LINEAR INTEGRATED CIRCUITS

Unit-1

Table of Content

The Operational Amplifier

- An operational amplifier (op-amp) is a direct coupled high-gain amplifier usually consisting of one or more differential amplifier and followed by a level translator and an output stage.

- A direct-coupled amplifier is a type of amplifier in which the output of one stage of the amplifier is coupled to the input of the next stage in such a way to permit signals with zero frequency, also referred to as direct current to pass from input to output.

- Operational amplifier is abbreviated as op-amp.

Application of op-amp

- The operational amplifier was originally designed for performing mathematical operations such as addition, subtraction, multiplication, integration.
- It can also be used for amplification of dc as well as ac input signal, active filters, oscillators, comparators, regulator and other by addition of external suitable feedback components.

Op-amp symbol

- The circuit schematic of an op-amp is a triangle as shown in Fig.1.
- It has 2 input terminals and 1 output terminal.
- The terminal with a (-) sign is called inverting input terminal.
- The terminal with (+) sign is called non-inverting input terminal

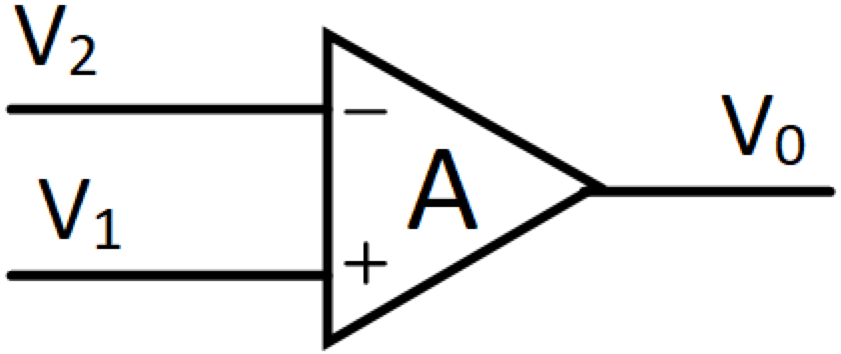


Fig.1. Schematic symbol for the op-amp

From the Fig.1.

V_1 = Voltage at the non-inverting input terminal (Volts).

V_2 = Voltage at the non-inverting input terminal (Volts).

V_0 = Output voltage (Volts).

All these voltages are measured with respect to ground.

A= Large signal voltage gain

Op-amp Packages

Basic op-amp diagram with supply voltage is shown in Fig.2.

- Op-amps have 5 basic terminals

➢2 input terminals

➢1 output terminal

➢2 power supply

- Positive power supply (V+)
- Negative power supply (V-)
- Power supply may range ± 5 V

 to ±22 V

Generally, ±15 V is used as power supply.

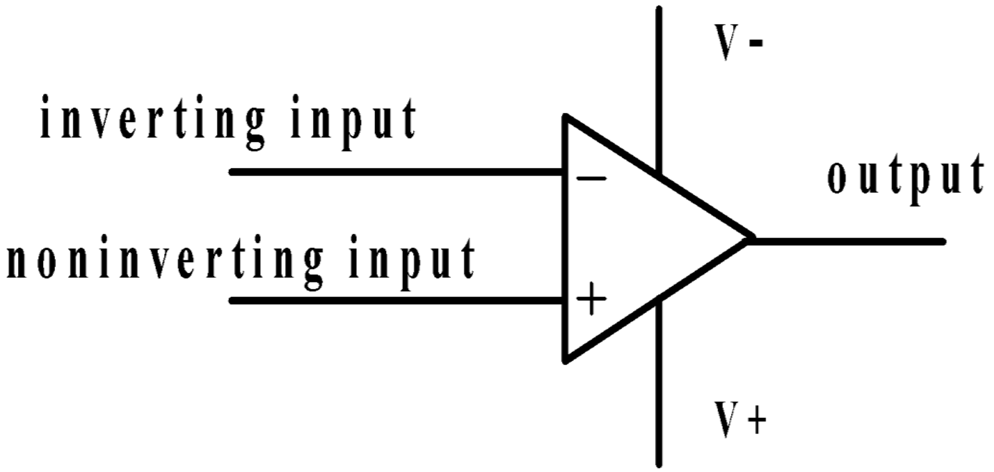


Fig. 2: Basic op-amp diagram with supply voltage

Op-amp packages

- There are 3 popular packages available:

(i) The flat package

(ii) The metal can or transistor (TO) package

(iii) The dual-in-line package (DIP) (8,12,14,16, 20 pins)

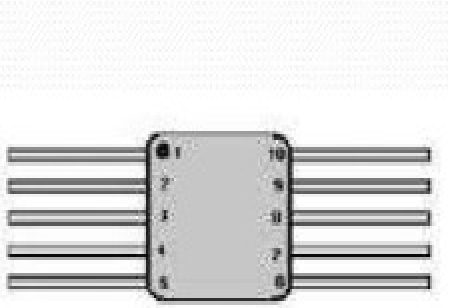


Fig. 3.a. Flat pack

Fig. 3.b. metal can package

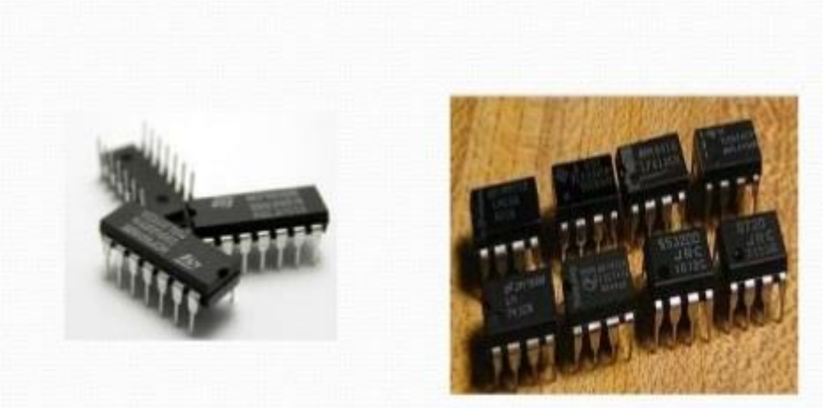


Fig. 3.c. Dual-in-line package (741)

Operational Amplifiers Pin configuration

The pin configuration of 8 pin mini DIP is shown as follows:

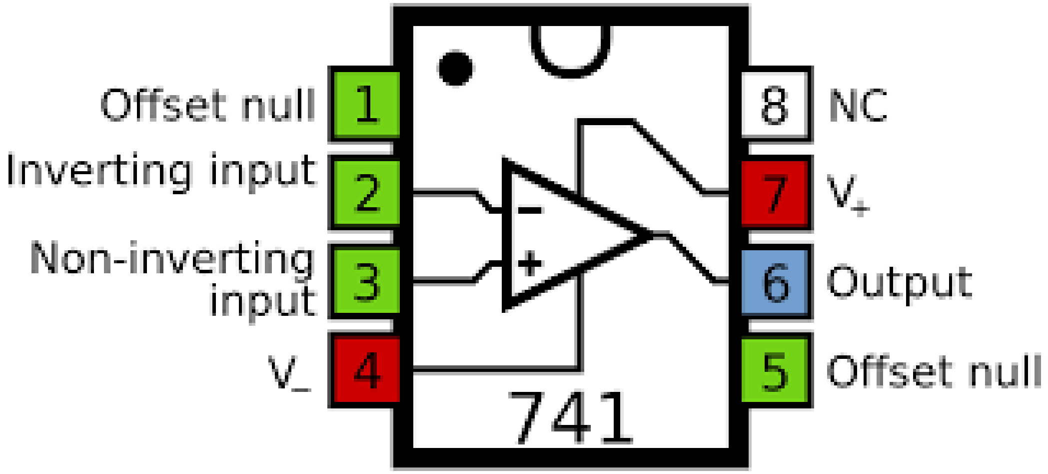


Fig. 4: Pin connection, LM741

Op-amp specifications

Temperature Ranges:

- All Ics are manufactured fall into one of 3 basic temperature grades:

(i) Military temperature range: -55^0 C to $+125^0$ C (or -55^0 C to $+85^0$ C)

(ii) Industrial temperature range: -20^0 C to $+85^0$ C (or -40^0 C to $+85^0$ C)

(iii) Commercial temperature range: 0^0 C to $+70^0$ C (or 0^0 C to $+75^0$ C)

Op-amp specifications (Cont.)

- 741 an internally compensated op-amp originally manufactured by Fairchild.
- Some of the well-known manufacturers of linear Ics are:

1. Fairchild---------------------------- μA, μAF
2. National semiconductor-------- LM, LH, LF, TBA
3. Motorola------------------------ MC, FC
4. RCA -------------------CA, CD
5. Texas Instruments------------- SN
6. Signetics--------------------N/S, NE/SE
7. Burn-Brown----------------BB

Op-amp specifications (Cont.)

- μA741 is also manufactured by other manufactures as follows:

1. National semiconductor----------LM741
2. Motorola------------------------------MC1741
3. RCA-------------------------------------CA3741
4. Texas Instruments------------------SN52741
5. Signetics-------------------------------N/S741

Some linear Ics are available in different classes such as A, C, E, S, and SC.

Op-amp specifications (Cont.)

➢741---------------Military graded op-amp

➢741C-------------Commercial grade op-amp

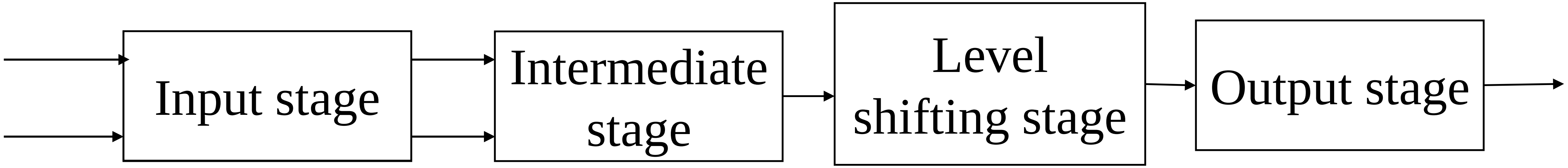
➢741A-------------Improved version of 741

➢741E-------------Improved version of 741C

➢741S-------------Military graded op-amp with higher slew rate

➢741SC-----------Commercial grade op-amp with higher slew rate

Block diagram representation of op-amp



Dual-input balanced-output differential amplifier

Dual-input unbalanced-output differential amplifier

Emitter follower using constant current source

Complementary symmetry push-pull amplifier

Fig. 5. Block diagram of an op-amp

- The op-amp consists of 4 stages namely input stage, intermediate stage, level shifting stage, output stage.

Block diagram representation of op-amp (Cont.)

- The input stage is the dual-input balanced output differential amplifier. The main purpose of the differential amplifier is to provide high gain to the difference mode signal and cancel the common mode signal. The input stage provides most of the voltage gain of the amplifier and also establishes the input resistance of the op-amp.
- The intermediate stage is driven by input stage. In most amplifiers the intermediate stage is dual input, unbalanced (single ended) output. Because, direct coupling is used, the dc voltage at the output of the intermediate stage is well above ground potential.
- Generally, the level translator (shifting) circuit is used after intermediate stage to shift the dc level at the output of the intermediate stage downward to zero volt with respect to ground. Here emitter follower using constant current source is used.

Block diagram representation of op-amp (Cont.)

- The final stage of op-amp is output stage, it consists of complementary symmetry push-pull amplifier. Due to the use of push-pull complementary amplifier, the output voltage swing increases, and current supplying capability of the op-amp raises. A well designed output stage also provides low output resistance.

Basic op-amp internal schematic

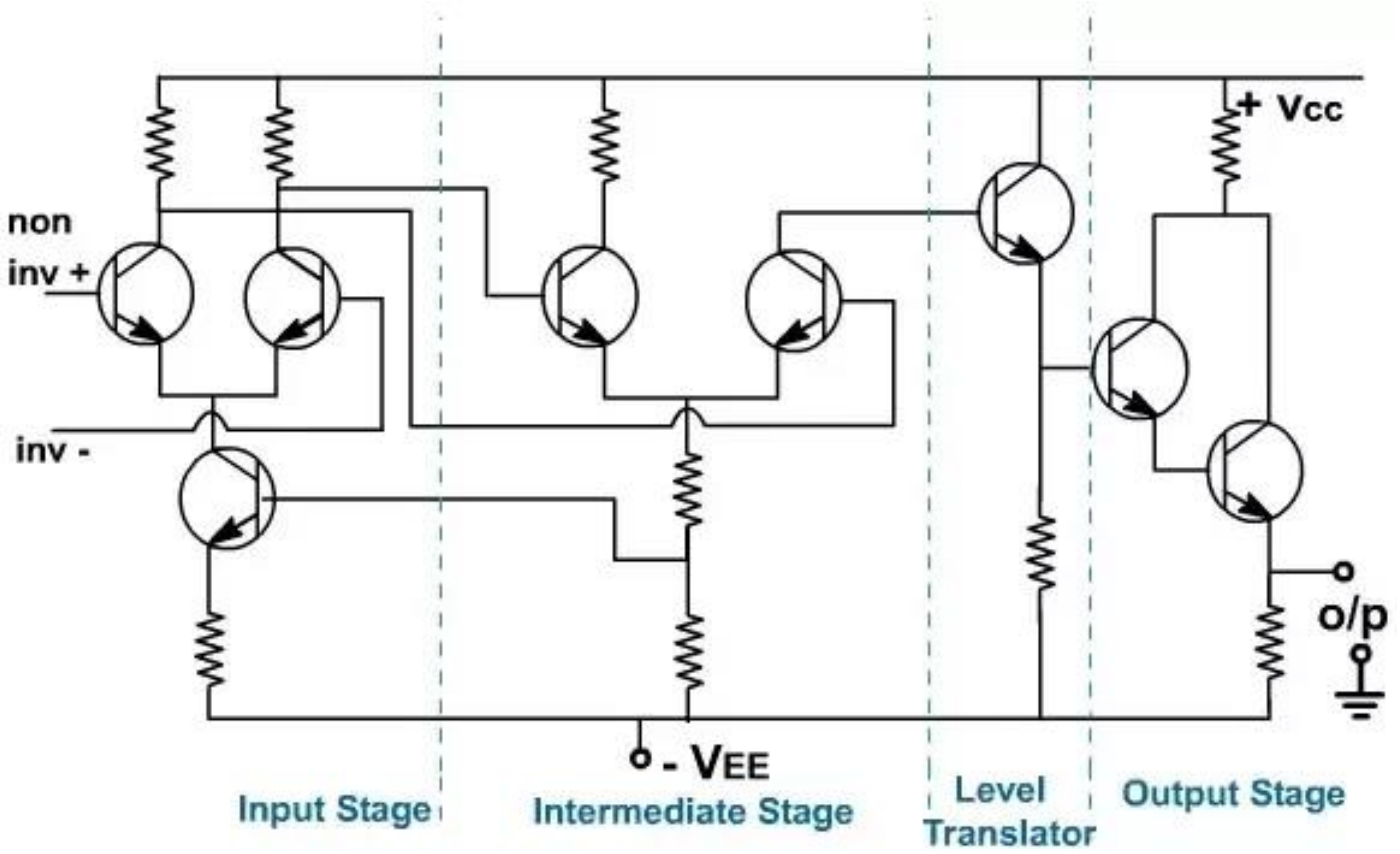


Fig. 6. Internal schematic of op-amp (MC 1435 op-amp)

The ideal op-amp

- An ideal op-amp would show the following characteristics:

1. Infinite voltage gain A

✓ for finite output voltage.

2. Infinite input resistance R_i

✓ so that almost any signal source can drive it and there is no loading of preceding stage.

3. Zero output resistance R_0

✓so that output can drive infinite number of other devices.

4. Zero output voltage when input voltage is zero.

5. Infinite bandwidth

✓so that any frequency from 0 to ∞ Hz can be amplified without attenuation.

The ideal op-amp (Cont.)

6. Infinite common-mode rejection ratio (CMRR)

✓so that output common-mode noise voltage is zero

✓CMRR is ratio of differential voltage gain to the common mode voltage gain.

7. Infinite slew rate (SR)

✓ so that output voltage changes occur simultaneously with input voltage changes.

✓Slew rate (SR) is defined as the maximum rate of change of output voltage per unit time and is expressed in volt per microsecond.

Equivalent circuit of an op-amp

- The equivalent circuit of an op-amp includes voltage gain (open loop voltage gain) (A), differential voltage (V_d) , output resistance (R_0), input resistance (R_i).
- The equivalent circuit of an op-amp is shown in Fig. 7.

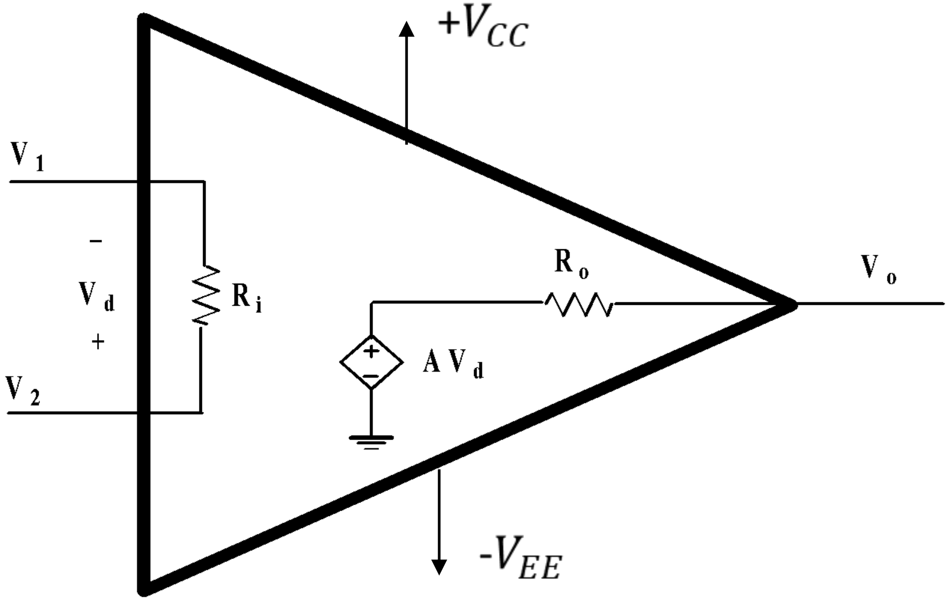


Fig.7. Equivalent circuit of an op-amp

Here, V_1 = input at inverting terminal
V_2 = input at non-inverting terminal
Output voltage= V_o =A V_d=A (V_2- V_1) ------------------- Equation—(1)
Equation (1) indicates that op-amp amplifies the difference between 2 input voltages.

Equivalent circuit of an op-amp (Cont.)

- The output can not exceed positive and negative saturation voltage.
- positive saturation voltage $(+V_{sat}) < +V_{cc}$ (positive power supply)
- negative saturation voltage

$(-V_{sat}) < -V_{EE}$ (negative power supply) .

- The ideal voltage transfer curve (assuming output offset voltage is zero) is shown in Fig. 8.

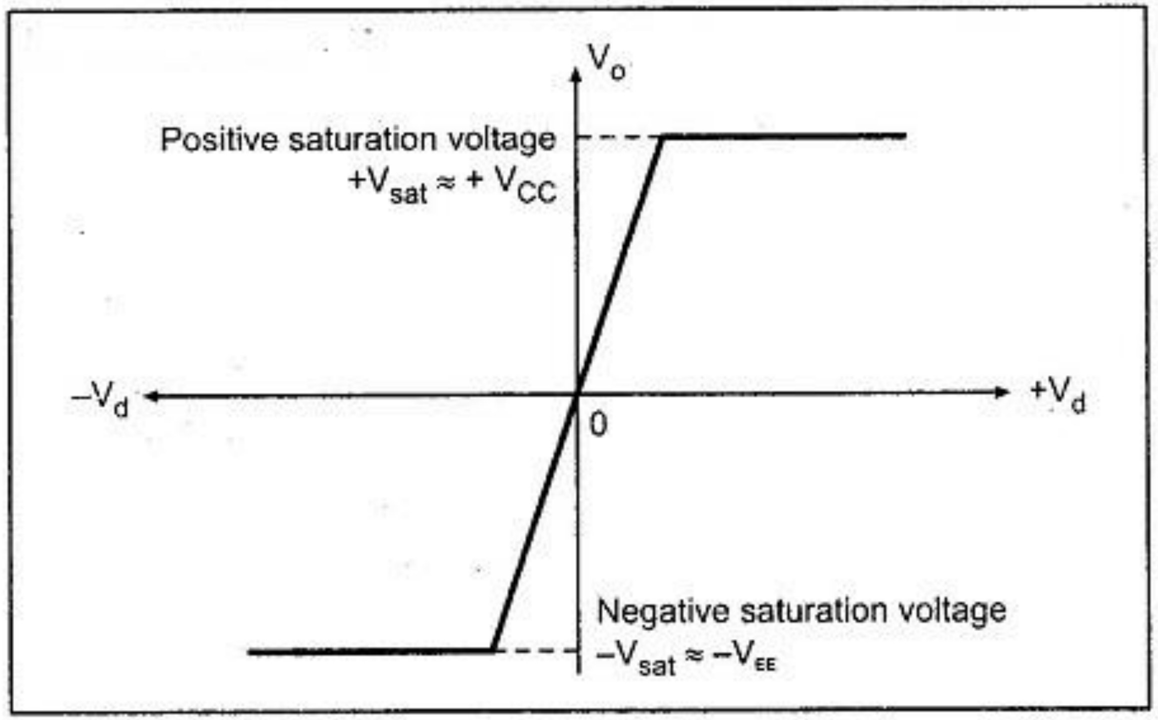


Fig. 8. Ideal voltage transfer curve

Open-loop configuration

- In open loop op-amp configuration, no connection either direct or via another network exists between the output and input terminals. (Output signal is not feedback to input).

There are 3 open-loop op-amp configurations:

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

Open-loop differential amplifier

- Op-amp amplifies both dc as well as ac input.
- The source resistance R_{i1} and R_{i2} are normally negligible compared to input resistance R_i.
- So the voltage drop across resistor assumed to be zero
- So, $V_1 = V_{i1}, V_2 = V_{i2}$
- Output voltage= $V_0 = AV_{id} = A(V_1 - V_2)$

  $=> V_0 = A(V_{in1} - V_{in2})$
- Here, gain A is referred as open-loop gain.

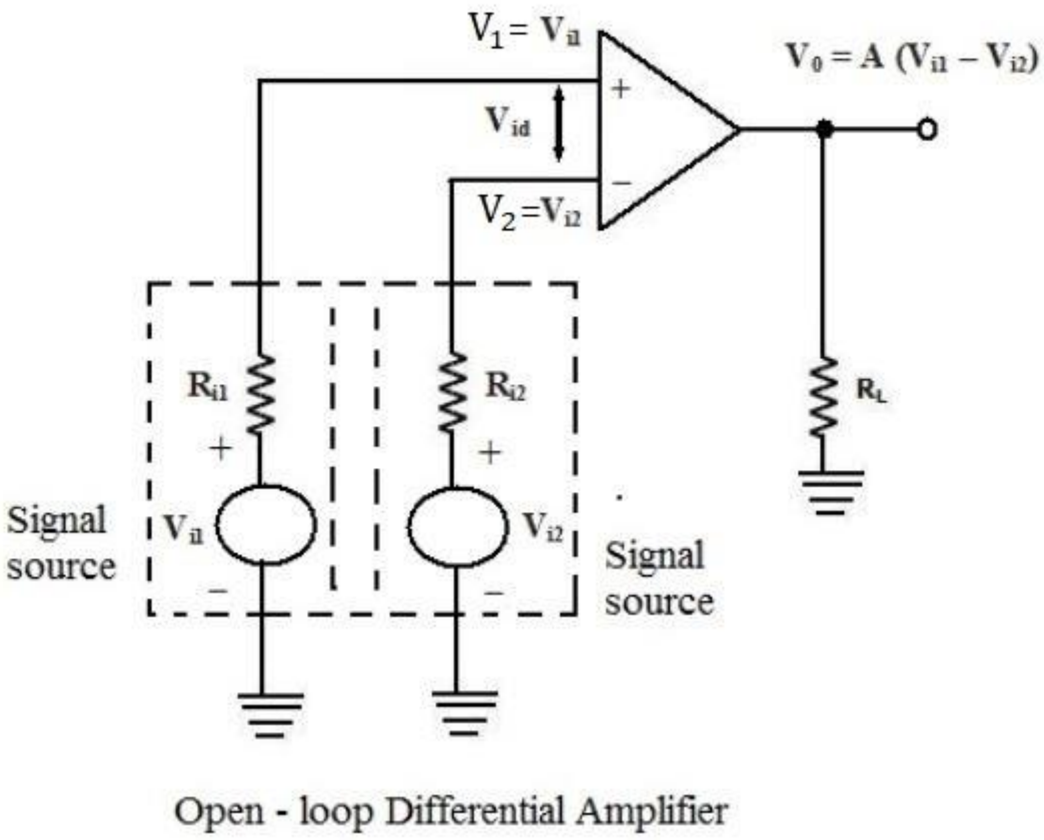


Fig. 9. Open-loop differential amplifier

Open-loop inverting amplifier

- Open-loop noninverting amplifier is shown in Fig. 10.
- From Fig. 10,
- $V_1 = 0, V_2 = V_i$
- Output voltage= $V_0 = AV_{id}$= $A(V_1 - V_2)$

  =>$V_0 = A(0 - V_i) = -A\,V_i$
- The negative sign indicates that the output of phase with respect to input by 180^0 or is of opposite polarity.
- Thus in inverting amplifier, the input signal is amplified by gain A and also inverted at output

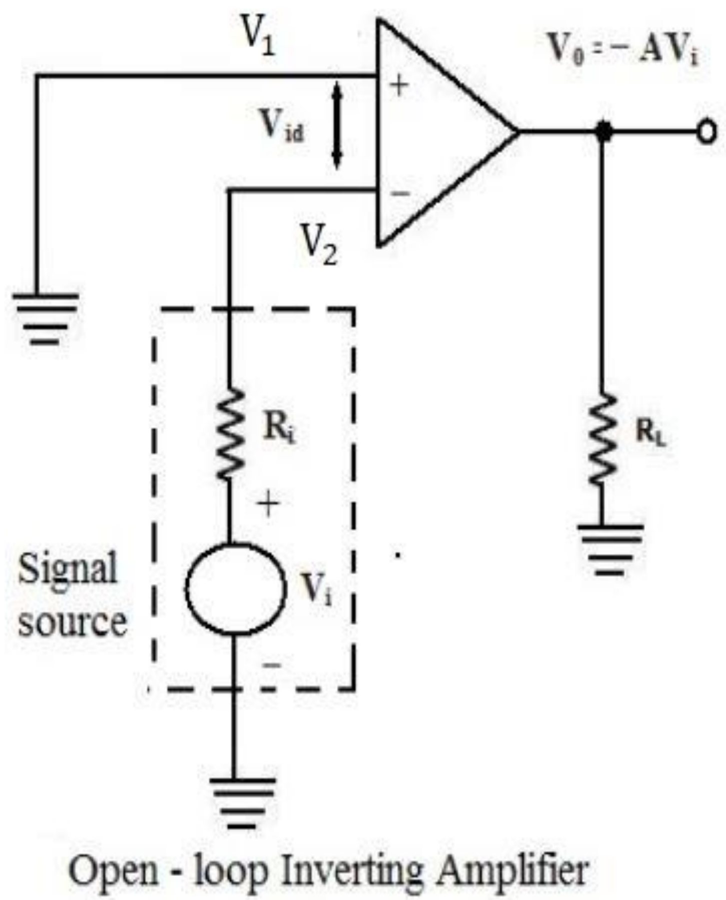


Fig. 10. Open-loop inverting amplifier

Open-loop non inverting amplifier

- Open-loop noninverting amplifier is shown in Fig. 11.
- From Fig. 11,
- $V_1 = V_i, V_2 = 0$
- Output voltage= $V_0 = AV_{id}$= $A(V_1 - V_2)$

=>$V_0 = A(V_i - 0) = A\, V_i$

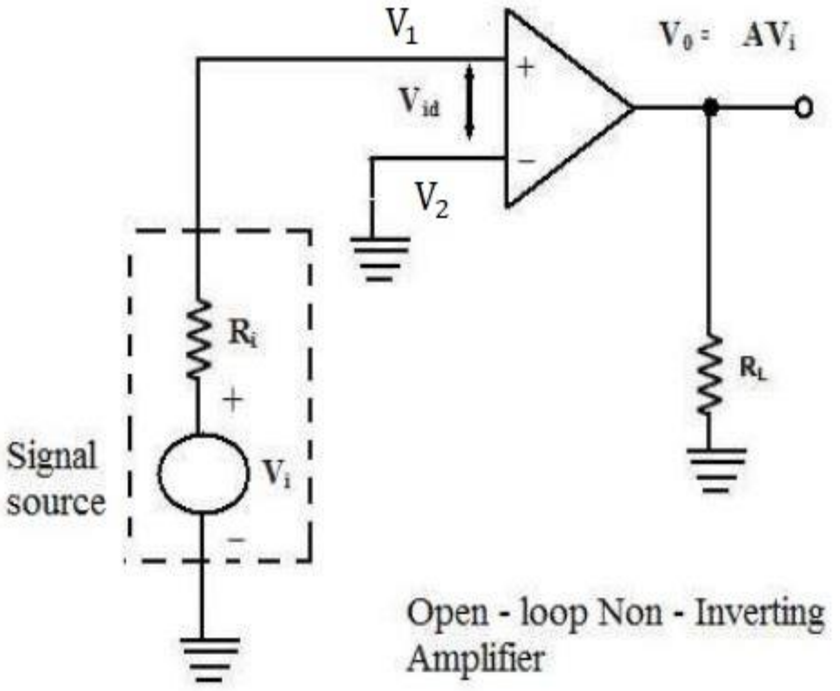


Fig. 11. Open-loop non-inverting amplifier

Problems

1. Q. Determine the output voltage for the open-loop inverting amplifier, if:

a. Input voltage=20 mV dc.

b. Input voltage=-50 µV peak sine wave

Assume op-amp is 741 (saturation voltage ± 14 V, A=2,00,000).

Ans:-

a. $V_0 = -A\ V_i$=-2,00,000X20X10^{-3}=-400 V

So, output voltage is -14V.

b. $V_0 = -A\ V_i$=-2,00,000X(-50)X10^{-6}=10 V

So, output voltage is 10 V.

Closed loop configurations (feedback in ideal op-amp)

- Open loop gain of an op-amp can be very high.
- This very high gain is no real use to us as it makes the amplifier both unstable and hard to control.
- The utility of an op-amp can be greatly increased by providing negative feedback. (Connecting output to the inverting terminal).
- The output in this case is not driven into saturation and circuit behaves in linear manner.
- For the feedback circuit for simplification, 2 assumptions considered.

(i) The current drawn by either of input terminals (non-inverting and inverting) is negligible.

(ii) The differential input voltage (V_d) between non-inverting and inverting input terminal is essentially zero (V_d=0)

Closed loop configurations (feedback in ideal op-amp) (Cont.)

There are 4 closed loop op-amp configurations are available.

1. Inverting amplifier
2. Non-inverting amplifier
3. Voltage follower
4. Differential amplifier

Inverting amplifier

The inverting amplifier is shown in Fig. 12.
Here, $R_1 = input\ resistance$,
R_f = feedback resistance
As we have considered 2 assumption for closed loop configuration
(i) $V_d = 0 \Rightarrow V_1 - V_2 = 0$,
As V_1=0, So, $V_2 = 0$. This is known as virtual ground.
(ii) The current drawn by either of input terminals (non-inverting and inverting) is negligible.

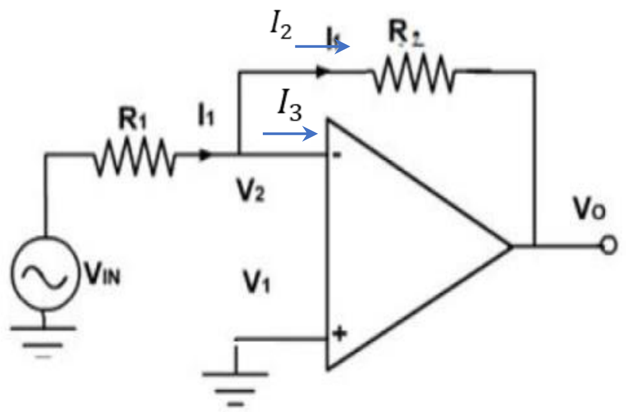


Fig.12. Inverting amplifier

Inverting amplifier (Cont.)

Applying KCL at point V_2

$I_1 = I_2 + I_3$ As $I_3 = 0$

$\Rightarrow \frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_0}{R_f}$ As $V_2 = 0$

$\Rightarrow \frac{V_{in}}{R_1} = \frac{-V_0}{R_f}$ => $V_0 = \frac{-R_f}{R_1} V_{in}$

$\Rightarrow$So, Output voltage= $V_0 = \frac{-R_f}{R_1} V_{in}$

- Closed loop gain of inverting amplifier

$= A_{CL} = \frac{V_0}{V_{in}} = \frac{-R_f}{R_1}$

- The negative sign indicate phase shift of 180^0.
- To avoid loading effect, R_1 should be large.

Non-inverting amplifier

The noninverting amplifier is shown in Fig. 13.

Here, $R_1 = input\ resistance$,

R_f = feedback resistance

As we have considered 2 assumption for closed loop configuration

$(i) V_d = 0 \Rightarrow V_1 - V_2 = 0$,

As $V_1 = V_{in}$, So, $V_2 = V_{in}$.

(ii) The current drawn by either of input terminals (non-inverting and inverting) is negligible. So, $I_3 = 0$.

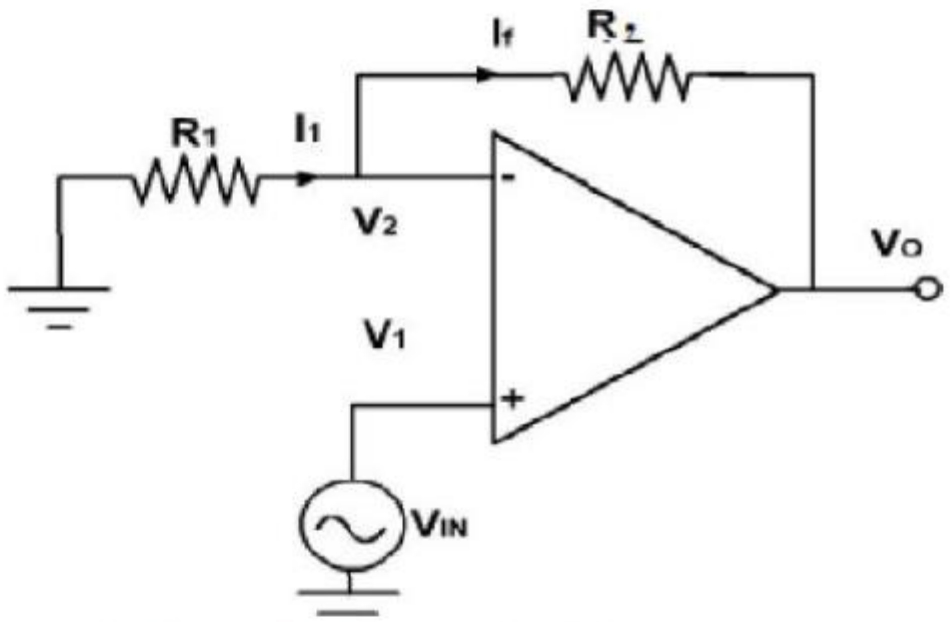


Fig.13. Non-inverting amplifier

Non-inverting amplifier (Cont.)

Applying KCL at point V_2

$I_2 = I_1 + I_3$ As $I_3 = 0$

$\Rightarrow \frac{V_0 - V_2}{R_f} = \frac{V_2 - 0}{R_1}$ As $V_2 = V_{in}$

$\Rightarrow \frac{V_0 - V_{in}}{R_f} = \frac{V_{in}}{R_1}$ => $V_0 = (1 + \frac{R_f}{R_1})\ V_{in}$

$\Rightarrow$So, Output voltage= $V_0 = (1 + \frac{R_f}{R_1})\ V_{in}$

- Closed loop gain of noninverting amplifier

$= A_{CL} = \frac{V_0}{V_{in}} = (1 + \frac{R_f}{R_1})$

Voltage follower

The voltage follower circuit is shown in Fig. 14.
In this circuit, $R_f = 0, R_i = \infty$.
Voltage across A is V_2 and B is V_1
As $V_d = 0 \Rightarrow V_1 - V_2 = 0$,
As $V_1 = V_{in}$, So, $V_2 = V_{in}$.
So, $V_0 = V_2 = V_{in}$
$\Rightarrow$So, Output voltage= $V_0 = V_{in}$
Closed loop gain of voltage follower
$= A_{CL} = \frac{V_0}{V_{in}} = 1$

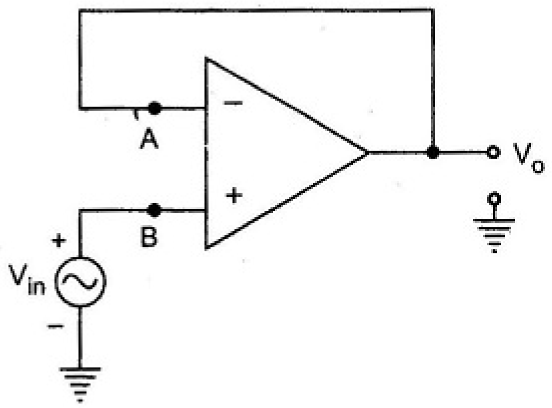


Fig.14. Voltage follower

Review of data sheet of an op-amp

- The various electrical parameters supplied in the data sheets are as follows:

1. Input offset voltage:

➢It is the voltage that must be applied between the input terminals of an op-amp to nullify the output.

➢Since this voltage could be positive or negative, its absolute value is listed on the data sheet.

➢For 741C, maximum value of input offset voltage is 6 mV.

2. Input offset current:

➢The algebraic difference between current in negative input and positive input is referred to as input offset current.

➢It is 200 nA maximum for 741C.

Review of data sheet of an op-amp (Cont.)

3. Input bias current:

- The average of the currents entering into the negative input and positive input terminal of op-amp is called input bias current.
- Its value is 500 nA for 741C.

4. Input resistance:

- This is the differential input resistance as seen at either of the input terminals with the other terminal connected to ground.
- For 741C, the input resistance is 2 MΩ.

Review of data sheet of an op-amp (Cont.)

<u>5. Input capacitance:</u>

- It is the equivalent capacitance that can be measured at either of the input terminal with the other terminal connected to ground.

<u>6. Offset voltage adjust range:</u>

- For 741C offset voltage adjustment range is ± 15 mV.

<u>7. Input voltage range:</u>

- This is the common-mode voltage that can be applied to both input terminals without disturbing the performance of an op-amp.
- For 741C is the range of ± 13 mV.

Review of data sheet of an op-amp (Cont.)

8. Common-mode rejection ratio (CMRR):

- For 741C, CMRR is typically 90 dB. $R_S \leq 10\ K\Omega$.
- The higher the value of CMRR, better is the matching between 2 input terminals and smaller the output common-mode voltage.

9. Supply Voltage rejection ratio:

- The change in op-amp's input offset voltage due to variations in supply voltage is called supply voltage rejection ratio.
- Some manufacturer use the term like power supply rejection ratio (PSRR) or power supply sensitivity (PSS).
- For 741C, SVRR=150 $\mu V/V$

Review of data sheet of an op-amp (Cont.)

10. Large signal voltage gain:

- Voltage gain=$\frac{Output\ voltage}{differential\ input\ voltage}$
- Since amplitude of output of voltage is much larger than differential input voltage.
- The voltage gain is large signal voltage gain.
- For 741C, typical value is 2,00,000. under the test condition $R_L \geq 2\ K\Omega$

11. Output voltage swing:

- The output voltage swing indicates the value of positive and negative saturation voltage of an op-amp, and never exceeds the supply voltage V^+ and V^-.
- For 741C, the output voltage swing is guaranteed to be between +13 V and -13 V for $R_L \geq 2\ K\Omega$

Review of data sheet of an op-amp (Cont.)

<u>12. Output resistance:</u>

- Output resistance R_0 is the resistance measured between the output terminal of the op-amp and the ground.
- It is 75 Ω for the 741C op-amp.

<u>13. Output short circuit current:</u>

- This is the current that may flow if an op-amp gets shorted accidentally.
- The short circuit current I_{SC} for 741C is 25 mA.
- This means that the built in short circuit protection is guaranteed to withstand 25 mA of current.

<u>14. Supply current:</u>

- Supply current I_S is the current drawn by op-amp from the power supply.
- It is 2.8 mA for 741C.

Review of data sheet of an op-amp (Cont.)

15. Power consumption:

- This gives the amount of quiescent power ($v_i = 0\ V$) that must be consumed by the op-amp so as to operate properly.
- It is 85 mW for 741C.

16. Transient response:

- Rise time overshoot (go past can intended stopping or turning point) are 2 characteristic of the transient response of any circuit.
- For 741C, rise time is 0.3 µsec, and overshoot is 5%.

17. Slew rate:

- Op-amp 741C has a low slew rate ($0.5 {}^{V}/_{\mu s}$)
  and there fore can not be used for high frequency application

DC Characteristics of Op-amp

DC Characteristics of op-amp:

An ideal op-amp draws no current from the source and It is response is also independent of temperature.

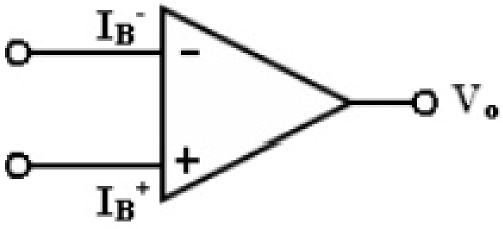
- But a real op-amp does not work this way.
- Current is taken from the input source into the op-amp inputs.
- Two inputs responds differently to current and voltage due to mismatch in transistor
- A real op-amp also shifts it is operation with temperature
- The non –ideal dc characteristics that add error components to the dc output voltage are:

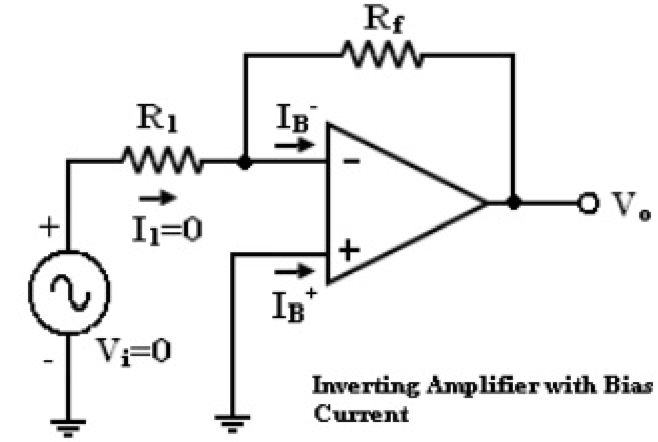
1. Input bias current
2. Input offset current
3. Input offset voltage
4. Thermal drift

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 (I_B^- & I_B^+ respectively).
- the transistors ar … e not … to internal imbal … puts.
- … cify the input bia …





Inverting Amplifier with Bias Current

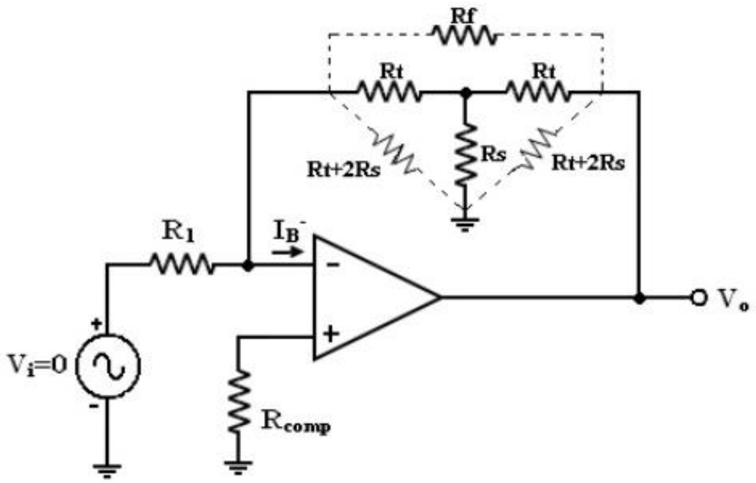
Input offset current

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

$$|I_{os}| = I_B^+ - I_B^-$$

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 $V_i = 0$.



$$V_1 = I_B^+ R_{comp}$$

And $$I_1 = V_1/R_1$$

KCL at node =a' gives,

Again

$$V_0 = I_2 R_f - V_1$$

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

$$V_o = 1M\Omega \ X \ 200nA$$

$$V_o = 200mV \text{ with } V_i = 0$$

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).

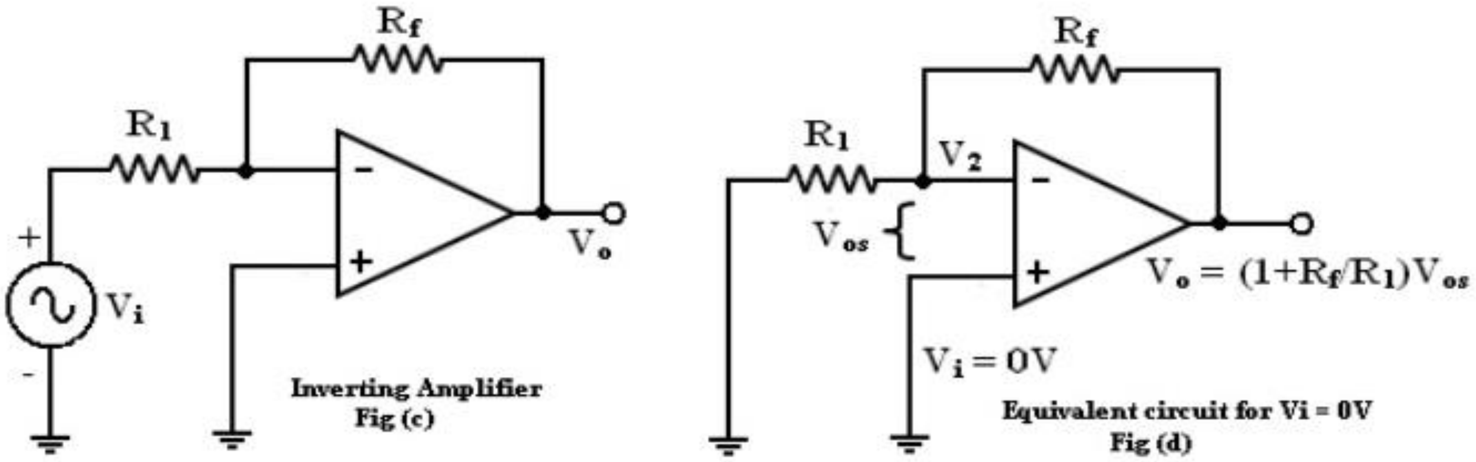
The T-network provides a feedback signal as if the network were a single feedback resistor.

Input offset voltage

In Spite 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 ($V_o = 0$).



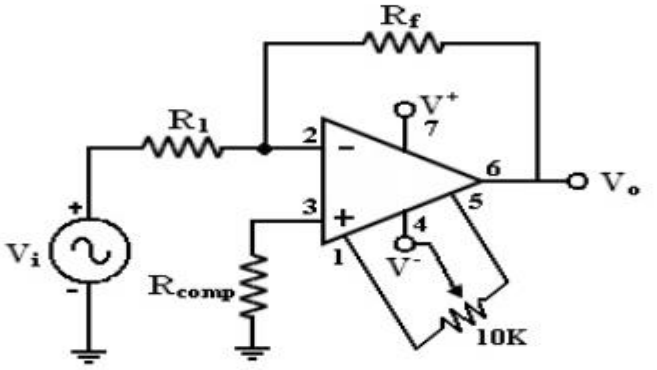
Total output offset voltage

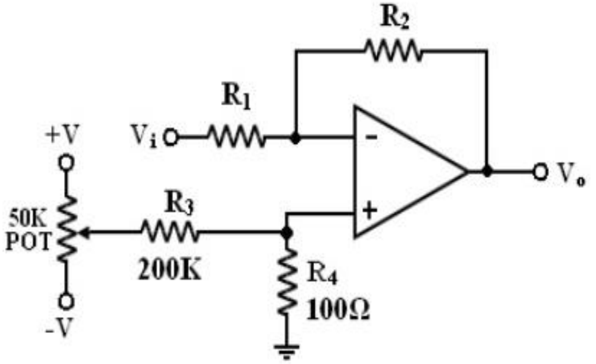
The total output offset voltage VOT could be either more or less than the offset voltage produced at the output due to input bias current (I_B) or input offset voltage alone(V_{os}).

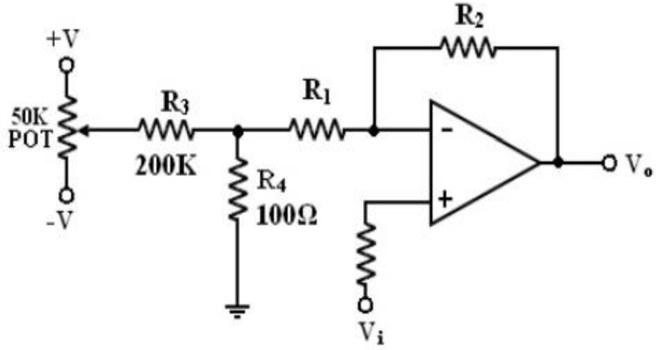
This is because I_B and V_{os} could be either positive or negative with respect to ground. Therefore the maximum offset voltage at the output of an inverting and non-inverting amplifier (figure b, c) without any compensation technique used is given by many op-amp provide offset compensation pins to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







Thermal drift

Bias current, offset current, and offset voltage change with temperature

A circuit carefully nulled at 25ºC may not remain. So when the temperature rises to 35ºC. This is called drift.

Offset current drift is expressed in nA/ºC.

These indicate the change in offset for each degree Celsius change in temperature.

AC Characteristics of Op-amp

AC Characteristics

- For small signal sinusoidal applications, ac characteristics of op-amp should be known:

1. Frequency response
2. Slew rate

I. Frequency response

- Ideally, an op-amp should have infinite bandwidth i.e., gain of op-amp remains same for frequencies.
- The practical op-amp gain decreases at higher frequencies.
- The reason for gain roll-off is due to the capacitive component in the equivalent circuit of op-amp.
- The capacitance is due to the physical characteristics of the device (BJT or FET) used and internal construction of op-amp.

- For an op-amp with only one break frequency, all the capacitors effect can be represented by single capacitor C as shown in figure.
- There is one pole $R_o C$ and one -20dB/decade roll-off comes into effect.

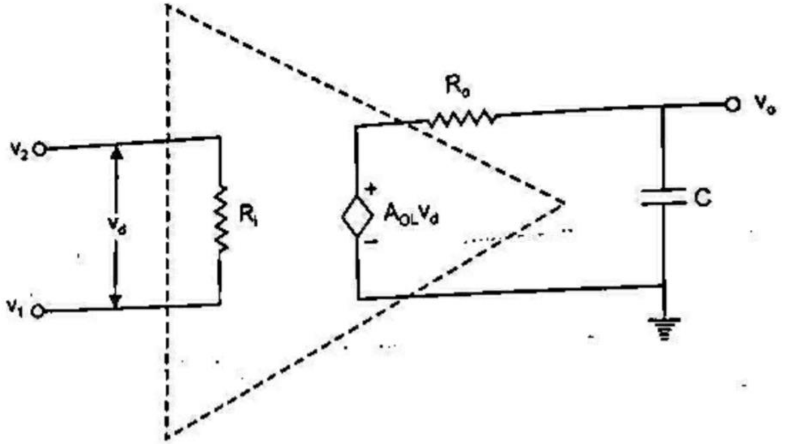


Fig 1: High frequency model of op-amp with single corner frequency.

- The open loop voltage gain of an op-amp with only one corner frequency is obtained from figure 1.

$$v_o = \frac{-jX_c}{R_o - jX_c} A_{OL} v_d$$

$$A = \frac{v_o}{v_d} = \frac{A_{OL}}{1 + j\,2\pi f R_o C}$$

$$A = \frac{A_{OL}}{1 + j(f/f_1)}$$

where

$$f_1 = \frac{1}{2\pi R_o C}$$

- The magnitude and phase angle of open loop voltage gain are:

$$|A| = \frac{A_{Ol}}{\sqrt{1 + (f/f_1)^2}}$$

$$\emptyset = -tan^{-1}(f/f_1)$$

- The magnitude and phase responses are shown in figure 2.

1. For frequency $f \ll f_1$, the magnitude of gain is 20 log A_{OL} $in\ dB$.
2. At frequency $f = f_1, the\ gain\ is\ 3dB\ down\ the\ dc\ value\ of\ A_{OL}. The\ frequency f_1$ is called corner frequency.
3. For $f \gg f_1, the\ gain\ rolls - off\ at\ the\ rate\ of\ -20dB/decade$ or -6dB/octave.

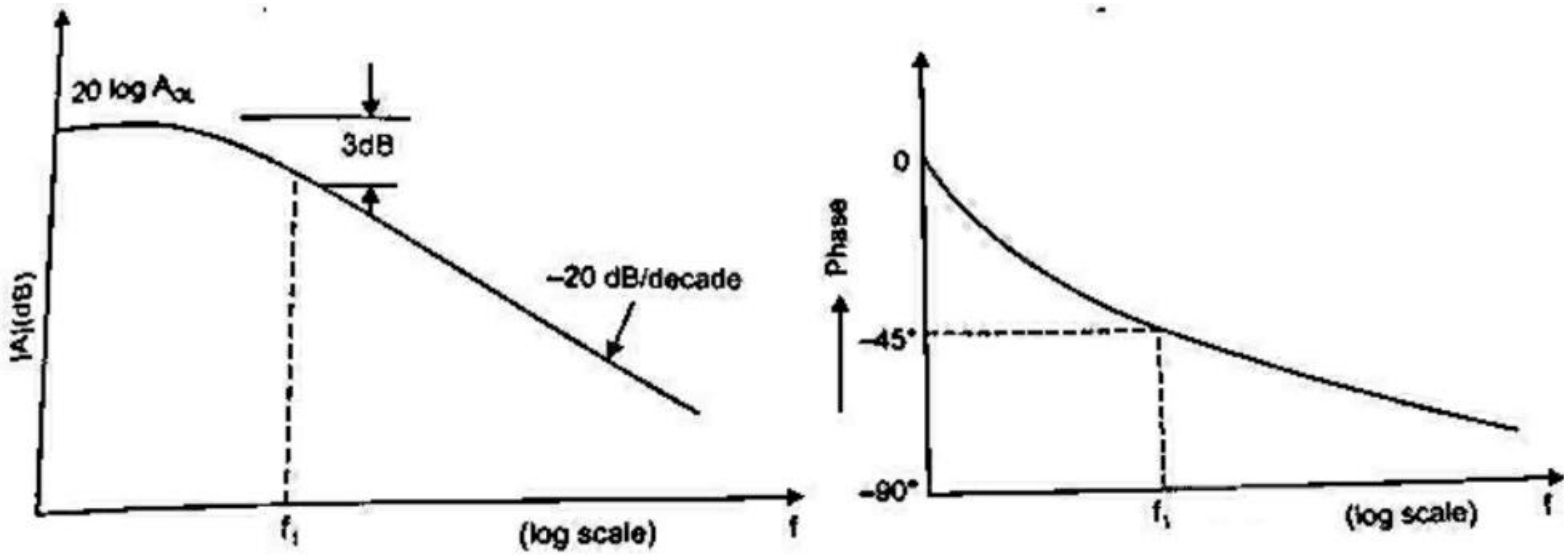


Fig 2: Open loop magnitude and phase characteristics for an op-amp with single break frequency

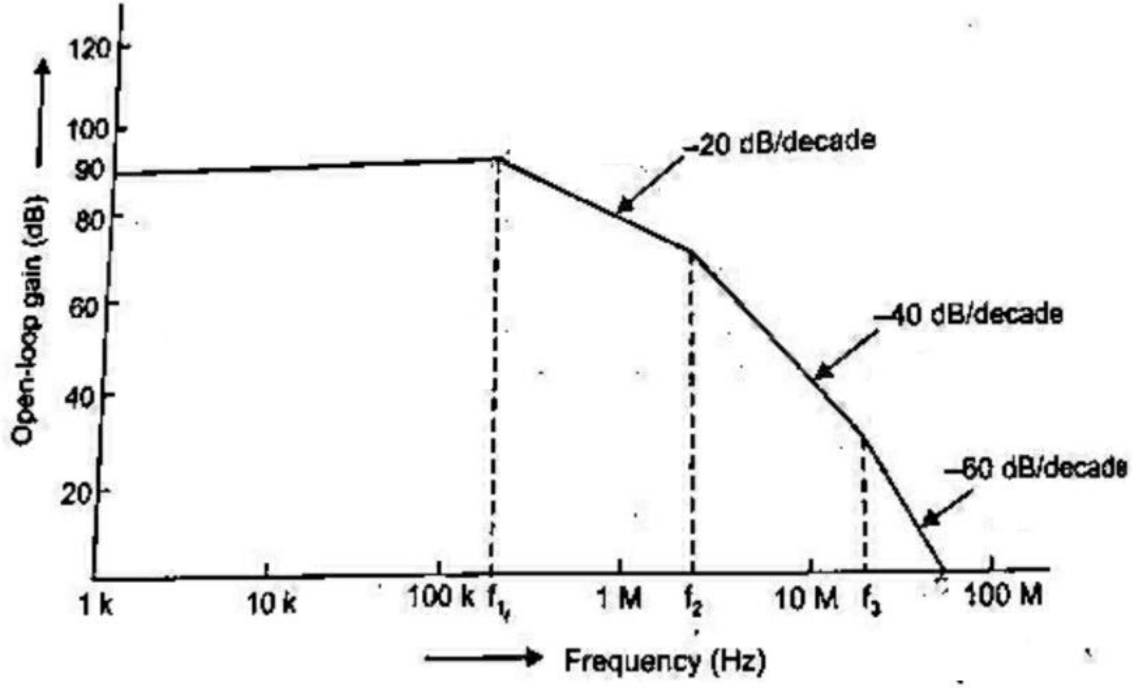
- The phase angle is zero at frequency *f=0.*
- At corner frequency, the phase angle is -45 degrees and at infinite frequency the phase angle is -90 degrees.
- The voltage transfer function is s-domain can be written as:

$$A = \frac{A_{OL}}{1 + j(f/f_1)} = \frac{A_{OL}}{1 + j(\omega/\omega_1)}$$

$$= \frac{A_{OL} \cdot \omega_1}{j\omega + \omega_1} = \frac{A_{OL} \cdot \omega_1}{s + \omega_1}$$

- A practical op-amp, has number of stages and each stage produces a capacitive component. Thus there will be different break frequencies due to number of RC pole pairs. The transfer function of an op-amp with three break frequencies:
- $$A = \frac{A_{OL}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}; 0< f_1< f_2< f_3$$

Transfer function: $A = \frac{A_{OL}\omega_1\omega_2\omega_3}{(s+\omega_1)(s+\omega_2)(s+\omega_3)}$ with $0<\omega_1< \omega_2 < \omega_3$



II. Stability of an Op-Amp

- Op-amps are rarely used in open loop configurations because of its high gain. The feedback affects the frequency response.
- Consider an op-amp amplifier using resistive feedback as shown in figure.
- Using the concept of negative feedback, the closed loop transfer function is:

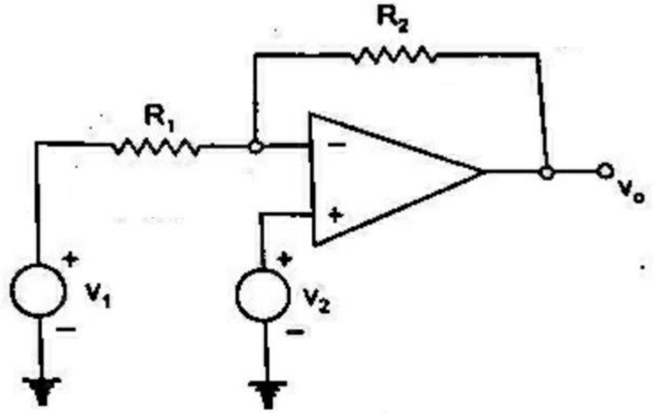
$$A_{CL} = \frac{A}{1 + A\beta} \text{ ,} where\ A\ is\ open\ loop\ voltage\ geain\ and\ \beta\ is\ feedback\ ratio.$$

- If $(1 + A\beta)$=0, the circuit becomes unstable with sustained oscillations.

$$1 + A\beta = 0$$

Or $1 - (-A\beta) = 0 \Rightarrow -A\beta = 1$

- $|A\beta| = 1\ and\ \lfloor -A\beta = 0\ or\ \lfloor A\beta = \pi.$



- Since op-amp is connected in inverting mode, it provides a phase shift of 180 degrees at low frequencies.
- At high frequencies, due to each corner frequency, an additional phase shift of maximum -90 degrees can take place in open loop gain A. For two corner frequencies, a maximum of phase shift associated with gain A is -180 degrees.
- Thus, at high frequencies, for some value of β, the magnitude of $A\beta$ becomes unity when A has an additional phase shift of 180 degrees making total phase shift zero.
- Then the amplifier oscillates leading to instability.
- The condition for instability means unbounded output i.e.,

$$(1 + A\beta) < 1 \quad \text{or} \quad A\beta < 0$$

III. **Frequency Compensation**

- For larger bandwidth and lower closed loop gain, suitable compensation techniques are used. Two types of compensation provided: (1) External (2) Internal

(1) External frequency compensation

The compensating network alters the open loop gain so that the roll-off is -20 dB/decade over a wide range of frequencies.

1.1 Dominant pole compensation

Let *A* be the uncompensated transfer function of an op-amp.

$$A = \frac{A_{ol}\omega_1\omega_2\omega_3}{(s+\omega_1)(s+\omega_2)(s+\omega_3)}$$

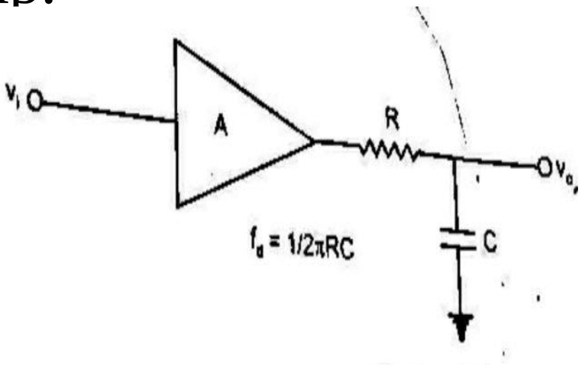
Introduce a dominant pole by adding RC network in series with op-amp.

The compensated transfer function is:

$$A' = \frac{v_o}{v_i} = A \cdot \frac{\frac{-j}{\omega C}}{R - \frac{j}{\omega C}} = \frac{A}{1 + j\frac{f}{f_d}}$$

where

$$f_d = \frac{1}{2\pi RC}$$



- Therefore

$$A' = \frac{A_{OL}}{\left(1 + j\frac{f}{f_d}\right)\left(1 + j\frac{f}{f_1}\right)\left(1 + j\frac{f}{f_2}\right)\left(1 + j\frac{f}{f_3}\right)}$$

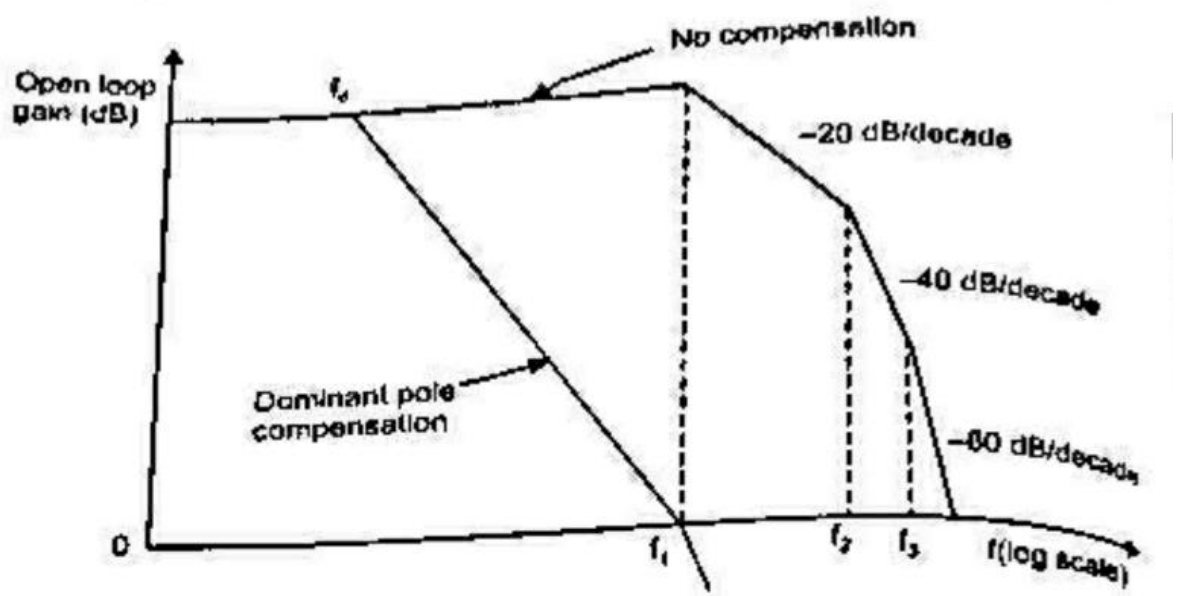
$$f_d < f_1 < f_2 < f_3,$$

- Usually f_d *is selected so that the compensated transfer function* A passes through 0dB at the pole f_1 *of uncompensated* A.

- The frequency f_d can be found graphically by having A' *pass through* $0dB$ *at* f_1 *with a slope of* -20dB/dec. The value of C is calculated as

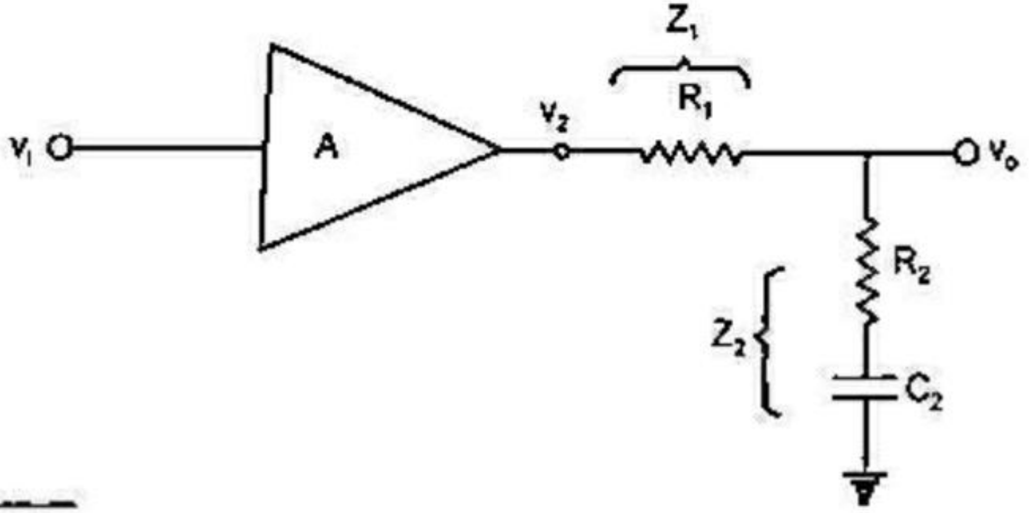
$$f_d = \frac{1}{2\pi RC}$$

- The disadvantage is that it reduces the open loop bandwidth drastically.



1.2 Pole zero compensation

- The uncompensated transfer function is altered by adding both pole and a zero.
- The zero should be at higher frequency than pole
- For the compensating network,



$$\frac{v_o}{v_2} = \frac{Z_2}{Z_1 + Z_2} = \frac{R_2}{R_1 + R_2} \cdot \frac{1 + j\frac{f}{f_1}}{1 + j\frac{f}{f_o}}$$

where $Z_1 = R_1$, $Z_2 = R_2 + \frac{1}{j\omega C_2}$, $f_1 = \frac{1}{2\pi R_2 C_2}$, $f_o = \frac{1}{2\pi (R_1 + R_2) C_2}$

- The compensating network is designed to produce a zero at the first corner frequency f_1 of the uncompensated transfer function *A*. The zero will cancel the effect of the pole at f_1.

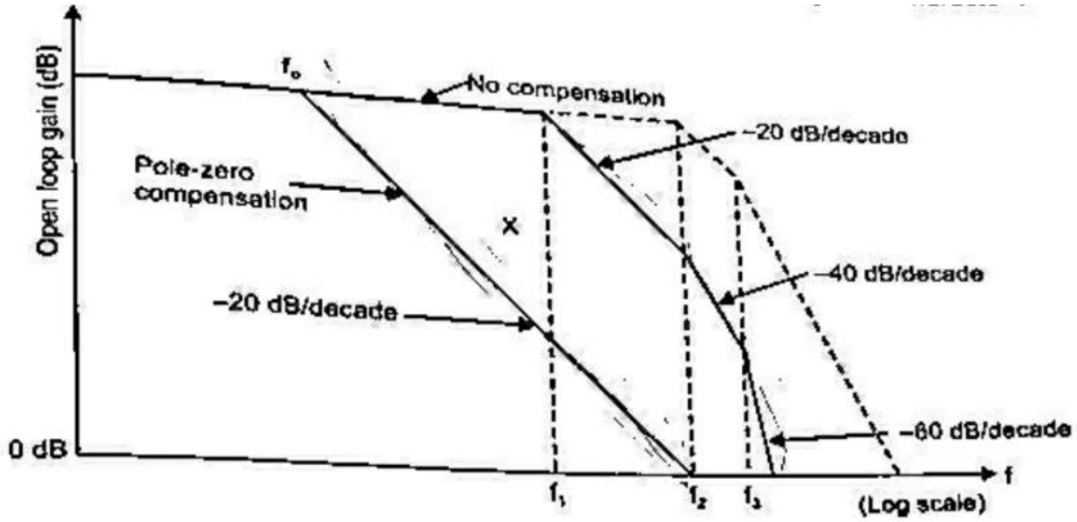
- The pole of the compensating network at f_0' is selected so that the compensated transfer function A' passes through 0dB at the second corner frequency f_2 of the uncompensated transfer function A.
- The frequency can be found graphically by having A' passes through 0dB at f_2 with a slope of -20dB/dec. Assuming the compensating network doesn't load the amplifier i.e., $R_2 \gg R_{1,}\ then$

$$A' = \frac{v_o}{v_i} = \frac{v_o}{v_2}\cdot\frac{v_2}{v_i} = A\cdot\frac{R_2}{R_1+R_2}\cdot\frac{1+j\frac{f}{f_1}}{1+j\frac{f}{f_o}}$$

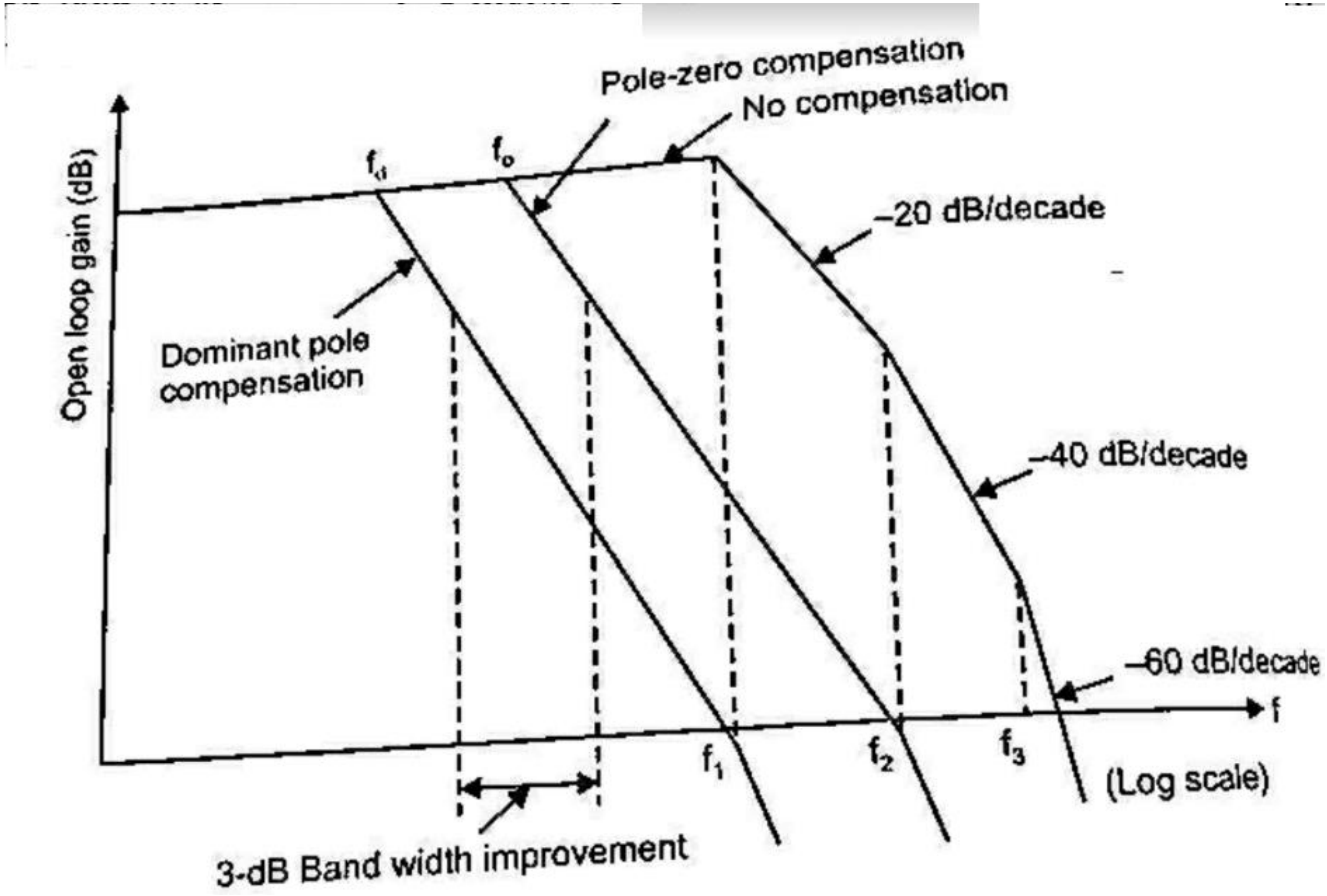
$$= \frac{A_{OL}}{\left(1+j\frac{f}{f_1}\right)\left(1+\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)}\cdot\frac{R_2}{R_1+R_2}\cdot\frac{1+j\frac{f}{f_1}}{1+j\frac{f}{f_o}}$$

$$= \frac{A_{OL}}{\left(1+j\frac{f}{f_o}\right)\left(1+j\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)}$$

$$0 < f_o < f_1 < f_2 < f_3$$



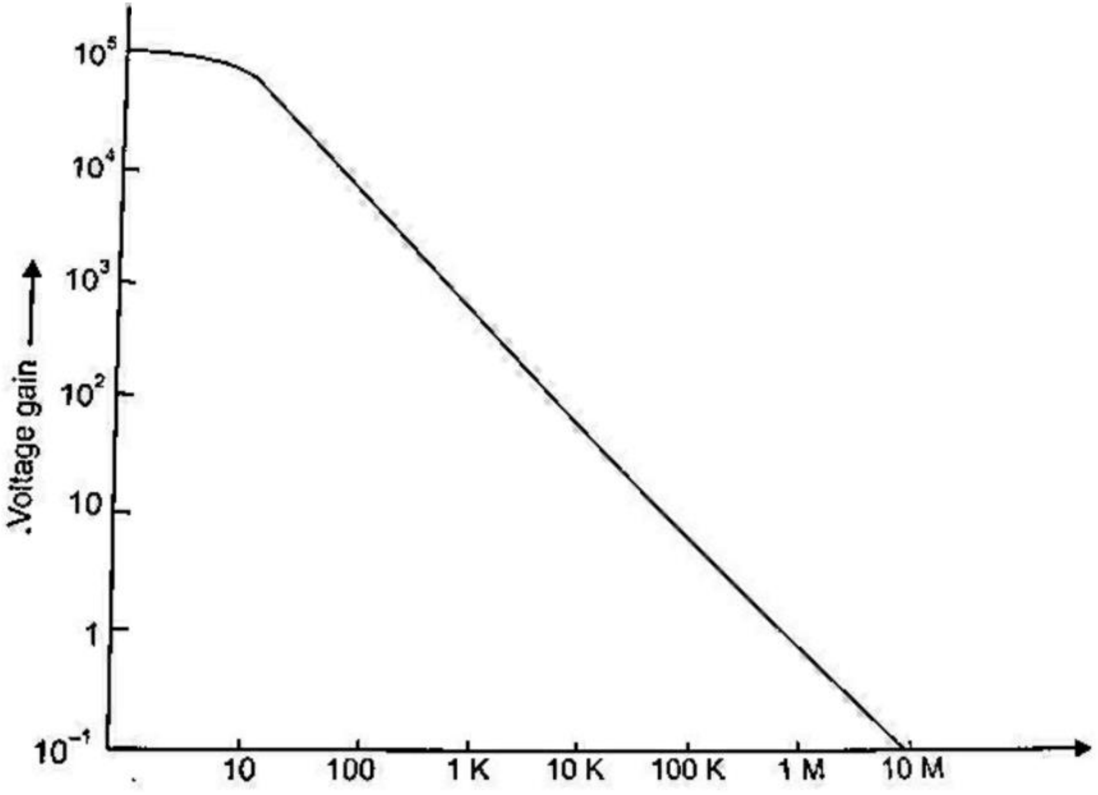
- *The improvement in bandwidth due to pole-zero compensation is given by* f_2- f_1



(2) Internal compensated op-amp

- For certain applications, the relatively broad bandwidth of uncompensated op-amp is not needed.
- For eg. in instrumentation circuit the op-amp is required to amplify relatively slow changing signals. It doesn’t require good high frequency response. For such applications, internally compensated op-amps are used.

- $\mu A741$ contains a capacitance of 30pF that internally shunts off signal current and thus reduces the available output signal at higher frequency.
- This internal compensating capacitor causes the open loop gain to roll-off at -20dB/dec and thus assures a stable circuit.



IV. Slew rate

- The rise time of an amplifier is defined as the time of output takes to change from 10%-90% of the final value for a stop input.
- Ideal response time should be zero i.e. output voltage respond instantaneously to any change in input.
- For large signal output, the op-amp's speed is limited by Slew rate, that measure how quickly an op-amp respond to changes in the input voltage.
- Op-amp slew rate is related to its frequency response. Op-amps with wider bandwidth have better slew rate.
- ***Slew rate is defined as the maximum rate if change of output voltage caused by a step input voltage and is specified in $V/\mu s$***.
- An ideal SR is infinity and practical value is $0.1\ V/\mu s\ to\ 1000 V/\mu s$.
- The SR improves with higher closed loop gain and dc supply voltage. It also decreases with increase in temperature.

Causes of Slew rate

- The capacitor used within or outside an op-amp to prevent oscillator. This capacitor prevents the output voltage from responding immediately to a fast changing input.
- The rate at which the voltage across the capacitor V_c increases is given by $\frac{dV_c}{dt} = \frac{I}{C}$
- I is the maximum current furnished by op-amp to the capacitor C.
- For obtaining faster slew rate, op-amp should have either higher current or small compensating capacitor.

$$SR = \left.\frac{dv_c}{dt}\right|_{max} = \frac{I_{max}}{C} = \frac{15\ \mu A}{30\ pF} = 0.5\ V/\mu s$$

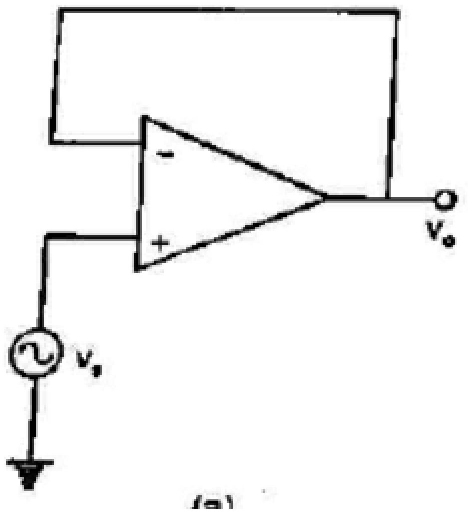
Slew rate for Sine wave

SR limits the response speed of all large signal waveshapes.

Consider a voltage follower

$$v_s = V_m \sin \omega t$$

$$v_o = V_m \sin \omega t$$



The rate of change of output is given by $\frac{dv_o}{dt} = V_m \omega \cos \omega t$

The maximum rate of change of output occurs when $\cos\omega t$=1.

$$SR = \left.\frac{dv_o}{dt}\right|_{max} = \omega V_m$$

Therefore, Slew Rate $= 2\pi f V_m$ V/s $= \frac{2\pi f V_m}{10^6}$ V/μs

f = input frequency (Hz),

V_m = peak output amplitude

f_{max} is the maximum frequency at which we obtain undistorted output voltage of peak value V_m is given by

$$f_{max}\,(\text{Hz}) = \frac{\text{Slew Rate}}{6.28 \times V_m} \times 10^6$$

f_{max} is the full power response