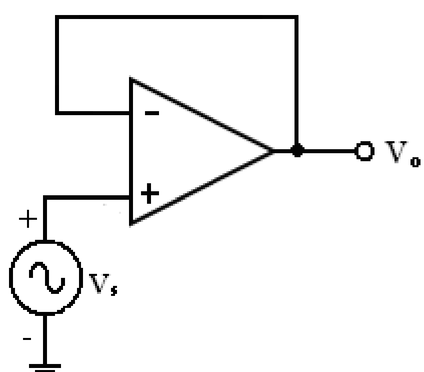
For 741 IC, the maximum internal capacitor charging current is limited to about 15µ A. So the slew rate of 741 IC is

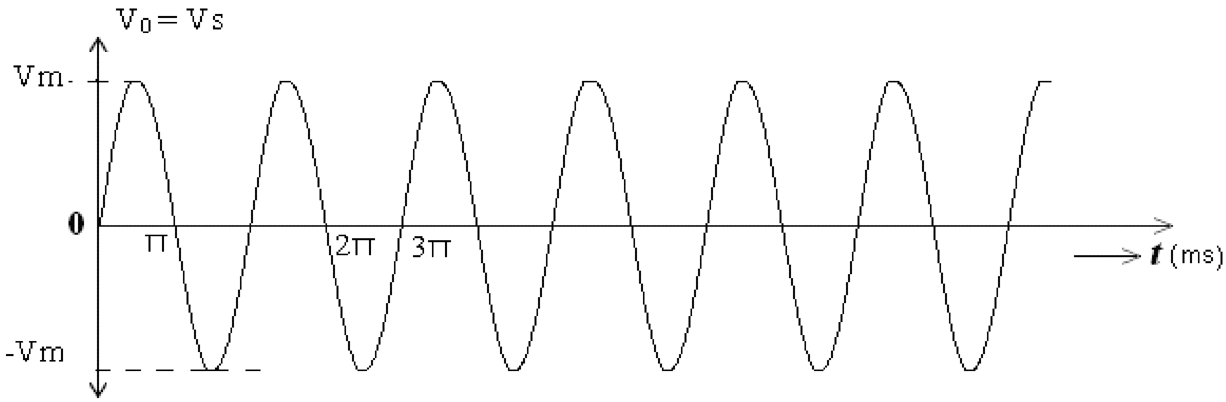
SR = dVc/dt |max = Imax/C .

For a sine wave input, the effect of slew rate can be calculated as consider volt follower -> The input is large amp, high frequency sine wave .

If Vs = Vm Sinwt then output V_0 = Vm sinwt . The rate of change of output is given by

dV_0/dt = Vm w coswt.





Input and Output Waveforms

The max rate of change ofoutput across when coswt =1

(i.e) SR = $dV_0/dt|_{max}$ = wVm.

SR = 2∏fVm V/s = 2∏fVm v/ms.

Thus the maximum frequency fmax at which we can obtain an undistorted output volt of peak value Vm is given by

fmax (Hz) = Slew rate/6.28 * Vm .

called the full power response. It is maximum frequency of a large amplitude sine wave with which op-amp can have without distortion.

DC Characteristics of op-amp:

Current is taken from the source into the op-amp inputs respond differently to current and voltage due to mismatch in transistor.

DC output voltages are,

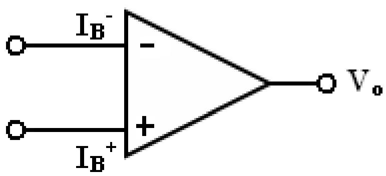
1. Input bias current
2. Input offset current
3. Input offset voltage
4. Thermal drift

Input bias current:

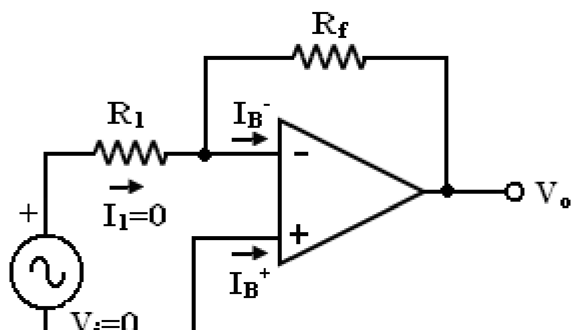
The op-amp's input is differential amplifier, which may be made of BJT or FET.

- In an ideal op-amp, we assumed that no current is drawn from the input terminals.
- The base currents entering into the inverting and non- inverting terminals

- Even though both the transistors are identical, I_B^- and I_B^+ are not exactly equal due to internal imbalance between the two inputs.
- Manufacturers specify the input bias current I_B



Input Bias Current



Inverting Amplifier with Bias Current

So, $I_B = \frac{I_B^+ + I_B^-}{2}$

If input voltage $V_i = 0V$. The output Voltage V_o should also be ($V_o = 0$)

$I_B = 500nA$

We find that the output voltage is offset by,

$$V_o = (I_B) R_f$$

Op-amp with a 1M feedback resistor

$V_o = 5000nA \text{ X } 1M = 500mV$

The output is driven to 500mV with zero input, because of the bias currents.

In application where the signal levels are measured in mV, this is totally unacceptable. This can be compensated. Where a compensation resistor R_{comp} has been added between the non-inverting input terminal and ground as shown in the figure below.

Current I_B^+ flowing through the compensating resistor R_{comp}, then by KVL we get,

$-V_1+0+V_2-V_o = 0$ (or)

$V_o = V_2 - V_1$ ——>(3)

By selecting proper value of R_{comp}, V_2 can be cancelled with V_1 and the $V_o = 0$. The value of R_{comp} is derived a

$V_1 = I_B^+ R_{comp}$ (or)

$I_B^+ = V_1 / R_{comp}$ ——>(4)

The node _a' is at voltage ($-V_1$). Because the voltage at the non- inverting input terminal is ($-V_1$). So with $V_i = 0$ we get,

$I_1 = V_1/R_1$ ——>(5)

$I_2 = V_2/R_f$ ——>(6)

For compensation, V_o should equal to zero ($V_o = 0$, $V_i = 0$). i.e. fromequation (3) $V_2 = V_1$. So that,

$I_2 = V_1/R_f$ ——>(7)

KCL at node _a' gives,

$I_B^- = I_2 + I_1$

$I_B \quad R_f \quad R_1$

Assume $I_B^- = I_B^+$ and using equation (4) & (8) we get

$R_{comp} \quad R_1 \quad R_f$

$R_{comp} = R_1 || R_f$ ———>(9)

i.e. to compensate for bias current, the compensating resistor, R_{comp} should be equal to the parallel combination of resistor R_1 and R_f.

Input offset current:

- Bias current compensation will work if both bias currents I_B^+ and I_B^- are equal.
- Since the input transistor cannot be made identical. There will always be some small difference between I_B^+ and I_B^-. This difference is called the offset current

$|I_{os}| = I_B^+ - I_B^-$ ——>(10)

Offset current I_{os} for BJT op-amp is 200nA and for FET op-amp is 10pA. Even with bias current compensation, offset current will produce an output voltage when $V_i = 0$.

$V_1 = I_B^+ R_{comp}$ ——>(11)

And $I_1 = V_1/R_1$ ——>(12)

KCL at node ‗a‘ gives,

Again $V_0 = I_2 R_f – V_1$

$V_o = I_2 R_f - I_B^+ R_{comp}$

$V_o = 1M\,\Omega \times 200nA$

$V_o = 200mV$ with $V_i = 0$

Equation (16) the offset current can be minimized by keeping feedback resistance small.

- Unfortunately to obtain high input impedance, R_1 must be kept large.
- R_1 large, the feedback resistor R_f must also be high. So as to obtain reasonable gain.

The T-feedback network is a good solution. This will allow large feedback resistance, while keeping the resistance to ground low (in dotted line).

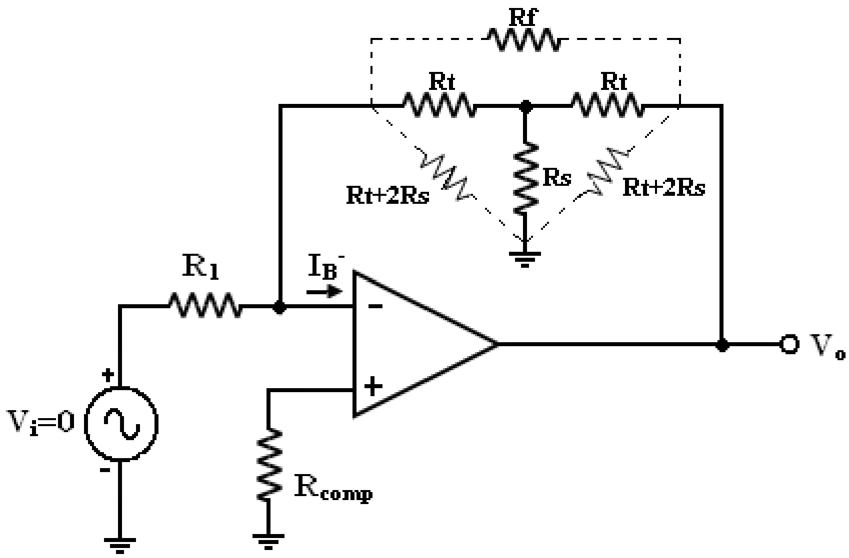
- The T-network provides a feedback signal as if the network were a single feedback resistor.

By T to Π conversion,

To design T- network first pick $R_t << R_f/2$ ——>(18)

Then calculate R_s

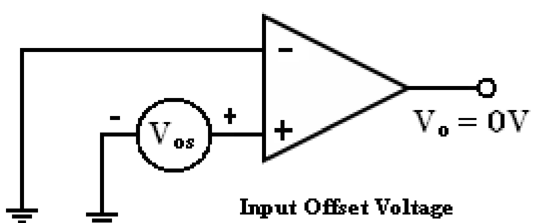
R_f 2 R_t



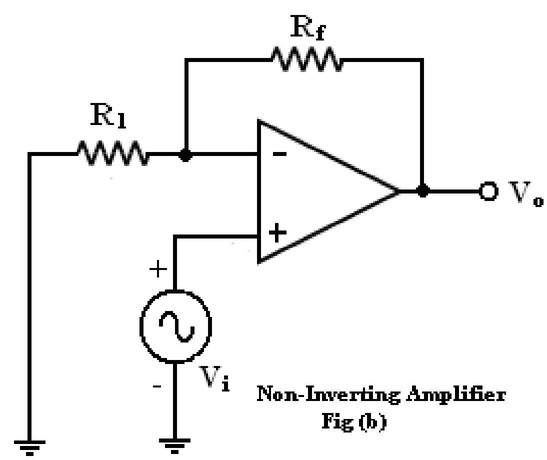
Input offset voltage:

Inspite of the use of the above compensating techniques, it is found that the output voltage may still not be zero with zero input voltage [$V_o \neq 0$ with $V_i = 0$]. This is due to unavoidable imbalances inside the op-amp and one may have to apply a small voltage at the input terminal to make output (V_o) = 0.

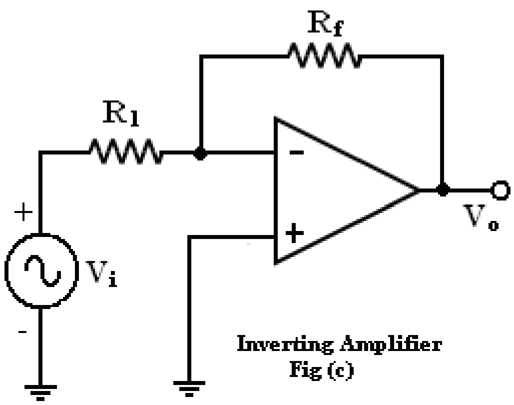
This voltage is called input offset voltage V_{os}. This is the voltage required to be applied at the input for making output voltage to zero ($V_o = 0$).



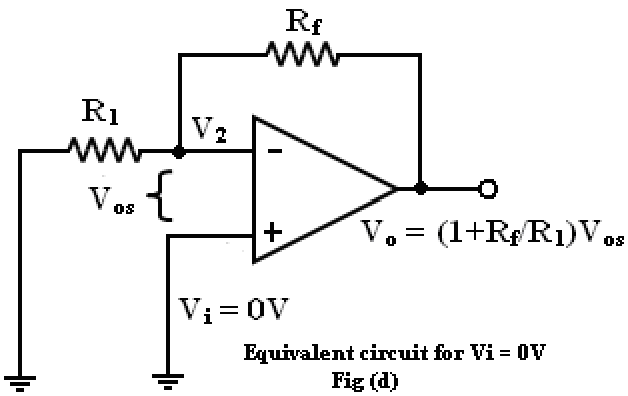
Input Offset Voltage
Fig (a)



Non-Inverting Amplifier
Fig (b)



Inverting Amplifier
Fig (c)



Equivalent circuit for Vi = 0V
Fig (d)

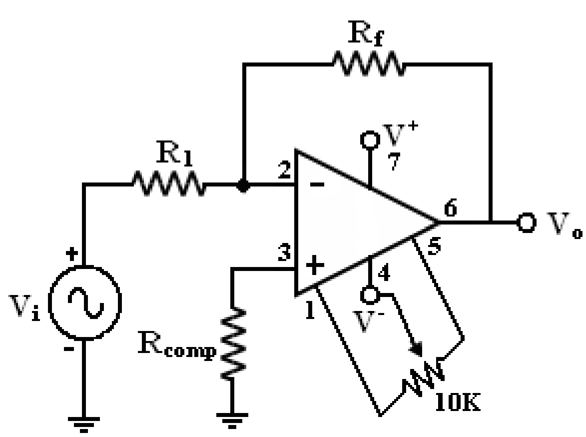
Let us determine the V_{os} on the output of inverting and non- inverting amplifier. If $V_i = 0$ (Fig (b) and (c)) become the same as in figure (d).

Total output offset voltage:

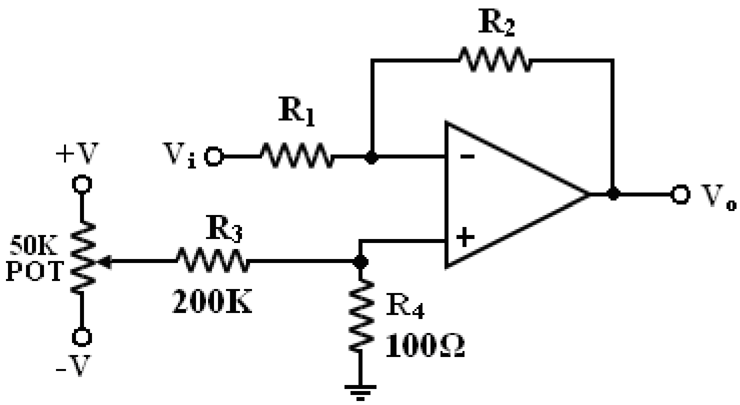
The total output offset voltage V_{OT} could be either more or less than the offset voltage produced at the output due to input bias current (I_B) or input offset voltage alone(V_{os}).

This is because I_B and V_{os} could be either positive or negative with respect to ground. Therefore the maximum offset voltage at the output of an inverting and non- inverting amplifier (figure b, c) without any compensation technique used is given by many op-amp provide offset compensation pins to nullify the offset voltage.

- 10K potentiometer is placed across offset null pins 1&5. The wipes connected to the negative supply at pin 4.
- The position of the wipes is adjusted to nullify the offset voltage.



When the given (below) op-amps does not have these offset null pins, external balancing techniques are used.



$$V_{os} = \pm \frac{VR_4}{R_3 + R_4}$$

Differential amplifier:

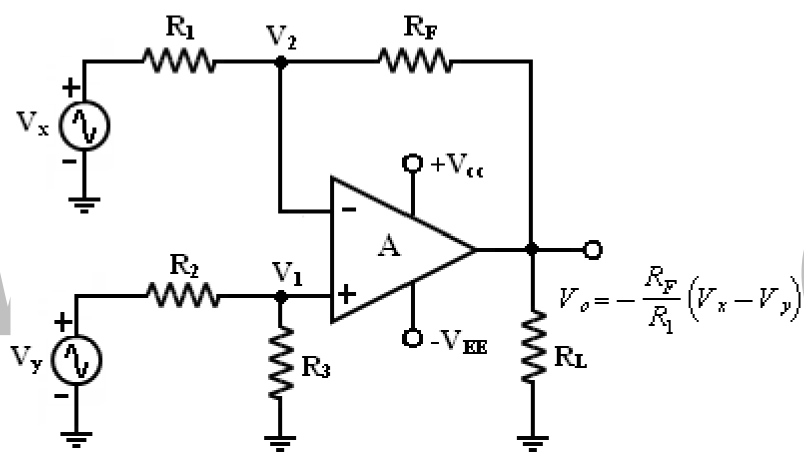
We will evaluate 2 different arrangements of the differential amplifier with -ve feedback. Classify these arrangements according to the number of op-amps used. i.e

1. Differential amplifier with one op-amp
2. Differential amplifier with two op-amps.

Differential amplifier are used in instrumentation and industrial applications to amplify differences between 2 input signals such as output of the wheat stone bridge circuit.

Differential amplifier preferred to these application because they are better able to reject common mode (noise) voltages than single input circuit such as inverting and non-inverting amplifier.

1. Differential Amplifier with one op-amp:



To analyse this circuit by deriving voltage gain and input resistance. This circuit is a combination of inverting and non-inverting amplifier. (i.e) When V_x is reduced to zero the circuit is non-inverting amplifier and when V_y is reduced to zero the circuit is invertingamplifier.

Voltage Gain:

The circuit has 2 inputs V_x and V_y . Use superposition theorem, when V_y = 0V, becomes inverting amplifier. Hence the o/p due to V_x only is

$V_{ox} = -R_F (V_x)$---------------------- (24.a)
R_1

Similarly, when V_x = 0V, becomes Non- inverting amplifier having a voltage divider network composed of R_2 and R_3 at the Non – inverting input.

Note : the gain of the differential amplifier is same as that of inverting amplifier.

Input Resistance:

The input resistance R_{if} of the differential amplifier is resistance determined looking into either one of the 2 input terminals with the other grounded,

With $V_y = 0V$,

Inverting amplifier, the input resistance whichis,

$RiFx \approx R_1$ -.....................-

(26.a) Similarly, ,$V_x = 0V$,

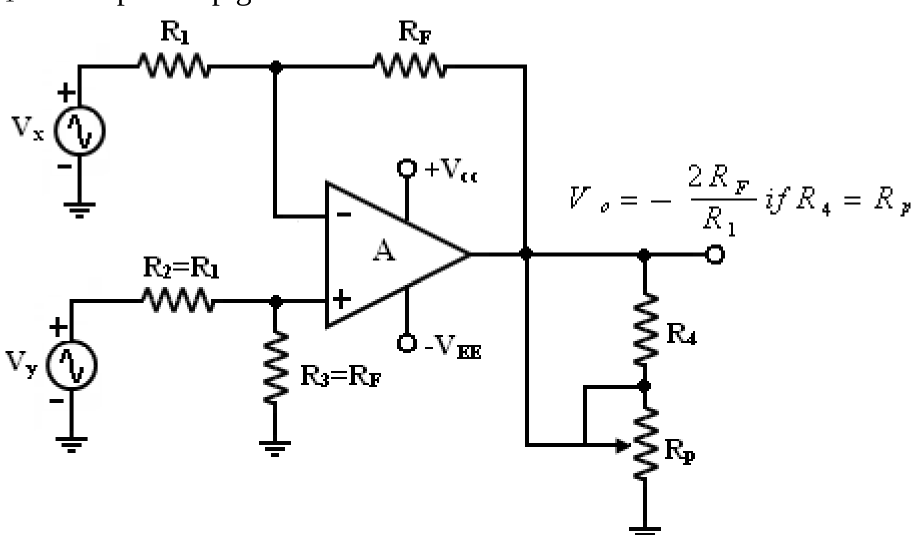
Non-inverting amplifier, the input resistance which is,

$RiFy \approx (R_2 + R_3)$ (26.b)

V_x and V_y are not the same. Both the input resistance can be made equal, if we modify the basic differential amplifier. Both R_1 and $(R_2 + R_3)$ can be made much larger than the source resistances. So that the loading of the signal sources does not occur.

Note: If we need a variable gain, we can use the differential amplifier. In this circuit $R_1 = R_2$, $R_F = R_3$ and the potentiometer $R_p = R_4$.

Depending on the position of the wiper in R voltage can be varied from the closed loop gain of $-2R_F/R_1$ to the open loop gain of A.



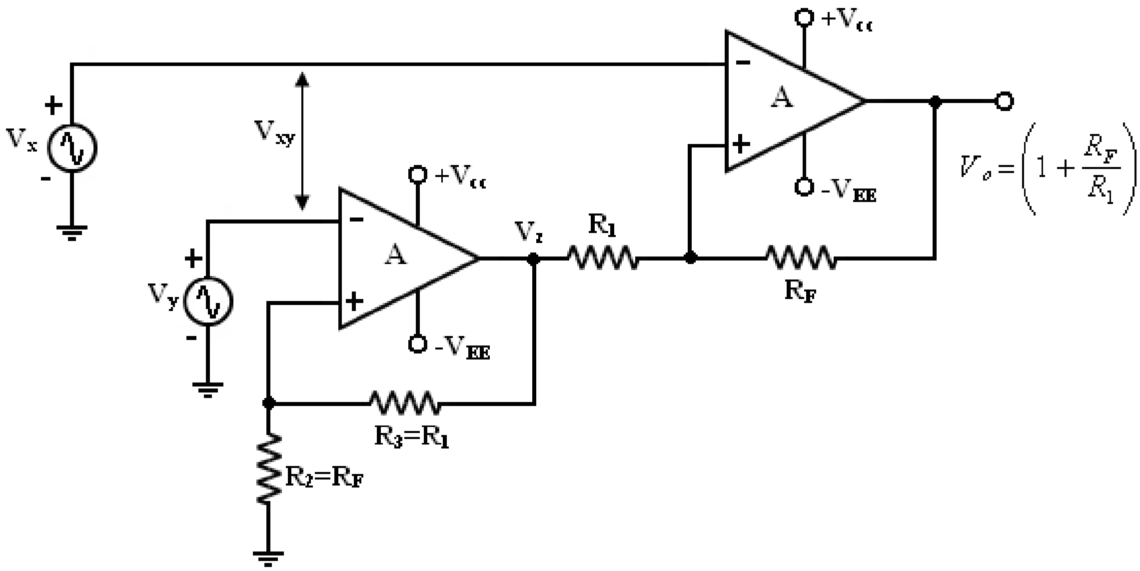
2. Differential Amplifier with 2 op-amps:

We can increase the gain of the differential amplifier and also increase the input resistance R_{if} if we use 2 op-amps.

Voltage gain:

It is compares of 2 stages 1. Non- inverting

. Differential amplifier with gain.



By finding the gain of these 2 stages, we can obtain the overall gain of the circuit, The o/p

$V_2 \left(1 \frac{R_f}{R_g} \right)_2$

Input Resistance:

The input resistance Rif of the differential amplifier is the resistance determined from either one of the two non- inverting terminals with the other grounded. The first stage A_1 is the non- inverting amplifier, its input resistance is

RiFy = Ri (1+AB)----------- (29. a)

Where Ri = open loop input resistance of the op-amp. B =
$R_2 / R_2 + R_3$

Similarly, with V_y shorted to ground ($V_y = 0$ V), the 2nd stage (A_2) also becomes non-inverting amplifier, whose input resistance is

RiFx = Ri (1+AB) ---------- (29. b)

Where Ri = open loop input resistance of the op-amp B =

$R_1/(R_1 + R_F)$

Since $R_1 = R_3$ and $R_F = R_2$, the Rify ≠ RiFx because the loading of the input sources V_x and V_y mayoccur. (Or)

The output signal may be smaller in amplitude than expected. This possible reduction in the amplitude ofthe output signal is drawback of differential amplifier.

To overcome this:

With proper selection of components, both RiFy and RiFx can be made much larger than the sourcesresistance so that the loading of the input sources does not occur.

Output resistance and Bandwidth of differential amplifier with feedback:

The output resistance of the differential amplifier should be the same as that of the non-inverting amplifier expect that $B = 1/A_D$ (i.e)

$R_{OF} = R_0 /(1+A/A_D)$ --------- (30)

A_D = closed loop gain of the differential amplifier R_0 =output resistance of the op-amp

A = open – loop volt gain of the op-amp

Remember that A_D is different for differential amplifier.

In the case of Inverting and Non- inverting amplifier, the bandwidth of the differential amplifier alsodepends on the closed loop gain of the amplifier and is given by,

f_F = Unity gain Bandwidth closedloop gain A_D

(or)

$f_F = (A)(f_0)$

Feedback amplifier:

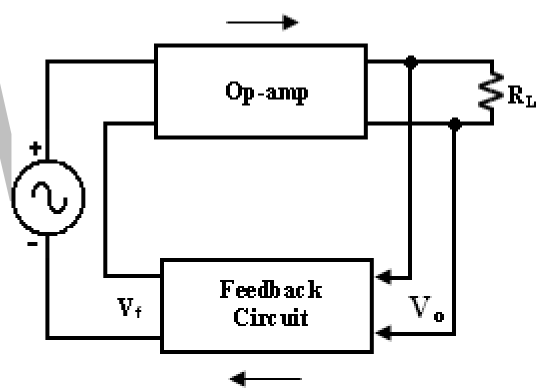
An op-amp that was feedback is called as feedback amplifier. A feedback amplifier is sometimes referred to as closed loop amplifier because the feedback forms a closed loop between the input and output. A closed loop amplifier can be represented by using 2 blocks.

1. One for an op-amp
2. Another for a feedback circuit.

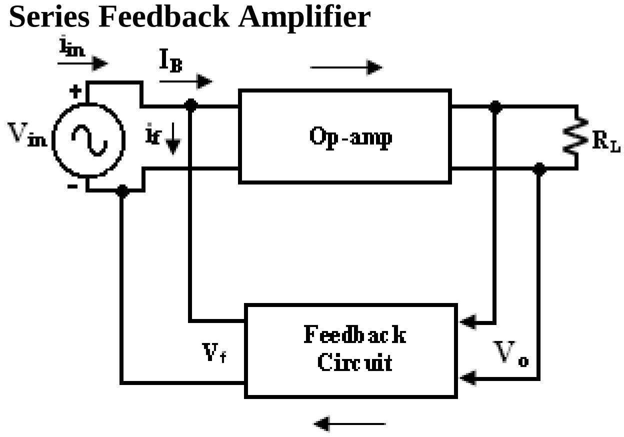
There are 4 ways to connect these 2 blocks according to whether volt or current.

1. Voltage Series Feedback
2. Voltage Shunt feedback
3. Current Series Feedback
4. Current shunt Feedback

Voltage series and voltage shunt are important because they are most commonly used.

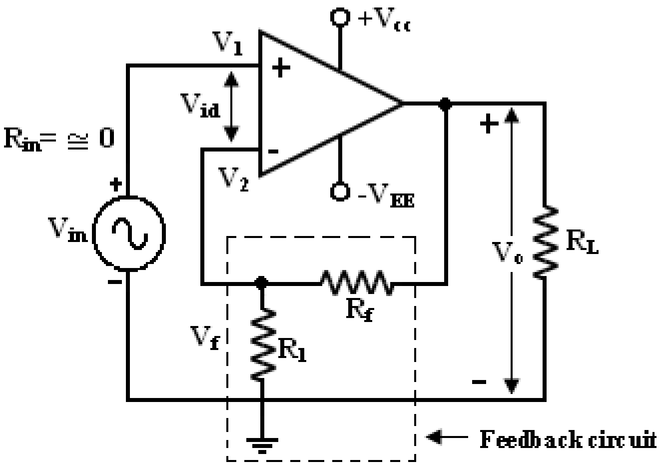


Voltage Series Feedback Amplifier



Voltage shunt feedback Amplifier

Voltage Series Feedback Amplifier:



Before Proceeding, it is necessary to define some terms.

Voltage gain of the op-amp with a without feedback:

Gain of the feedback circuit are defined as open loop volt gain (or gain without feedback) $A = V_0 / Vid$

Closed loop volt gain (or gain with feedback) $A_F = V_0 / Vin$

Gain of the feedback circuit => $B = V_F / V_0$.

1. Negative feedback:

KVL equation for the input loop is,

$Vid = Vin - V_f$ ----------------------(1)

Vin = input voltage.

V_f = feedback voltage.

Vid = difference input voltage.

The difference volt is equal to the input volt minus the f/b volt. (or) The feedback volt always opposes the input volt (or out of phase by 180^0 with respect to the input voltage) hence the feedback is said to be negative.

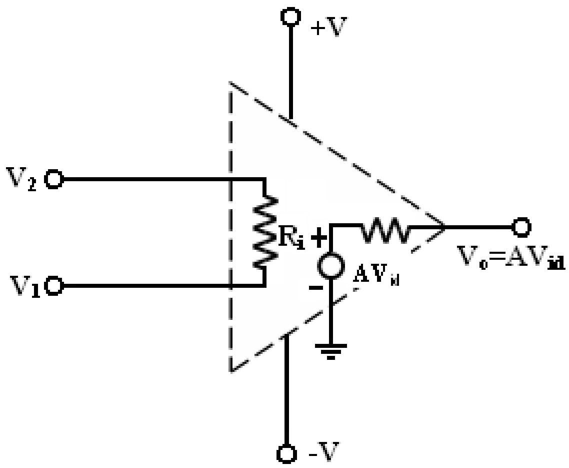
It will be performed by computing

1. Closed loop volt gain
2. Input and output resistance
3. Bandwidth

1. Closed loop volt gain:

The closed loop volt gain is $A_F = V_0 / Vin$

$V_0 = Avid = A(V_1 - V_2)$



A = large signal voltage gain.

From the above eqn, $V_0 = A(V_1 - V_2)$

Refer fig, we see that, $V_1 = Vin$

$V_2 = V_f = R_1 V_0$

-

$R_1 + R_f$ Since $Ri >> R_1$

$V_0 = AVin - \quad R_1 V_0$

-

$R_1 + R_f$

$V_0 + \quad A\ R_1\ V_0 = AVin$

-____

$R_1 + R_f$

3. Difference input voltage ideally zero (Vid)

Reconsider eqn $V_0 = A\ Vid$

$Vid = V_0 / A$

Since A is very large (ideally α)

Vid t 0 ---(7.a)

(i.e) V_1 t V_2 --(7.b)

Eqn (7.b) says that the volt at the Non- inverting input terminal of an op-amp is approximately equal to that at the inverting input terminal provided that A, is vey large.

From the circuit diagram,

$V_1 = Vin$

$V_2 = V_F = R_1 V_0 / R_1 + R_F$

Sub these values of V_1 and V_2 in eqn (7.b) we get

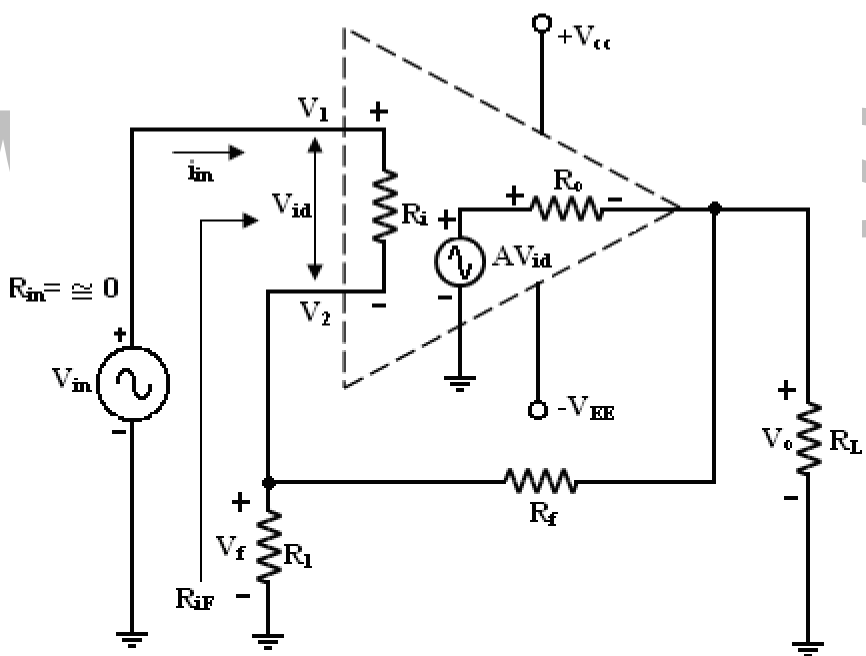
$Vin = R_1 V_0 / R_1 + R_F$ (i.e) $A_F = V_0 / Vin = 1 + R_F/R_1$

4. Input Resistance with feedback:

From the below circuit diagram Ri -> input resistance

Rif -> input resistance of an op-amp with feedback

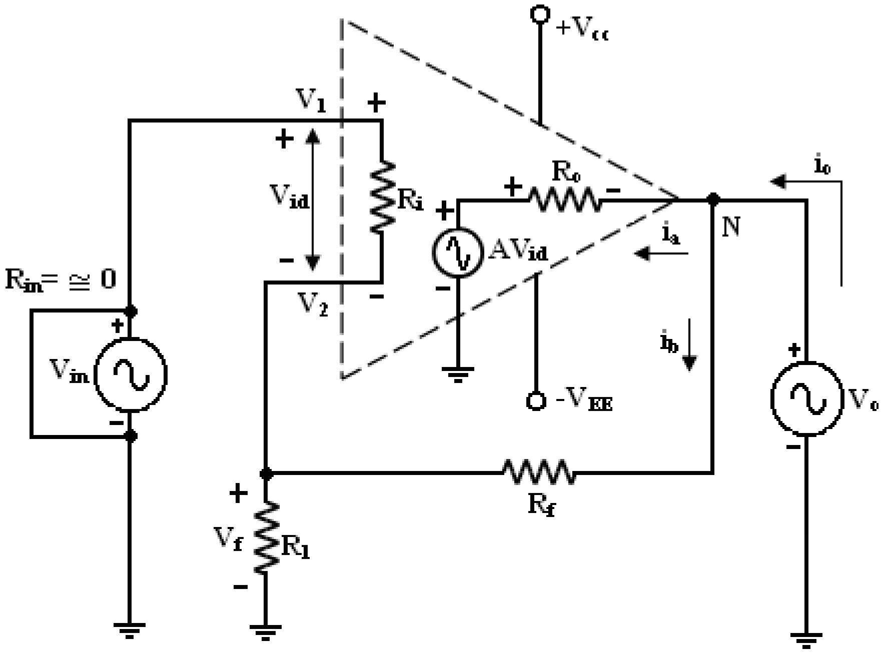
Derivation of input resistance with Feedback:



The input resistance with feedback is defined as,

This means that the input resistance of the op-amp with feedback is (i+AB) times that without feedback.

5. Output Resistance with feedback:



This resistance can be obtained by using Thevenin‘s theorem. To find out o/p resistance with feedback R_{OF} reduce independent source Vin to zero, apply an external voltage V_0, and calculate the resulting current i_0.

The R_{OF} is defined as follows,

$R_{OF} = V_0 / i_0$ ---(9.a)

KCL at o/p node ‗N‘ we get,

$i_0 = i_a + i_b$

Since $((R_F + R_1) \| R_i >> R_0$ and $i_0 >> i_b$

. i_0 t i_a

The current i_0 can be found by writing KVL eqn for the o/p loop

$V_0 - R_0 i_0 - AVid = 0$

$$i_0 = \frac{V_0 - AVid}{R_0}$$

$Vid = V_1 - V_2$

$= 0 - V_F$

This result shows that the output resistance of the voltage series feedback amplifier is 1/(1+AB) the output resistance of R_0 the op-amp. (i.e) The output resistance of the op-amp with feedback is much smaller than the output resistance without feedback.

6. Bandwidth with feedback:

The bandwidth of the amplifier is defined as the band (range of frequency) for which the gain remains constant. The Frequency at which the gain equals 1 is known as unity gain bandwidth (UGB). The relationship between the breakfrequency f_0 , open loop volt gain A, bandwidth with feedback f_F and closed loop gain A_F .

For an op-amp with a single break frequency f_0 , the gain bandwidth product is constant and equal to the unity-gain bandwidth. (UGB).

UGB = (A) (f_0) (10.a)

A = open loop volt gain

f_0 = break frequency of an op-amp ((or) only for a single break frequency op-amp UGB = A_F f_F ---- (10.b)

A_F = closed loop volt gain

f_F = bandwidth with feedback.

Equating eqn 10.a and 10.b

$Af_0 = A_F f_F$

$f_F = Af_0 / A_F$ ---------------(10.c)

For the non- inverting amplifier with feedback

$A_F = A/(1+AB)$

Sub the value of A_F in eqn 10.c, we get

$f_F = Af_0 / A/(1+AB)$

$f_F = (1+AB) f_0$ --------(10.d)

eqn 10.d -> bandwidth of the non- inverting amplifier with feedback is = bandwidth of the with feedback f_0 times (1+AB)

7. Total o/p offset voltage with feedback (Vout)

In an open loop op-amp the total o/p offset voltage is equal to either the +ve or –ve saturation volt.

Vout = +ve (or) –ve saturation volt.

With feedback the gain of the Non- inverting amplifier changes from A to A/(1+AB), the total output offset voltage with feedback must also be 1/(1+AB) times the voltage without feedback. (i.e)

Total o/p offset Vout with feedback = Total o/p offset volt without feedback

----

1+AB

Vout = ±Vsat

--------- ----(11)

1+AB

1/(1+AB) is < I and ±Vsat = Saturation voltages. The maximum voltages the output of an op-amp can reach.

Note:

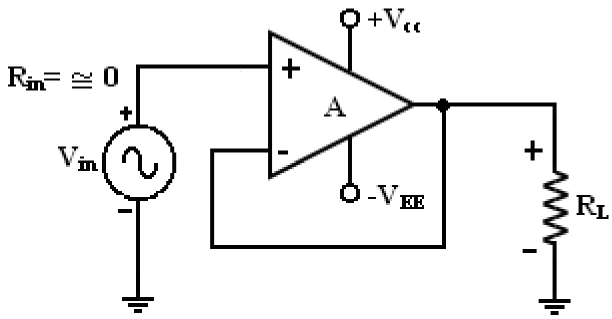
Open-loop even a very small volt at the input of an op-amps can cause to reach maximum value (+ Vsat)because of its very high volt gain. According to eqn for a gain op-amp circuit the Vout is either +ve or –ve volt because Vsat can be either +ve or –ve.

Conclusion of Non-Inverting Amplifier with feedback:

The char of the perfect volt Amplifier:

1. It has very high input resistamce.
2. Very low output resistance
3. Stable volt gain
4. large bandwidth

8. Voltage Followe r: [Non-Inverting Buffer]



The lowest gain that can be obtained from a non- inverting amplifier feedback is 1.

When the Non-Inverting amplifier is designed for unity and it is called a voltage follower, becausethe output voltage is equal to and in phase with the input or in volt follower the output follows the input.

It is similar to discrete emitter follower, the volt follower is preferred, because it had much higherinput resistance and output amplitude is exactly equal to input.

To obtain the voltage follower, from this circuit simply open R_1 and short R_F .

In this figure all the output volt is fed back into the inverting terminal of the op-amp.The gain of the feedback circuit is 1 (B = A_F =1) A_F = 1R_{iF} =AR_i

R_{OF} =R_0 /A

f_F = Af_0

Vout = ±Vsat- A

Since 1+ A t A.

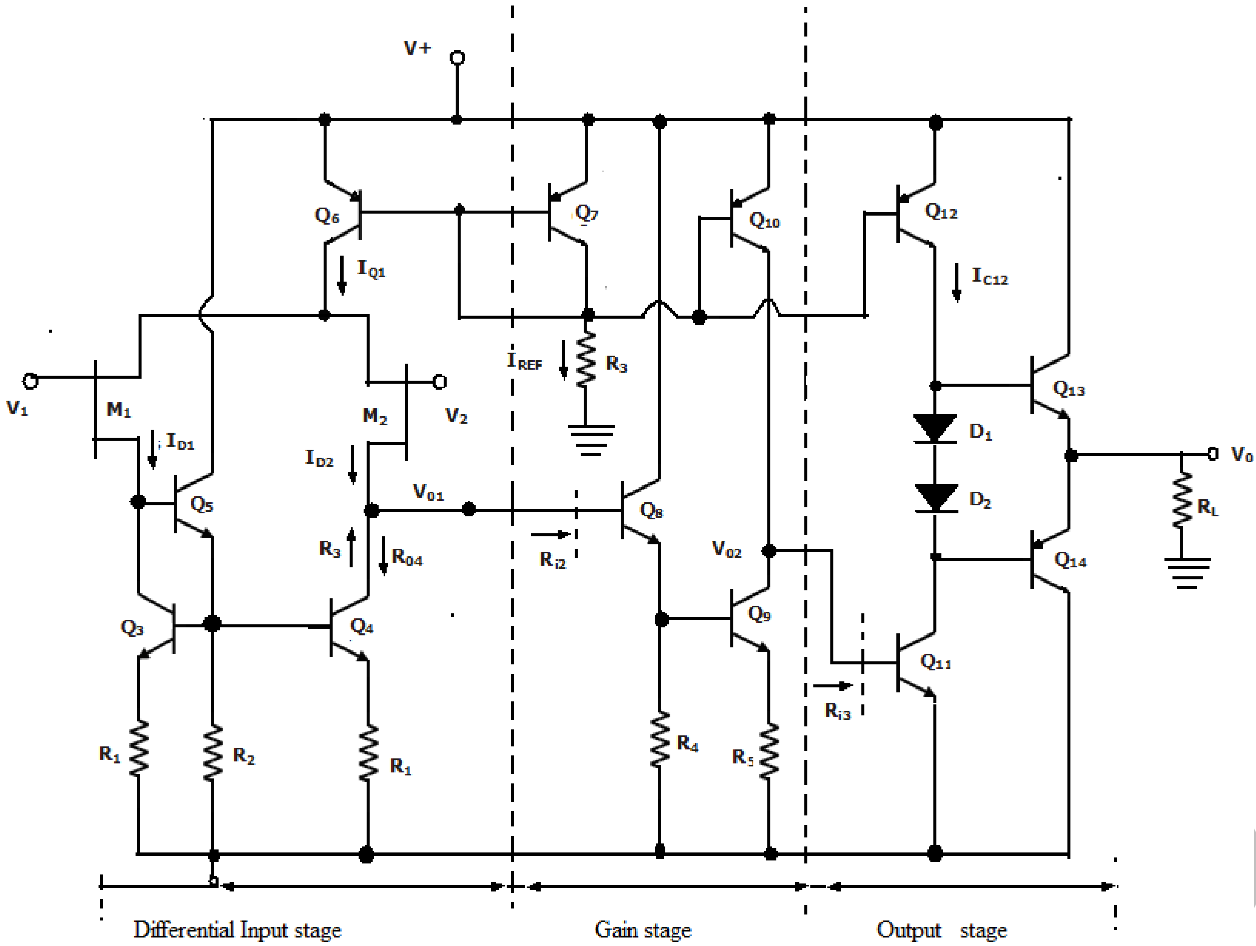
UNIT II

CHARACTERISTICS OF OPAMP

General Operational Amplifier:

An operational amplifier generally consists of three stages, anmely,1. a differential amplifier 2. additional amplifier stages to provide the required voltage gain and dc level shifting 3. an emitter- follower or source follower output stage to provide current gain and low output resistance.

A low- frequency or dc gain of approximately 10^4 is desired for a general purpose op-amp and hence, the use of active load is preferred in the internal circuitry of op-amp. The output voltage is required to be at ground, when the differential input voltages is zero, and this necessitates the use of dual polarity supply voltage. Since the output resistance of op-amp is required to be low, a complementary push-pull emitter – follower or source follower output stage is employed. Moreover, as the input bias currents are to be very small of the order of picoamperes, an FET input stage is normally preferred. The figure shows a generalop-amp circuit using JFET input devices.



Input stage:

The input differential amplifier stage uses p-channel JFETs M_1 and $M_{2.}$ It employs a three-transistor active load formed by Q_3 , Q_4 , and Q_5 . the bias current for the stage is provided by a two-transistor current source using PNP transistors Q_6 and $Q_{7.}$ Resistor R_1 increases the output resistance seen looking into the collector of Q_4 as indicated by $R_{04.}$ This is necessary to provide bias current stability against the transistor parameter variations. Resistor R_2 establishes a definite bias current through Q_5 . A single ended output is taken out at the collector of Q_4 .

MOSFET‘s are used in place of JFETs with additional devices in the circuit to prevent any damage for the gate oxide due to electrostatic discharges.

Gain stage:

The second stage or the gain stage uses Darlington transistor pair formed by Q_8 and Q_9 as shown in figure. The transistor Q_8 is connected as an emitter follower, providing large input resistance.Therefore, it minimizes the loading effect on the input differential amplifier stage. The transistor Q_9 provides an additional gain and Q_{10} acts as an active load for this stage. The current mirror formed by Q_7 and Q_{10} establishes the bias current for Q_9 . The V_{BE} drop across Q_9 and drop across R_5 constitute the voltage drop across R_4 , and this voltage sets the current through Q_8 . It can be set to a small value, such that the base current of Q_8 also is very less.

Output stage:

The final stage of the op-amp is a class AB complementary push-pull output stage. Q_{11} is an emitter follower, providing a large input resistance for minimizing the loading effects on the gain stage. Bias current for Q_{11} is provided by the current mirror formed by Q_7 and Q_{12}, through Q_{13} and Q_{14} for minimizing the cross over distortion. Transistors can also be used in place of the two diodes.

The overall voltage gain A_V of the op-amp is the product of voltage gain of each stage as given by

$A_V = |A_d||A_2||A_3|$

Where A_d is the gain of the differential amplifier stage, A_2 is the gain of the second gain stage and A_3 is the gain of the output stage.

IC 741 Bipolar operational amplifier:

The IC 741 produced since 1966 by several manufactures is a widely used general purpose operational amplifier. Figure shows that equivalent circuit of the 741 op-amp, divided into various individual stages. The op-amp circuit consists of three stages.

1. the input differential amplifier
2. The gain stage
3. the output stage.

A bias circuit is used to establish the bias current for whole of the circuit in the IC. The op-amp is supplied with positive and negative supply voltages of value ± 15V, and the supply voltages as low as ±5V can also be used.

Bias Circuit:

The reference bias current I_{REF} for the 741 circuit is established by the bias circuit consisting of two diodes-connected transistors Q_{11} and Q_{12} and resistor R_5. The widlar current source formed by Q_{11} , Q_{10} and R_4 provide bias current for the differential amplifier stage at the collector of Q_{10}.

Transistors Q_8 and Q_9 form another current mirror providing bias current for the differential amplifier. The reference bias current I_{REF} also provides mirrored and proportional current at the collector of the double – collector lateral PNP transistor $Q_{13.}$ The transistor Q_{13} and Q_{12} thus form a two-output current mirror with Q_{13A} providing bias current for output stage and Q_{13B} providing bias current for $Q_{17.}$ The transistor Q_{18} and Q_{19} provide dc bias for the output stage. Formed by Q_{14} and Q_{20} and they establish two V_{BE} drops of potential difference between the bases of Q_{14} and Q_{18} .

Input stage:

The input differential amplifier stage consists of transistors Q_1 through Q_7 with biasing provided by Q_8 through $Q_{12.}$ The transistor Q_1 and Q_2 form emitter – followers contributing to high differential input resistance, and whose output currents are inputs to the common base amplifier using Q_3 and Q_4 which offers a large voltage gain.

The transistors Q5, Q6 and Q7 alo ng with resistors $R_{1,}$ R_2 and R_3 from the active load for input stage. The single-ended output is available at the collector of $Q_{6.}$ the two null terminals in the input stage facilitate the null adjustment. The lateral PNP transistors Q_3 and Q_4 provide additional protection against voltage breakdown conditions. The emitter-base junction Q_3 and Q_4 have higher emitter-base breakdown voltages of about 50V. Therefore, placing PNP transistors in series with NPN transistors provide protection against accidental shorting of supply to the input terminals.

Gain Stage:

The Second or the gain stage consists of transistors Q_{16} and $Q_{17,}$ with Q_{16} acting as an emitter – follower for achieving high input resistance. The transistor Q_{17} operates in common emitter configuration with its collector voltage applied as input to the output stage. Level shifting is done for this signal at this stage.

Internal compensation through Miller compensation technique is achieved using the feedback capacitor C_1 connected between the output and input terminals of the gain stage.

Output stage:

The output stage is a class AB circuit consisting of complementary emitter follower transistor pair Q_{14} and Q_{20} . Hence, they provide an effective loss output resistance and current gain.

The output of the gain stage is connected at the base of Q_{22} , which is connected as an emitter – follower providing a very high input resistance, and it offers no appreciable loading effect on the gain stage. It is biased by transistor Q_{13A} which also drives Q_{18} and $Q_{19,}$ that are used for establishing a quiescent bias current in the output transistors Q_{14} and Q_{20}.

Ideal op-amp characteristics:

1. Infinite voltage gain A.
2. Infinite input resistance R_i, so that almost any signal source can drive it and there is noloading of the proceeding stage.
3. Zero output resistance R_o, so that the output can drive an infinite number of other devices.
4. Zero output voltage, when input voltage is zero.
5. Infinite bandwidth, so that any frequency signals from o to ∞ HZ canbe amplified with outattenuation.
6. Infinite common mode rejection ratio, so that the output common mode noise voltage iszero.
7. Infinite slew rate, so that output voltage changes occur simultaneously with input voltagechanges.

Open – loop op-amp Configuration:

The term open- loop indicates that no feedback in any form is fed to the input from the output. When connected in open – loop, the op-amp functions as a very high gain amplifier. There are three open – loop configurations of op-amp namely,

1. differential amplifier
2. Inverting amplifier
3. Non-inverting amplifier

The above classification is made based on the number of inputs used and the terminal to which the input is applied. The op-amp amplifies both ac and dc input signals. Thus, the input signals can be either ac or dc voltage.

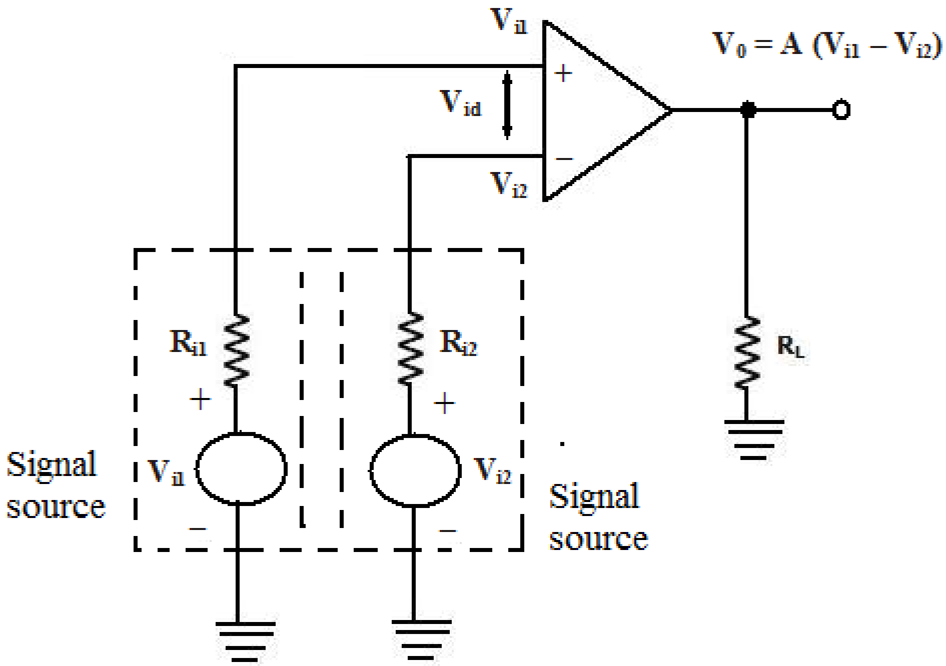
Open – loop Differential Amplifier:

In this configuration, the inputs are applied to both the inverting and the non- inverting input terminals of the op-amp and it amplifies the difference between the two input voltages. Figure shows the open-loop differential amplifier configuration.

The input voltages are represented by V_{i1} and $V_{i2.}$ The source resistance R_{i1} and R_{i2} are negligibly small in comparison with the very high input resistance offered by the op-amp, and thus the voltage drop across these source resistances is assumed to be zero. The output voltage V_0 is given by

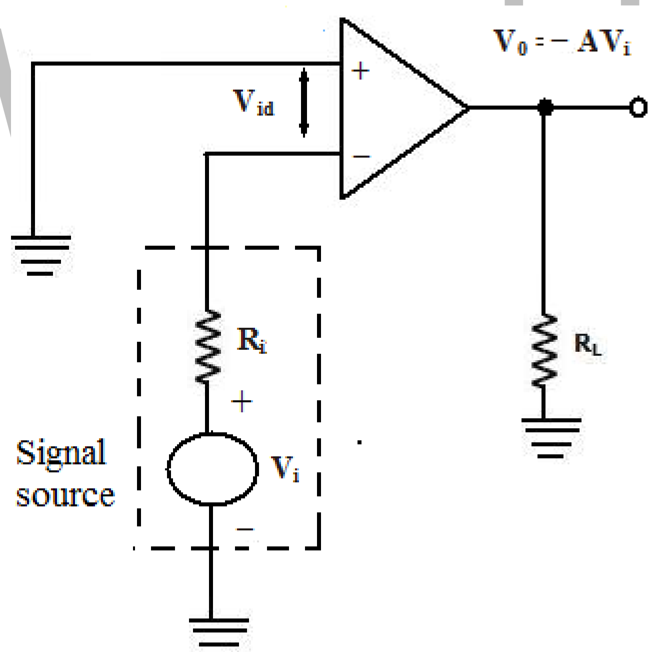
$V_0 = A(V_{i1} – V_{i2})$

where A is the large signal voltage gain. Thus the output voltage is equal to the voltage gain A times the difference between the two input voltages. This is the reason why this configuration is called a differential amplifier. In open – loop configurations, the large signal voltage gain A is also called open- loop gain A.



Open - loop Differential Amplifier

Inverting amplifier:



Open - loop Inverting Amplifier

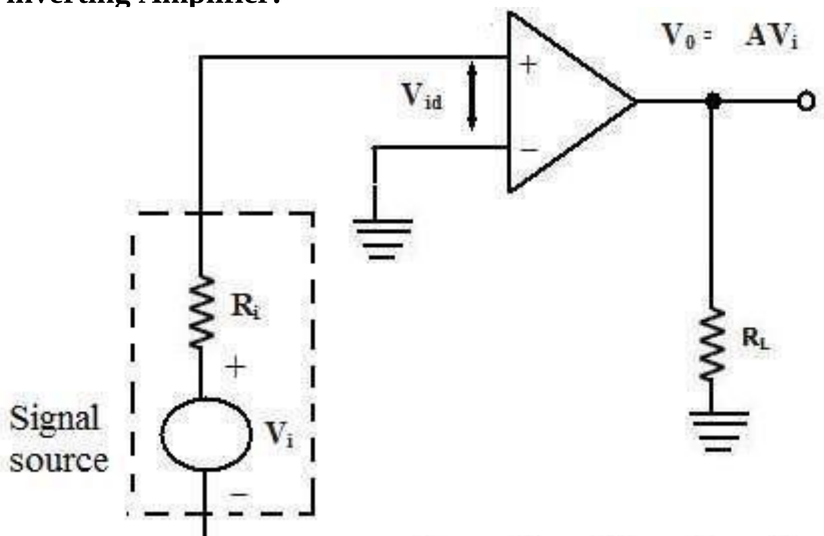
In this configuration the input signal is applied to the inverting input terminal of the op-amp and the non- inverting input terminal is connected to the ground. Figure shows the circuit of an open – loop inverting amplifier.

The output voltage is 180^0 out of phase with respect to the input and hence, the output voltage V_0 is given by,

$V_0 = -AV_i$

Thus, in an inverting amplifier, the input signal is amplified by the open- loop gain A and in phase – shifted by 180^0.

Non-inverting Amplifier:



Open - loop Non - Inverting Amplifier

Figure shows the open – loop non- inverting amplifier. The input signal is applied to the non- inverting input terminal of the op-amp and the inverting input terminal is connected to the ground.

The input signal is amplified by the open – loop gain A and the output is in-phase with input signal.

$V_0 = AV_i$

In all the above open- loop configurations, only very small values of input voltages can be applied. Even for voltages levels slightly greater than zero, the output is driven into saturation, which is observed from the ideal transfer characteristics of op-amp shown in figure. Thus, when operated in the open- loop configuration, the output of the op-amp is either in negative or positive saturation, or switches between positive and negative saturation levels. This prevents the use of open – loop configuration of op-amps in linear applications.

Limitations of Open – loop Op – amp configuration:

Firstly, in the open – loop configurations, clipping of the output waveform can occur when the output voltage exceeds the saturation level of op-amp. This is due to the very high open – loop gain of the op-amp. This feature actually makes it possible to a mplify very low frequency signal of the order of microvolt or even less, and the amplification can be achieved accurately without any distortion. However, signals of such magnitudes are susceptible to noise and the amplification for those application is almost impossible to obtain in the laboratory.

Secondly, the open – loop gain of the op – amp is not a constant and it varies with changing temperature and variations in power supply. Also, the bandwidth of most of the open- loop op amps is negligibly small. This makes the open – loop configuration of op-amp unsuitable for ac applications. The open – loop bandwidth of the widely used 741 IC is approximately 5Hz. But in almost all ac applications, the bandwidth requirement is much larger than this.

For the reason stated, the open – loop op-amp is generally not used in linear applications. However, the open – loop op amp configurations find use in certain non – linear applications such as comparators, square wave generators and astable multivibrators.

Closed – loop op-amp configuration:

The op-amp can be effectively utilized in linear applications by providing a feedback from the output to the input, either directly or through another network. If the signal feedback is out- of-phase by 180^0 with respect to the input, then the feedback is referred to as negative feedback or degenerative feedback. Conversely, if the feedback signal is in phase with that at the input, then the feedback is referred to as positive feedback or regenerative feedback.

An op – amp that uses feedback is called a closed – loop amplifier. The most commonly used closed – loop amplifier configurations are 1. Inverting amplifier (Voltage shunt amplifier) 2. Non-Inverting amplifier (Voltage – series Amplifier)

Inverting Amplifier:

The inverting amplifier is shown in figure and its alternate circuit arrangement is shown in figure, with the circuit redrawn in a different way to illustrate how the voltage shunt feedback is achieved. The input signal drives the inverting input of the op – amp through resistor R_1 .

The op – amp has an open – loop gain of A, so that the output signal is much larger than the error voltage. Because of the phase inversion, the output signal is 180^0 out – of – phase with the input signal. This means that the feedback signal opposes the input signal and the feedback is negative or degenerative.

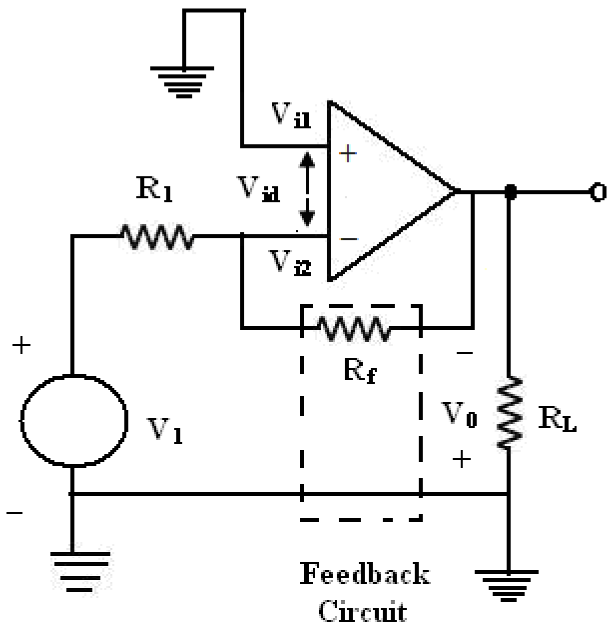
Virtual Ground:

A virtual ground is a ground which acts like a ground . It may not have physical connection to ground. This property of an ideal op – amp indicates that the inverting and non – inverting terminals of the op –amp are at the same potential. The non – inverting input is grounded for the inverting amplifier circuit. This means that the inverting input of the op –amp is also at ground potential. Therefore, a virtual ground is a point that is at the fixed ground potential (0V), though it is not practically connected to the actual ground or common terminal of the circuit.

The open – loop gain of an op – amp is extremely high, typically 200,000 for a 741. For ex, when the output voltage is 10V, the input differential voltage V_{id} is given by

Further more, the open – loop input impedance of a 741 is around 2MΩ. Therefore, for an input differential voltage of 0.05mV, the input current is only

Since the input current is so small compared to all other signal currents, it can be approximated as zero. For any input voltage applied at the inverting input, the input differential voltage V_{id} is negligibly small and the input current is ideally zero. Hence, the inverting input acts as a virtual ground. The term virtual ground signifies a point whose voltage with respect to ground is zero, and yet no current can



The expression for the closed – loop voltage gain of an inverting amplifier can be obtained from figure. Since the inverting input is at virtual ground, the input impedance is the resistance between the inverting input terminal and the ground. That is, $Z_i = R_1$. Therefore, all of the input voltage appears across R_1 and it sets up a current through R_1 that equals . The current must flowthrough R_f because the virtual ground accepts negligible current. The left end of R_f is ideally grounded, and hence the output voltageappears wholly across it. Therefore,

The input impedance can be set by selecting the input resistor R_1. Moreover, the above equation shows that the gain of the inverting amplifier is set by selecting a ratio of feedback resistor R_f to the input resistor R_1. The ratio R_f/R_1 can be set to any value less than or greater than unity. This feature of the gain equation makes the inverting amplifier with feedback very popular and it lends this configuration to a majority of applications.

Practical Considerations:

1. Setting the input impedance R_1 to be too high will pose problems for the bias current, and it is usually restricted to 10KΩ.
2. The gain cannot be set very high due to the upper limit set by the fain – bandwidth (GBW = A_v * f) product. The A_v is normally below 100.
3. The peak output of the op – amp is limited by the power supply voltages, and it is about 2V less than supply, beyond which, the op – amp enters into saturation.
4. The output current may not be short – circuit limited, and heavy loads may damage the op – amp. When short – circuit protection is provided, a heavy load may drastically distort the output voltage.

Practical Inverting amplifier:

The practical inverting amplifier has finite value of input resistance and input current, its open voltage gain A_0 is less than infinity and its output resistance R_0 is not zero, as against the ideal inverting amplifier with finite input resistance, infinite open – loop voltage gain and zero output resistance respectively.

Figure shows the low frequency equivalent circuit model of a practical inverting amplifier. This circuit can be simplified using the Thevenin's equivalent circuit shown in figure. The signal source Vi and the resistors R_1 and R_i are replaced by their Thevenin's equivalent values. The closed – loop gain A_V and the input impedance R_{if} are calculated as follows.

The input impedance of the op- amp is normally much larger than the input resistance R_1. Therefore, we can assume $V_{eq} \approx V_i$ and $R_{eq} \approx R_1$. From the figure we get,

$V_0 \; IR_0 \; AV_{id}$

and $V_{id} \; IR_f \; V_0 \; 0$

Substituting the value of V_{id} *from above eqn , we get,*

$V_0 \; 1 \; A \; I \; R_0 \; @AR_f$

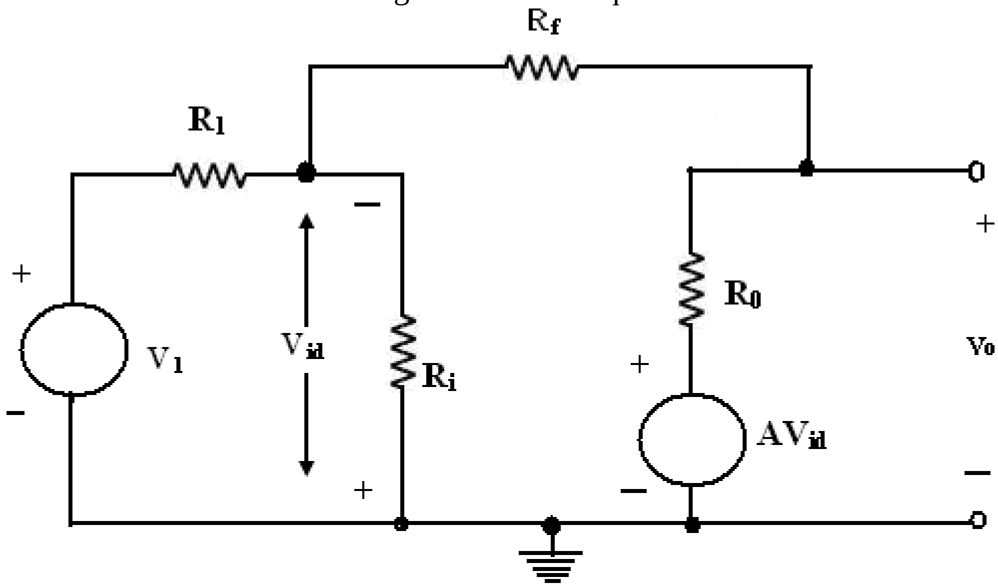
Also using the KVL , we get

$V_i \; I \; R_1 \; R_f \; V_0$

Substituting the value of I derived from above eqn and obtaining the closed loop gain A_v*, we get*

It can be observed from above eqn that when A>> 1, R_0 is negligibly small and the product AR_1 >> $R_0 + R_f$, the closed loop gain is given by

Which is as the same form as given in above eqn for an ideal inverter.

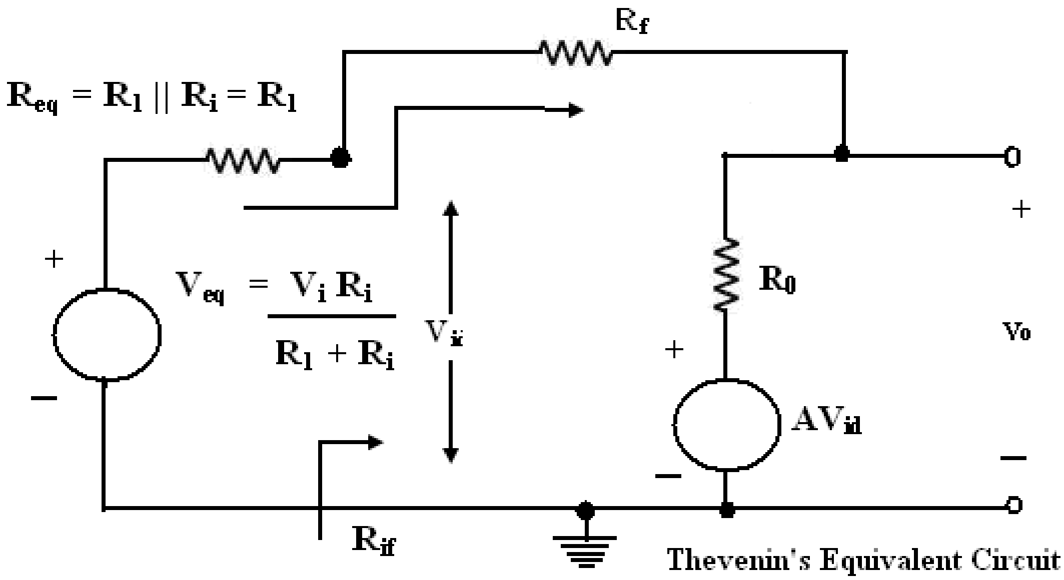


Equivalent Circuit of a Practical Inerting Amplifier

Input Resistance:
From figure we get,
Using KVL, weget,

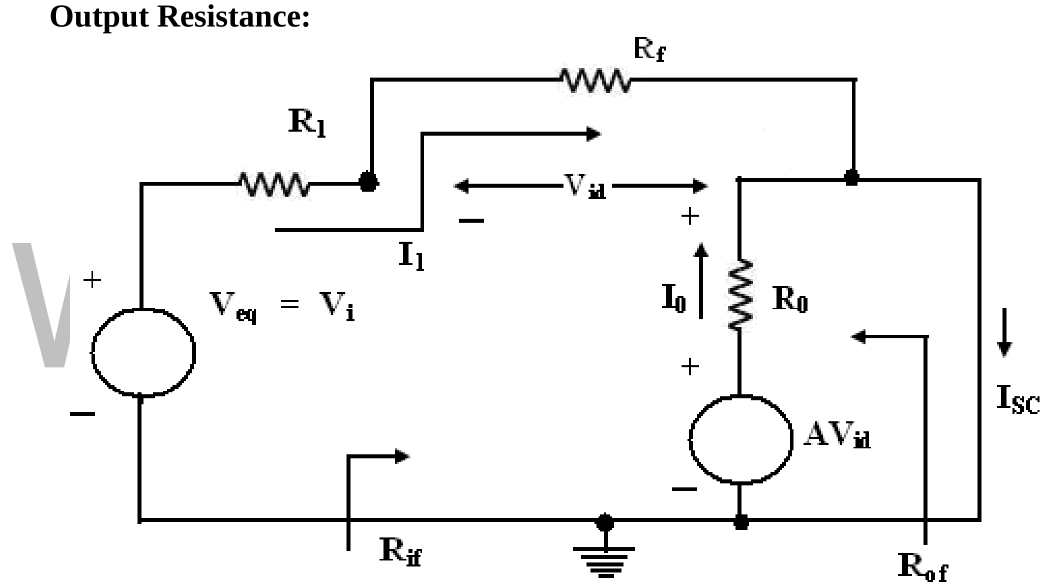
$$V_{id} - I_1 (R_f + R_0) + AV_{id} = 0$$

which can be simplified for R_{if} as



Thevenin's Equivalent Circuit

Output Resistance:



Equivalent circuit to determine Rof

Figure shows the equivalent circuit to determine R_{of} . The output impedance R_{of} without the load resistance factor R_L is calculated from the open circuit output voltage V_{oc} and the short circuit output current I_{SC} .

Non –Inverting Amplifier:

The non – inverting Amplifier with negative feedback is shown in figure. The input signal drives the non – inverting input of op-amp. The op-amp provides an internal gain A. The external resistors R_1 and R_f form the feedback voltage divider circuit with an attenuation factor of β. Since the feedback voltage is at the inverting input, it opposes the input voltage at the non – inverting input terminals, and hence the feedback is negative or degenerative.

The differential voltage V_{id} at the input of the op-amp is zero, because node a is at the same voltage as that of the non- inverting input terminal. As shown in figure, R_f and R_1 form a potential divider. Therefore,

V

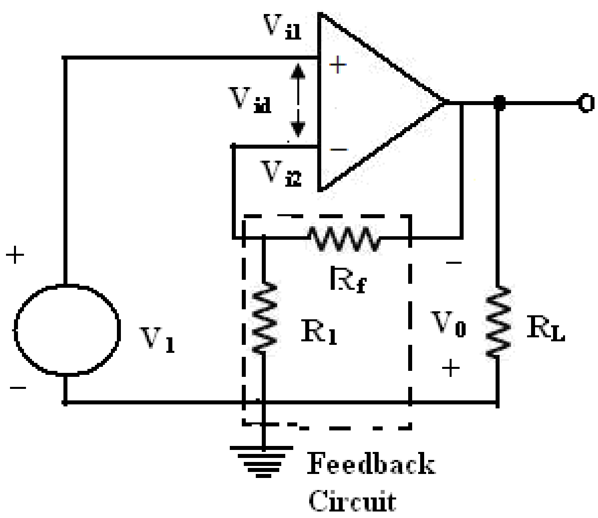
Since no current flows into the op-amp.

Eqn can be written as

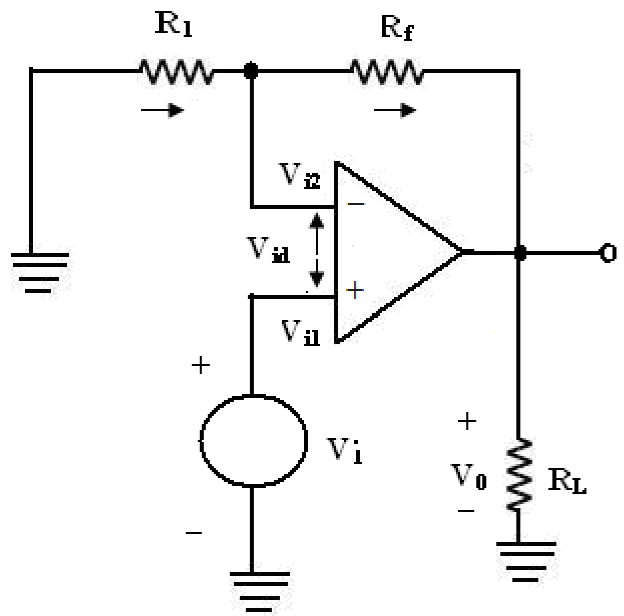
Hence, the voltage gain for the non – inverting amplifier is given by

Using the alternate circuit arrangement shown in figure, the feedback factor of the feedback voltage divider network is

From the above eqn, it can be observed that the closed – loop gain is always greater than one and it depends on the ratio of the feedback resistors. If precision resistors are used in the feedback network, a precise value of closed – loop gain can be achieved. The closed – loop gain does not drift with temperature changes or op – amp replacements.



Its alternate Circuit Arrangement



Closed Loop Non – Inverting Amplifier

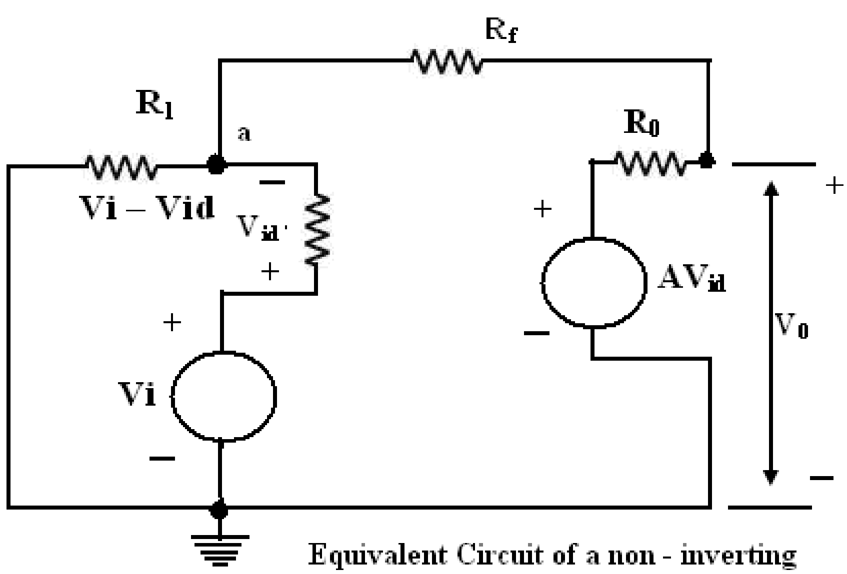
The input resistance of the op – amp is extremely large (approximately infinity,) since the op –

amp draws negligible current from the input signal.

Practical Non –inverting amplifier:

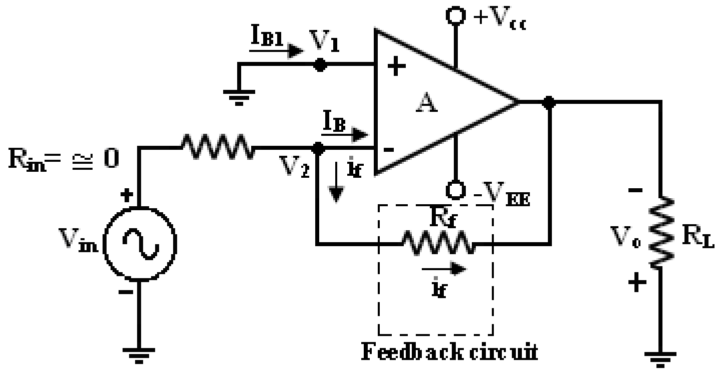
The equivalent circuit of a non- inverting amplifier using the low frequency

model is shownbelow in figure. Using Kirchhoff's current law at node a,



Equivalent Circuit of a non - inverting Amplifier using low frequency

Voltage Shunt Feedback Amplifier:[Inverting Amplifier]



The input voltage drives the inverting terminal, and amplified as well as inverted output signal also applied to the inverting input via feedback resistor R_F .

Note:

Non-inverting terminal is grounded and feedback circuit has R_F and extra resistor R_1 is connected in series with the input signal source Vin.

We derive the formula for

1. Voltage gain
2. Input and output resistance
3. Bandwidth
4. Total output offset voltage.

1. Closed – loop voltage gain A_F :

A_F of volt shunt feedback amplifier can be obtained by writhing KCL eqn at the input node V_2 .

$i_{in} = i_F + I_B$---------- (12.a)

Since R_i is very large, the input bias current is negligibly small.

i_{in} t i_F

(i.e) $\dfrac{Vin - V_2}{R_i} = \dfrac{V_2 - V_0}{R_F}$ (12.b)

Consider, from eqn,

$V_1 - V_2 = - V_0 / A$

Since $V_1 = 0V$

$V_2 = -V_0 / A$

Sub this value of V_2 in eqn (12.b) and rearranging,

$\dfrac{Vin + V_0 / A}{R_i} = \dfrac{-(V/A) - V_0}{R_F}$

$A_F = \dfrac{V_0}{Vin} = - \dfrac{AR_F}{R_1 + R_F + AR_1}$ (exact)----------(13)

The –ve sign indicates that the input and output signals are out of phase 180^0 . (or opposite polarities).

Because of this phase inversion the diagram is known as Inverting amplifier with feedback. Since the internal gain A of the op-amp is very large (α) , $AR_1 >> R_1 + R_F$, (i.e) eqn (13)

$A_F = V_0 / Vin = -R_F / R_1$ (Ideal)

To express eqn (13) in terms of eqn(6). To begin with, we divide both numerator and denominator of eqn (13) by $(R_1 + R_F)$

$A_F = AR_F / R_1 + R_F$

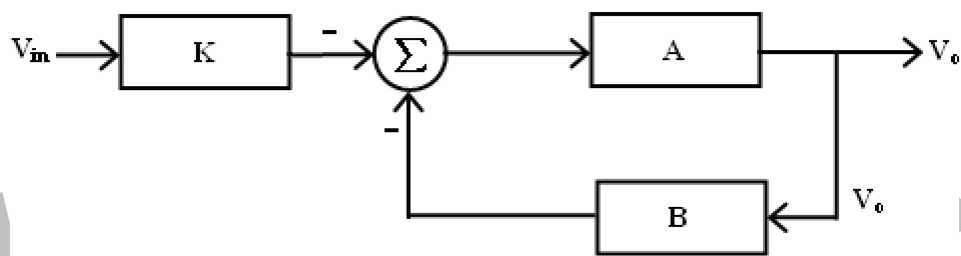
-----------------   ---(15)

$1 + AR_1 (R_1 + R_F)$

$A_F = - AR/ 1+AB)$

Where $K = R_F / (R_1 + R_F)$

$B = R_1 / (R_1 + R_F)$ Gain of feedback.



The comparison of eqn (15) with feedback (6) indicates that in addition to the phase inversion (-sign), the closed loop gain of the inverting amplifier in K times the closed loop gain of the Non-inverting amplifier where K< 1. To derive a ideal closed loop gain, we can use Eqn 15 as follows,

If AB >> 1, then (1+AB) = AB and $A_F = K/B = -R_F / R_1$ ------- (16)

2. Input Resistance with feedback:

Easiest method of finding the input resistance is to millerize the feedback resistor R_F.

(i.e) Split R_F in to its 2 Miller components as shown in fig.

In this circuit, the input resistance with feedback Rif is then

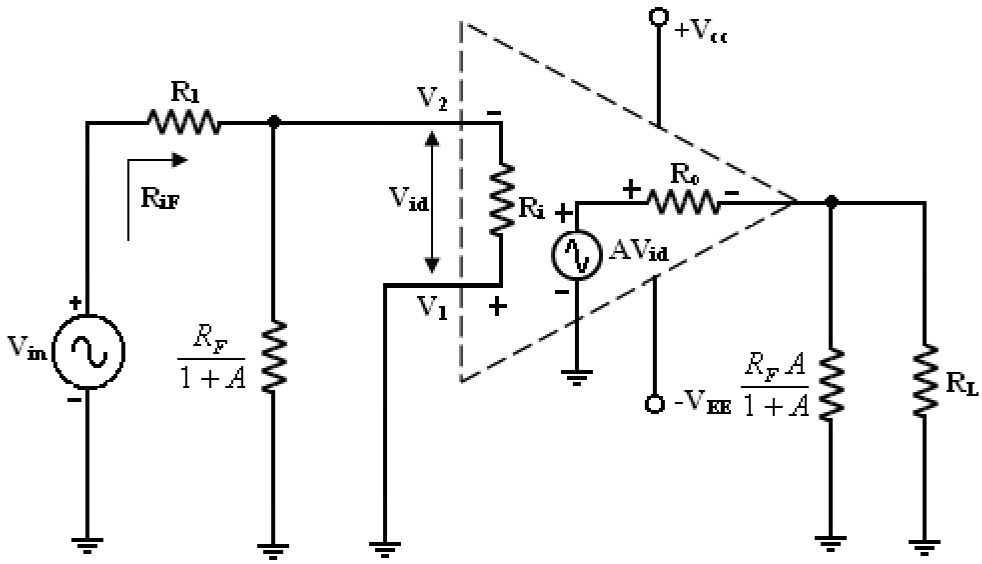
$Rif = R_1 + R_F$

----- || (Ri)----------(18)

1+A

Since Ri and A are very large.

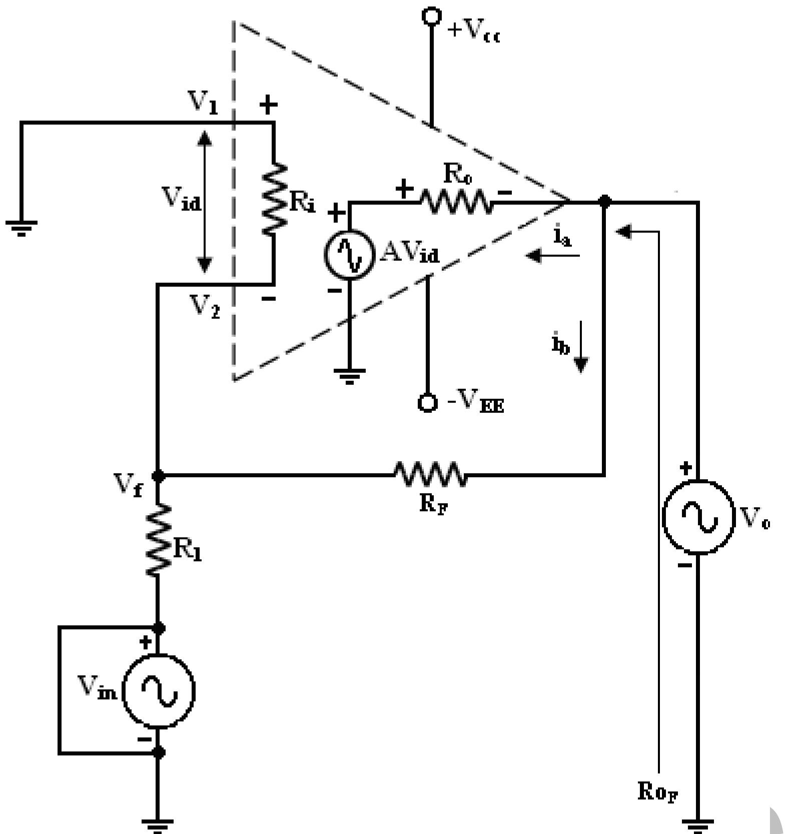
$R_1 + R_F$----- || (R_1) t 0Ω



1+A

3. Output Resistance with feedback:

The output resistance with feedback R_{OF} is the resistance measured at the output terminal of the feedback amplifier. Thevenin's circuit is exactly for the same as that of Non-inverting amplifier because the output resistance R_{OF} of the inverting amplifier must be identical to that of non – inverting amplifier.



R_0 = Output Resistance of the op-amp

A = Open loop volt gain of the op-amp

B = Gain of the feedback circuit.

4. Bandwidth with Feedback:

The gain Bandwidth product of a single break frequency op-amp is always constant.

Gain of the amplifier with feedback < gain without feedback

The bandwidth of amplifier with feedback f_F must be larger than that without feedback.

$f_F = f_0 (1+AB)$ -----------(21.a)

f_0 = Break frequency of the op-amp

$$= \frac{\text{unity gain Bandwidth}}{\text{Open- loop voltage gain}} = \frac{\text{UGB}}{A}$$

Sub this value of f_0 in eqn (21.a)

f_F = UGB------- (1+AB)A
f_F = UGB (K)------(21.b)A_F
Where K = $R_F/(R_1 + R_F)$; A_F = AK/1+AB

Eqn 10.b and 21.b => same for the bandwidth.

Same closed loop gain the closed loop bandwidth for the inverting amplifier is

< that of Non –inverting amplifier by a factor of K(<1)

5. Total output offset voltage with feedback:

When the temp & power supply are fixed, the output offset voltage is a function ofthe

gain of an op-amp.

Gain of the feedback < gain without feedback.

The output offset volt with feedback < without feedback.

Total Output offset Voltage with f/b =Total output offset volt without f/b- 1+AB

Vout = ±Vsat -------------- (22)1+AB

±Vsat = Saturation Voltage

A = open-loop volt

gain of the op-amp

B = Gain of the f/b

circuit

B= $R_1/(R_1 + R_F)$
In addition, because of the –ve f/b,
1. Effect of noise
2. Variations in supply voltages
3. Changes in temperature on the output voltage of inverting amplifier are reduced.