Linear IC Applications.

(1)

Books.

1. op-Amps and linear Integrated ckts
   — Ramakant A. Gayakwad.
2. Linear Integrated circuits.

   — Roy chowdary.
3. Linear & Digital Integrated ckts By.
   — Godse & Bhashi.

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Integrated ckts (ICs) meaning that: Digi
components in each ckt are fabricated on
the same "chip". ICs have become a
vital part of modern electronic ckt
design. They are used in the comp
industry, automobile industry, home appliances
communication, and control system where
they permit miniaturization and superior
performance not possible with discrete
components.

* IC are now being used in all types of electronic equipment because of the long, trouble-free service they provide.

* They are economical because they are mass produced.

Classification according to their mode of operation, ICs are of two basic types: Digital or Linear.

* Digital ICs are complete functioning logic networks that are equivalents of basic transistor logic circuits.

They are used to form such circuits as gates, counters, multiplexers, demultiplexers, shift registers and others.

Digital circuits are primarily concerned with only two levels of voltages (or currents) high or low. Therefore, accurate control of operating region characteristics is not required in digital circuits, unlike in linear ckts. For this reason, digital ckts are easy to design and are produced in large quantities as low-cost devices.

* Linear ICs are equivalents of discrete transistor networks, such as amplifiers, filters, freq multipliers, and modulators, that often require additional external components for

satisfactory operation.

For ex, external resistors are necessary to control the voltage gain and freq response of an op-amp.

In linear ckts the output electrical signals vary in proportion to the i/p signals applied or the physical quantities they represent.

Since the electrical signals are analogous to physical quantities, linear ckt are also referred to as analog circuits.

of all presently available linear ICs, the majority are operational amplifiers. with suitable external components, the op-amp is used in amplifiers, active filters, integrators, differentiators, and in countless other applications.

* A wide variety of special-purpose linear ICs is available for uses in comparators, voltage regulators,

digitall interfacing ckts and in radio freq and power amplifiers.

* In addition to the op-amp and special purpose linear ICs, component arrays are also available in IC form. Such arrays may consists of groups of isolated transistors, diodes, and resistors as well as of Darlington pairs or individual stages such as differential and cascode amplifiers.

* op-amps are further classified into two groups: general purpose and special purpose. General purpose op-amps may be used for a variety of applications, such as integrator, summing amplifier and differentiator, and others.

* An example of a widely used general-purpose op-amp is the 741/351 on the otherhand special purpose op-amps are used only for the specific applications they are designed for.

For ex, the LM 380 op-amp can used only for audio power applications.

Types of Integrated ckts.

* Integrated circuits may be classified as either monolithic or hybrid.

* Most linear ICs are produced by the monolithic process in that all transistor and passive elements (resistors and capacitors) are fabricated on a single piece of semiconductor material, usually silicon.

"Monolithic" is a Greek-based word meaning "one stone".

* In monolithic ICs all components (active and passive) are formed simultaneously by a diffusion process.

* Then a metallization process is used in interconnecting these components to form the desired circuit.

Electrical isolation between the Components in monolithic ICs can be achived by any one of these isolation techniques: dielectric, beam-lead & PN- junction.

However the PN junction isolation is most economical and is commonly used.

* The monolithic process makes low-cost mass production of ICs possible. Monolithic ICs exibit good thermal stability because all the components are integrated on the same chip very close to each other.
* However, the large values of resistance and capacitance that are required in some linear ckts cannot be formed using the monolithic process.
* There is no method available to fabricate transformers or to form large

values of inductors in integrated form.

However if these components are required in a given application, external discrete components can be used with the IC.

In hybrid ICs, passive components (such as resistors and capacitors) and the interconnections between them are formed on an insulating substrate. The substrate is used as a chassis for the integrated components. Active components such as transistors and diodes, as well as monolithic integrated ckts, are then connected to form a complete ckt.

Advantages

1. Less power consumption.
2. Costs less
3. More compact.
4. More reliable
5. Higher gain can be obtained.
6. Easy design.

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Classification of IC's:-

Integrated Circuits

- According to mode of operation
  1. Linear
  2. Digital
- According to fabrication process involved
  1. Monolithic
  2. Hybrid
     - (a) Thick film
     - (b) Thin film
- According to level of Integration
  1. SSI
  2. MSI
  3. LSI
  4. VLSI
  5. ULSI
  6. GSI
- According to package
  1. Dual in-line package (DIP)
  2. Flat pack
  3. Metal Can pack

isolation isolation

Classification according to level of integration (or) IC chip size and circuit complexity :-

Invention of transistor (Ge)		1947.
Development of silicon transistor		1955–1959.
Silicon planar Technology	junction transistor diode	1959.
First ICs, Small Scale Integration (SSI)	3 to 30 gates/chip (or) 100 transistors/chip (Logic gates, Flip-flops)	1960–65
Medium scale Integration (MSI)	30 to 300 gates/chip (or) 100 to 1000 transistors/chip (Counters, multiplexers, Adders)	1965–1970
large scale Integration (LSI)	300 to 3000 gates/chip (or) 1000 to 20,000 transistors/chip (8 bit microprocessors, ROM, RAM)	1970–1980
Very large scale Integration (VLSI)	More than 3000 gates/chip (or) 20,000 – 10,00,000 transistors/chip (16 to 32 bit microprocessors)	1980–
Ultra large scale Integration (ULSI)	$10^6 - 10^7$ transistors/chip (Special processors, virtual reality machines, smart sensors)	1990–20
Giant scale Integration	$> 10^7$ transistors/chip...	

Manufacturers' Designations for Integrated circuits.

* In the United States alone there are well over 30 IC manufactures producing millions of ICs per year.

* Each manufacturer uses a Specific code and assigns a specific type no to the ICs it produces.

* i.e each manufacturer uses its own identifying initials followed by its own type no

~~For ex: the 741 type of internally initials followed by its own type number~~

* For ex: the 741 type of internally compensated op-amp was originally manufactured by Fairchild and is sold as the μA741. where μA represents the identifying initials used by Fairchild.

Initials used by some of the well known manufacturers of linear ICs are as follows.

Fair child	μA.
	μAF
National Semiconductor	LM.
	LH
	LF
	TBA.
Motorola	MC
	MFC.
RCA	CA
	CD.
Texas Instruments	SN
Sprague	ULN.
	ULS.
	ULX.
intersil	ICL
	IH.
Siliconix, INC	L
Signetics	N/S
	NE/SE
	SU.
Burr-Brown	BB.

The initials used by manufacturers in designating digital ICs may differ from those used for linear ICs.

For ex., DM and CD are initials used for digital monolithic and CMOS (Complementary metal-oxide semiconductor) digital ICs, respectively, by National Semiconductor.

In addition to producing their own ICs, a number of manufacturers also produce one another's popular ICs. In second-sourcing such ICs, the manufacturers usually retain the original type no. of the IC in their own IC designation.

For ex., Fairchild's original μA741 is also manufactured by various other manufacturers under their own designations.

National Semiconductor	LM741
Motorola	MC1741
RCA	CA3741
Texas Instruments	SN52741
Signetics	N5741.

Note that the last three digits in each manufacturer's designation are 741. All these op-amps have the same specifications and, therefore behave the same.

Development of integrated circuits

The development of linear ICs can be traced back to early 1960s. when arrays were first fabricated on a single silicon chip. The arrays are combinations of isolated components such as diodes and transistors & individual stages such as differential amplifiers and Darlington pairs.

The use of such IC arrays helped minimize the temp-drift prob inherent in discrete transistor and diode ckt. It also greatly reduced the size of discrete electronic ckts.

In 1963 Fairchild Semiconductor introduced the first IC op-amp, its μA702 which set the stage for the development of other IC op-amps. The unequal supply voltages, such as $+V_{CC} = 12V$ and $-V_{EE} = -6V$. Relatively low I/P resistance and low voltage gain (3600 V/V) were the major draw backs of the μA702 op-amp. For these reasons the μA702 was not universally accepted.

In 1965 Fairchild introduced the μA 709, an improved op-amp compared to μA 702.

Compared to the μA 702 which set the stage for the development of other IC op-amps.

The μA 709 has symmetrical supply voltages such as $+V_{cc} = +15V$ and $-V_{EE} = -15V$, much higher i/p resistance (400 kΩ) and voltage gain of 45,000 V/V.

The μA 709 was the first quality op-amp and is therefore remembered for its historical significance.

The μA 709 is also regarded as a first generation op-amp.

Another ex of first generation op-amp is MC1537.

The disadvantages of first generation op-amps are as follows.

1. No short ckt protection: The op-amp is susceptible to burnout if output is accidentally shorted to ground.

2. A possible latch up problem:- output voltage can be latched up to some value and then fails to respond to changes in i/p signal applied.

3. Requires an external freq compensating n/w (two capacitors and a resistor) for stable operation.

This means that when an external compensating n/w is not used the op-amp may oscillate.

Ideally, these compensating components should be internally integrated so that no extra work of connecting them to the op-amp is required.

The next major advancement in the IC op-amp technology came in 1968 with the introduction of the Fairchild μA 741. an internally compensated op-am unlike the μA 709, it has short ckt protection, has no latch-up prob and is inherently stable.

It has very high i/p resistance (2 MΩ), extremely high voltage gain (200000 V/V) and offset null capability.

It is one of the most widely used general purpose op-amps in industry even today.

The 741 is an ex. of second generation op-amps.

other ex. of second generation op-amps are

LM 101, LM 307, μA 748 and MC 1558

General purpose op-amps such as the 741 and 307 are used in the greatest percentage of applications.

IC PACKAGE TYPES classification according to package

Three basic types of linear IC packages are

1. The FLAT PACK

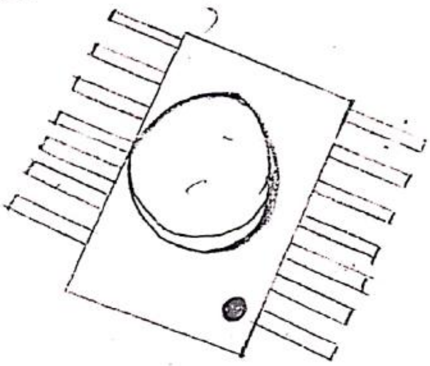
2. The metal can or transistor pack.

3. The dual-in-line package (for short, DIP).

FLAT PACK:-

In the Flat pack, the chip is enclosed in a rectangle ceramic case with terminals leads extending through the sides and ends.

The Flat pack comes with 8, 10, 14 or 16 leads. These leads accomodate the power supplies, inputs, outputs and several special connections required to complete the circuit.



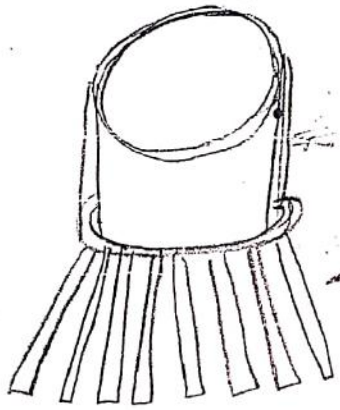
14-lead Flat pack.

METAL CAN or TRANSISTOR PACK.

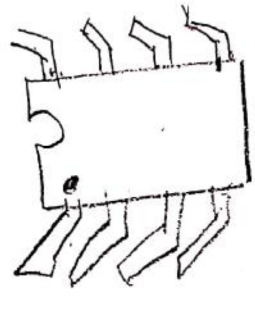
In the metal can or transistor pack, the chip is encapsulated in a metal (or) plastic case. The transistor pack is available with 3, 5, 8, 10 (or) 12 pins. Most of the Voltage regulator ICs, such as the LM117 have 3 pins. power op-amps and audio power amplifiers are usually available in 5-pin packages. The metal can package is best suited for power amplifiers because metal is a good heat conductor and consequently has better dissipation capability than a flat-pack (or) dual-in-line package. In addition, the metal can package permits the use of external heat sinks. Most of the general-purpose op-amps come in 8, 10, or 12-pin packages.

DUAL-IN-LINE PACKAGE:-

In the dual-in-line package (DIP), the chip is mounted inside a plastic or cermic case. The DIP is most widely used package type because it can be mounted easily. The 8-pin dual in-line packages are referred to as mini DIPS. Dual-in-line packages are available with 12, 14, 16, and 20 pins.



8, 10, and 12 lead versions.
8 lead metal can



8 lead Dual in line package

8 lead Dual in line plastic package.

Selection of IC package:-

Type of IC package	criteria for selection
(1) DIP	i) For experimental (or) breadboarding purposes as easy to mount (ii) If blending (or) soldering of the leads is not required. (iii) suitable for printed circuit boards because of its lead construction and more spacing between the leads.
(2) Metal can	(i) Heat disscipation is important. (ii) for high power applications like power amplifiers, voltage regulators etc.
(3) Flat pack	(i) More reliability is required. (ii) Light in weight (iii) suited for airborne applications.

Temperature Ranges:-

All ICs manufactured fall into one of the three basic temperature grades:

1. Millitary temperature range: $-55^\circ C$ to $+125^\circ C$ (or) ($-55^\circ C$ to $+85^\circ C$)
2. Industrial temperature range: $-20^\circ C$ to $+85^\circ C$ (or) ($-40^\circ C$ to $+85^\circ C$)
3. commercial temperature range: 0° to $+70^\circ C$ (or) (0° to $+75^\circ C$).

power supplies for Integrated circuits:-

Most linear ICs require both a positive and a negative supply. A few linear ICs use unequal power supplies eg: op-amp 702. and some ICs require only a positive supply eg: 324.

The two power supplies required for a linear IC are usually equal in magnitude +15V & -15V, for example. ... voltages must be referenced, to a common ... nd.

When ~~a single supply is used~~,

Some Dual-supply op-amp ICs can also be operated from a single supply voltage, provided that a special external circuit is used with it.

Digital ICs, generally require only one positive supply.

Motorola uses the symbols $+V_{CC}$ and $-V_{EE}$ to represent positive and negative voltages resepectively.

Instead of using two seperate power supplies, we can use a single power supply to obtain $+V_{CC}$ and $-V_{EE}$.

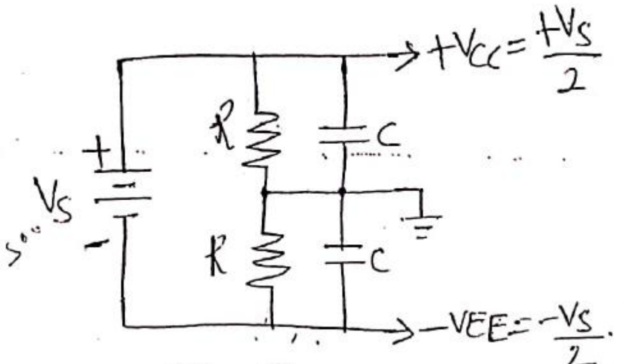


Fig (a)

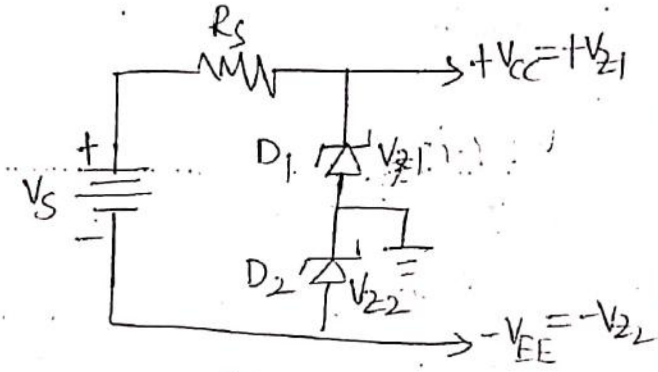
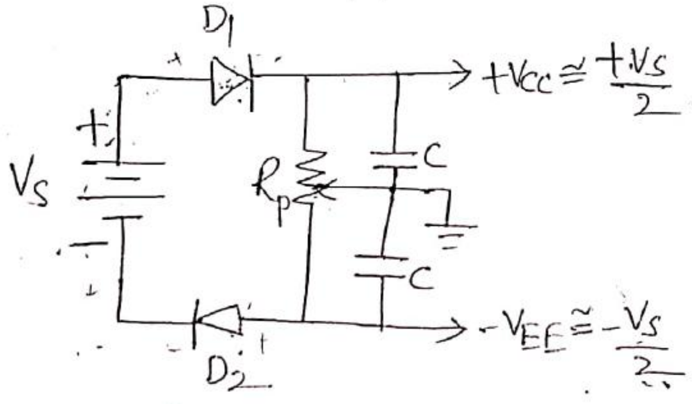


Fig (b)



In figure (a) the value of the value of the total resistance (2R) should be $\geq 10k\Omega$ so that it doesn't draw much current from the supply V_S.

The two capacitors provide for decoupling (bypass) of the power supply. They range in value from 0.01 to $10\mu F$.

Here, using resistive potential divider network and a ground it is converted to dual supply. Each positive and negative supply obtained has a magnitude equal to half of the single supply voltage used i.e ($V_S/2$)

In Fig (b) Zener diodes appropriate voltage rating are used to obtain symmetrical supply voltages (other than $V_s/2$). The value of R_s be chosen such that it supplies sufficient current for diodes to operate in the avalanche mode.

In Fig (c), The potentiometer is used to assure equality between $+V_{CC}$ and $-V_{EE}$ values. Since many times practical due to mismatch in the devices, equal positive and negative voltages are not available. Diodes D_1 and D_2 are intended to protect the IC if the positive and negative leads of the supply voltage V_s are accidentally reversed.

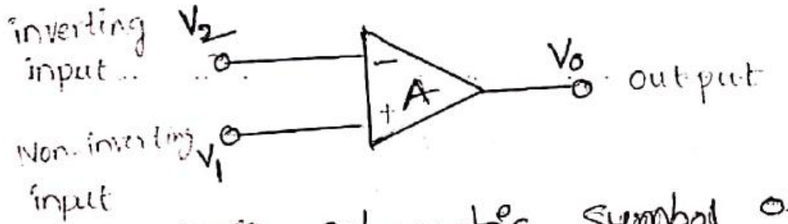
Basic Information of op-amp:-

An operational amplifier is a direct-coupled high-gain amplifier usually consisting one (or) more differential amplifiers and usually followed by a level translator and an output stage. The out-put stage is generally a push-pull (or) push-pull Complementary - symmetry pair. An operational amplifier is available as a single integrated circuit package.

The operational amplifier is a versatile device that can be used to amplify dc as well as AC input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication and integration. Thus the name operational amplifier stems from

Its original use for these mathematical operations and is abbreviated to op-amp. With the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications, such as ac and dc signal amplification, active filters, oscillators, comparators, regulators and others.

<u>op-amp schematic symbol:-</u>



fig(1) schematic symbol of op-amp.

The schematic symbol of an op-amp is shown in fig(1). It has two input terminals and one output terminal. Other terminals have not been shown for simplicity.

The '−' & '+' symbols at the input refer to the inverting and non-inverting input terminals respectively i.e., if $V_1 = 0$, output V_0 is 180° out of phase with input signal V_2. And, when $V_2 = 0$, output V_0 will be in phase with the input signal applied at V_1.

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

V_2 = Voltage at the inverting input (Volts)

V_0 = output voltage (Volts)

All these voltages are measured w.r.t. ground. Here,

$A =$ large - signal voltage gain ~~of~~ an op-amp

THE IDEAL OP-AMP:-

An ideal op-amp has the following electrical characteristics.

(1) Infinite voltage gain A.

(2) Infinite input resistance (R_i) so that almost any signal source can drive it and there is no loading of the preceding stage.

(3) Zero output resistance (R_o) so that 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 signal from 0 to ∞ Hz can be amplified without attenuation.

(6) Infinite common-mode rejection ratio so that the output common-mode noise voltage is zero.

(7) Infinite slew rate so that output voltage changes occur simultaneously with input voltage changes.

It can be seen that

(1) an ideal op-amp draws no current at both the input terminals i.e, $i_1 = i_2 = 0$.

amp.

Here, the output voltage is

$$V_0 = AV_{id} = A(V_1 - V_2) \quad \rightarrow (1)$$

where A = Large - signal voltage gain

V_{id} = difference input voltage

V_1 = Voltage at the non-inverting input terminal w.r.t. ground.

V_2 = Voltage at the inverting terminal w.r.t. ground.

→ Equation (1) indicates that the output voltage V_0 is directly proportional to the algebraic difference between the two input voltages. In otherwords, the op-amp amplifies the difference between the two input voltages; it does not amplify the input voltages themselves. Thats why the polarity of the output voltage depends on the polarity of the difference voltage.

voltage Transfer curve of an op-amp:-

The graph of output voltage V_0 plotted against the differential input voltage V_{id}; assuming gain constant is called voltage tranfer curve (or) characteristics of op-amp.

Note:- In both cases below, the output offset voltage is assumed to be zero.

(ii) Since Voltage gain is '∞', the voltage between the inverting and non-inverting terminals, i-e differential input voltage $V_d = (V_1 - V_2)$ is essentially zero for finite output voltage V_o.

(iii) The output voltage V_o is independent of the current drawn from the output as $R_o = 0$. The output thus can drive an infinite number of other devices.

EQUIVALENT CIRCUIT OF AN OP-AMP:-

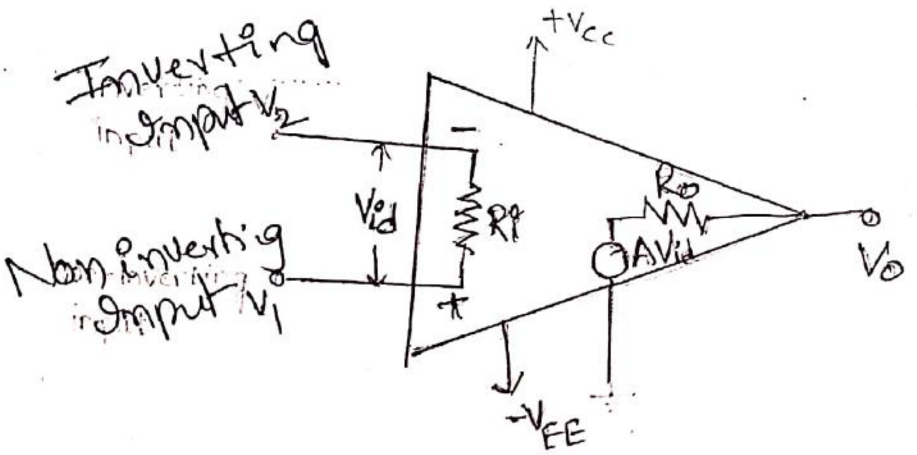


fig Equivalent circuit of an op-amp

Figure shows an equivalent circuit of an op-amp. This circuit includes important values: A, R_i and R_o. Note that AV_{id} is an equivalent thevenin voltage source, and R_o is the thevenin equivalent resistance looking back into the output terminal of an op-amp.

The equivalent circuit is useful in analyzing the basic principles of op-amps and in observing the effects of feedback arrangements.

Ideal voltage Transfer curve:-

Ideally open loop gain of an op-amp is '∞'.

$$A = \frac{V_o}{V_{id}} = \infty$$

$$V_{id} = \frac{V_o}{\infty} = 0$$

$$V_o = A V_{id}$$

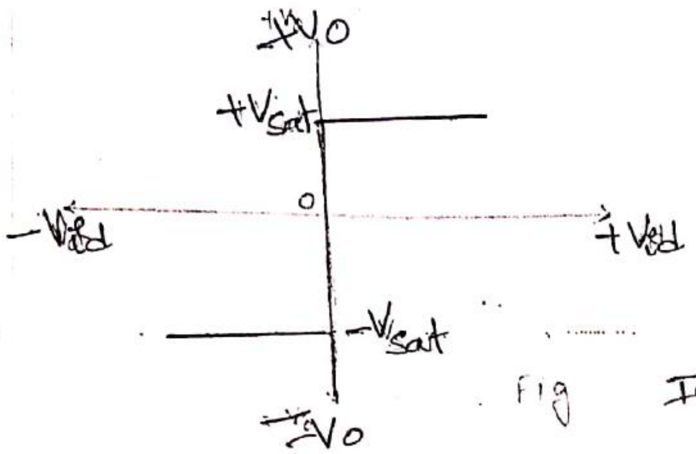
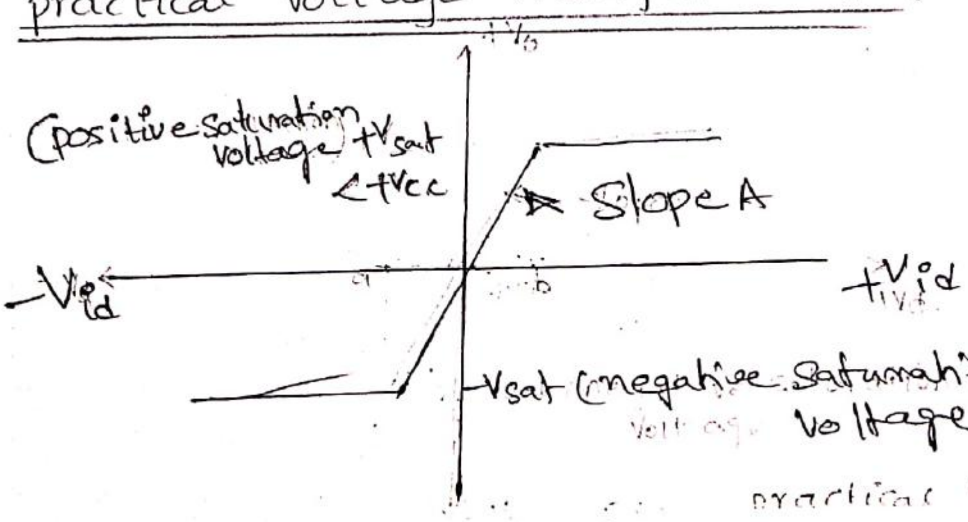


Fig Ideal Voltage transfer curve

Thus for zero input, the output of op-amp is always at saturation level ± Vsat, due to infinite gain. Thus voltage transfer curver for ideal op-amp is vertical line

Thus ideally range of input for linear operation of the op-amp is zero.

practical Voltage Transfer curve:-



practical voltage transfer

The graphic representation of practical op-amp is shown in figure., where the output voltage V_0 is plotted against input difference voltage V_{id}, keeping gain 'A' constant.

→ Note that the output voltage cannot exceed the positive and negative saturation voltages.

→ These saturation voltages are specified by an output voltage swing rating of the op-amp for given values of supply voltages.

→ This means that the output voltage is directly proportional to the input difference voltage only until it reaches the saturation voltages & thereafter output voltage remains constant.

→ practical 'A' is finite for the op-amp. For example op-amp 741 IC has 2×10^5

$$V_0 = A \times V_{id} \Rightarrow \pm V_{sat} = 2 \times 10^5 \, V_{id}.$$

Saturation voltages are almost $\pm 15V$.

$$V_{id} = \frac{\pm 15}{2 \times 10^5} = \pm 75 \mu V.$$

Hence practically till V_{id} is between $-75\mu V$ & $+75\mu V$, the output will vary linearily with input. But once V_{id} exceeds $\pm 75 \mu V$, the output is saturated.

In fig

(i) If V_{id} is greater than corresponding to b, the output attains $+V_{sat}$

(ii) If V_{id} is less than corresponding to a, the output attains $-V_{sat}$.

(iii) Range a-b is input range for which o/p varies linearily with the i/p.

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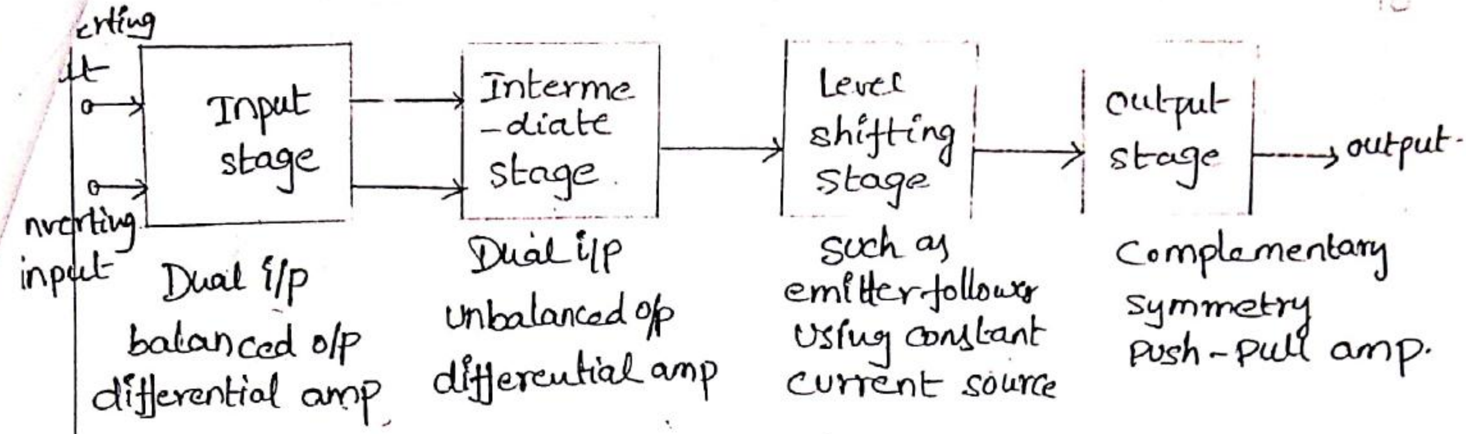
Block diagram of a typical op-amp:-



(1) Input stage:-

The input stage is the dual-input, balanced-output differential amplifier. This stage generally provides most of the voltage gain of the amplifier and also establishes the high input impedance of the op-amp to avoid loading on the sources. The function of a differential amplifier is to amplify the difference between the two input signals.

(2) Intermediate stage:-

The intermediate stage is usually another differential amplifier, which is driven by the output of the first stage. It is dual input, unbalanced (single-ended) output. The overall gain requirement of the op-amp is very high. The input stage alone cannot provide such a high gain. The main function of the intermediate stage is to provide an additional voltage gain required. The intermediate stage is not a single amplifier but the chain of cascaded amplifiers called multistage amplifiers.

(3) Level shifting stage (Level translator):-

All the stages are directly coupled to each other. As the op-amp amplifies d.c. signals also, the coupling capacitors are not used to cascade the stages. Hence the d.c. quiscent voltage level of previous stage gets applied as the input to next stage. Hence stage by stage d.c. level increases above ground potential. such a high d.c voltage level may drive the transistors into saturation. This further may ca[use] distortion in the output due to clipping. This may limit maximum a.c output voltage swing. Hence before the o/p stage, it is necessary to bring such a high d.c. voltage level to zero volts with respect to ground.

The level transalator (shifting stage) is used after the intermediate stage to shift the dc level at the output of the intermediate stage downward to zero volts w.r.t ground. It is emitter follower using constant current source.

(4) output stage:-

The final stage is usually a push-pull complementary symmetry amplifier output stage. This stage increases the output voltage swing and raises the current supplying capability of the op-amp. A well-designed output stage also provides low output resistance.

Questions: regarding above topic:-

(1) with the help of neat block diagram explain the function of various building blocks of an op-amp.

1. ⓐ, 7. ⓐ, 12. ⓑ, 30. ⓐ, 42. ⓐ Questions in question Bank

Features of 741 IC

(1) No external frequency compensation required.

(2) short circuit protection

(3) offset null capability

(4) Large common-mode and diffential voltage ranges.

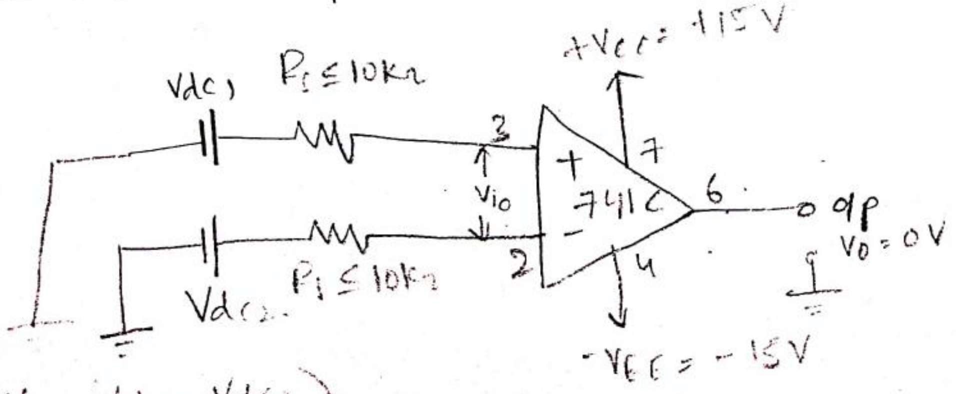
(5) low power consumption

(6) No Latch-up problem.

Electrical parameters (or) characteristics of generalized op-amp & IC741:-

Input offset ~~current~~ voltage :-

Input offset voltage is the voltage that must be applied between the two input terminals of an op-amp to null the output. In the figure Vdc1 & Vdc2 are dc voltages and R_s represents the source resistance. Input offset voltage is denoted by V_{io}. This voltage V_{io} will be positive (or) negative. For a 741C the maximum value of V_{io} is 6mV dc. The smaller the value of V_{io}, the better the input terminals are matched. for The 714C precission op-amp has $V_{io} = 150 \mu V$ maximum.



$V_{io} = (V_{dc1} - V_{dc2})$

Input offset current :-

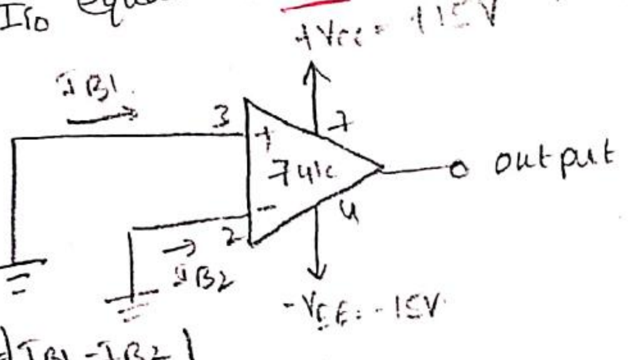
The algebraic difference between the currents into the inverting and noninverting terminals is referred to as input offset current I_{io}, so,

$$I_{io} = |I_{B1} - I_{B2}|$$

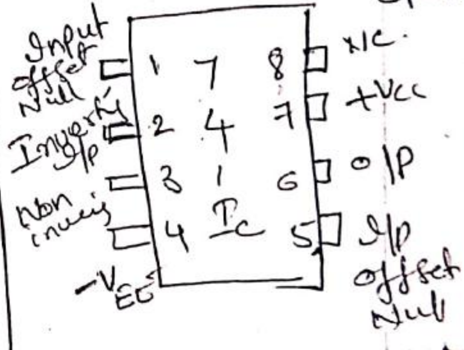
where I_{B1} is the current into the noninverting input and I_{B2} is the current into the inverting input.

The input offset current for the 741C is 200nA max. The input offset current between two input terminals is As the matching between I_{B1} and I_{B2} becomes improved, the difference between I_{B1} and I_{B2} decreases further. smaller; that is, the I_{io} value decreases further.

The precision op-amp 714C has a maximum value of I_{io} equal to 6nA



Pinconfiguration of 741IC op-Amp



$$I_{io} = |I_{B1} - I_{B2}|$$

Input Bias current :-

Input bias current I_B is the average of the currents that flow into the inverting and noninverting input terminals of the op-amp.

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

I_B = 500nA maximum, for the 741C, whereas I_B for the precision 714C is ±7nA. Note that the two inputs currents I_{B1} & I_{B2} are actually the base currents of the differential amplifier stage.

Differential Input Resistance:- Differential (often referred to as input resistance) R_i (often referred to as input resistance) The equivalent resistance that can be measured at either the inverting (or) noninverting input terminal with the other terminal connected to ground.

For the 741C the input resistance is a relatively high $2M\Omega$.

Input Capacitance:- Input capacitance (C_i) is the equivalent capacitance that can be measured at either the inverting (or) noninverting terminal with the other terminal connected to ground.

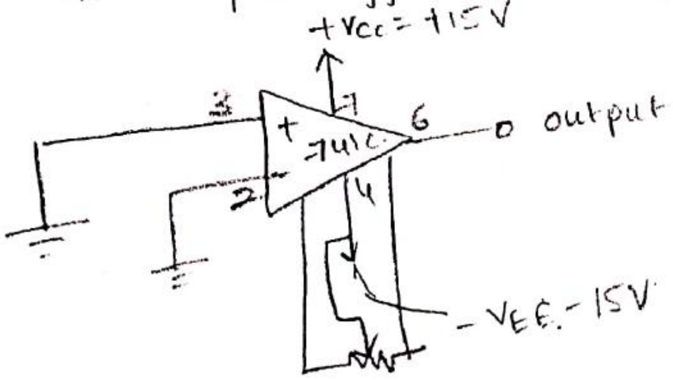
A typical value of C_i is 1.4pF for the 741C.

Offset voltage Adjustment Range:-

One of the features of the 741 family op-amps is an offset voltage null capability. The 741 op-amps have pins 1 and 5 marked as offset null this purpose. As shown in fig, a 10 kΩ potentiometer can be connected between offset null pins 1 and 5 and the wiper of the potentiometer can be connected ~~between~~ to the negative supply $-V_{EE}$. By ~~varfations~~ varying the potentiometer, the output offset voltage (O/P voltage without any I/P applied) can be reduced to zero volts. Thus the offset voltage adjustment range is the range through which the input offset voltage can be adjusted by varying the 10-kΩ potentiometer.

For the 741 IC the offset voltage adjustment range is ±15mV.

Very few op-amps have the offset voltage null capability, those are 301, 748, & 777. This means that for most of op-amps we have to design an offset voltage compensating network in order to reduce the output offset voltage to zero.



<u>Input voltage range:-</u>

when the same voltage is applied to both input terminals, the voltage is called a common-mode voltage V_{cm} and the op-amp is said to be operating in the common-mode configuration. For the 741C the range of the input common mode voltage is $\pm$ 13V maximum. This means that the common-mode voltage applied to both input terminals can be as high as +13V (or) as low as -13V without disturbing proper functioning of the op-amp. In other words, The i/p voltage range is the range of common-mode ~~configuration~~ ~~All offset of~~ voltages over which the offset specification apply. obviously, the common-mode configuration is used only for test purposes to determine the

... between the inverting & noninverting

Common-mode Rejection Ratio:

The common mode rejection ratio (CMRR and
defined as the ratio of the differential voltage uic
gain (Ad) to the common mode voltage gain Acm ~~supply~~

That is $$CMRR = \frac{A_d}{A_{cm}}.$$

The differential voltage gain A_d is the same as ~~that~~ large-signal voltage gain A.

The common mode voltage gain A_{cm} is

$$A_{cm} = \frac{V_{ocm}}{V_{cm}}$$

where V_{ocm} = output common mode voltage.

V_{cm} = input common mode voltage.

A_{cm} = common-mode voltage gain.

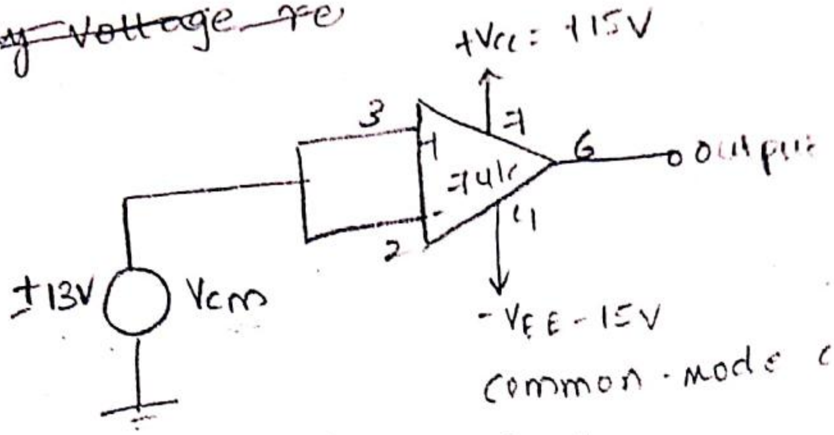
Generally the A_{cm} is very small & $A_d = A$ is very large, the CMRR is very large. CMRR is expressed in decibles. For the 741C, CMRR is 90dB.

Note that this value of CMRR is determined under the test condition that the i/p source resistance $R_s \leq 10K\Omega$ & R_s is assumed to be zero because most of the practical voltage sources have negligible source resistances.

The higher the value of CMRR, the better is the matching between two i/p terminals and the smaller is the output common-mode voltage. For the 741C precision op-amp, CMRR = 120dB. This means that the 714C has a better ability to reject [illegible] such as electrical noise than the

741C and is preferred in noise environment.

~~Supply Voltage re~~



common-mode configuration

<u>Supply Voltage Rejection Ratio:-</u>

The change in op-amp's input offset voltage V_{io} caused by variations in supply voltages is called the supply voltage rejection ratio (SVRR).

It is also called power supply rejection ratio (PSRR) and the power supply sensitivity (PSS).

It is expressed in micro volts per volt or decibels.

$$SVRR = \frac{\Delta V_{io}}{\Delta V}$$

where ΔV = Change in supply voltages.

ΔV_{io} = Change in input offset voltage

For the 741C, $SVRR = 150 \mu V/V$. On the other hand, for the 714C $SVRR = 20 \log \left(\frac{\Delta V_{io}}{\Delta V}\right) = 104 dB$.

or equivalently $SVRR = 6.31 \mu V/V$.

This means that the lower the value of SVRR in micro volts/volt, the better for op amp performance.

Large Signal Voltage gain:-

Since the op-amp amplifies difference voltage between two i/p terminals, the voltage gain of amplifier is defined as

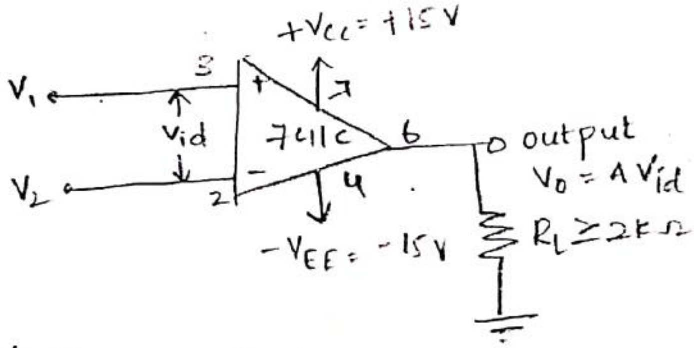
$$\text{Voltage gain} = \frac{\text{output voltage}}{\text{differential input voltage}}$$

i.e,

$$A = \frac{V_0}{V_{id}}$$

Because output signal amplitude is much larger than the input signal, the voltage gain is commonly called large signal voltage gain.

Under the test conditions $R_L \geq 2k\Omega$ & $V_0 = \pm 10V$ (or 20V peak to peak), the large signal voltage gain of the 741C is <u>200,000</u> typically.



Output voltage swing:-

The output voltage swing V_{omax} of the 741C is guaranteed to be between −13 and +13V for $R_L \geq 2k\Omega$, i.e, giving a 26-V peak to peak undistorted sine wave for ac input signals. In fact, the output voltage swing indicates the values of positive and negative saturation voltages of the op-amp. The output voltage never exceeds these limits for given supply voltages

Output Resistance:-

Output resistance (R_o) is the equivalent resistance that can be measured between the output terminal of the op-amp and the ground (or common point). It is 75Ω for the 741C op-amp.

Output short-circuit current:-

If the output terminal of the op-amp is shorted to ground, the current through the short would certainly be much higher in value than either I_B (or) I_{IO}. This high current may damage the op-amp if it does not have output short-circuit protection. The 741 family op-amps do have short-circuit protection circuitry built in.

The short-circuit current I_{SC} = 25mA for the 741C op-amp. This means that the built-in short circuit protection is guaranteed to withstand 25mA of current in protecting the opamp.

Supply current:- supply current I_S is the current drawn by the op-amp from the power supply. The supply current for the 741C op amp the

$I_S = 2.8mA$.

power consumption:- power consumption P_C is the amount of quiescent power ($v_{in} = 0V$) that must be consumed by the op-amp in order to operate properly. The amount of power consumed by the 741C is 85 mW.

Transient Response:-

The response of any practically useful network to a given input is composed of two parts: the transient and steady-state response. The transient response is that portion of the complete response before the output attains some fixed value. once reached, this fixed value remains at that level and is therefore, referred to as a steady-state value. The response of the network after it attains a fixed value is independent of time and is called the steady-state response. unlike, the steady-state response, the transient response is time variant. The rise time and the percent of overshoot are the characteristics of the transient response. The time required by the output to go from 10% to 90% of its final value is called the rise time. Conversely, overshoot is the maximum amount by which the output deviates from the steady-state value. overshoot is generally expressed as a percentage. The rise time is 0.3 µs and overshoot is 5% for the 741C op-amp for $V_{in} = 20mV$.

The transient response is one of the important considerations in selecting an op-amp in ac application. In fact, the rise time is inversely proportional to the unity gain bandwidth of an op-amp. This means that the smaller the value of rise time, the higher is the band width.

<u>slew rate:-</u> slew rate (SR) is defined as the maximum rate of change of output voltage per unit of time and is expressed in volts per micro seconds.

$$SR = \frac{dV_o}{dt} \Big|_{maximum} \ V/\mu s.$$

Slew rate indicates how rapidly the o/p of an op-amp change in response to changes in the input frequency.

The slew rate changes with change in voltage gain and is normally specified at unity (+1) gain.

The slew rate of an op-amp is fixed, if the slope requirements of the output signal are greater than the slew rate, then distortion occurs. Thus slew rate is one of the important factors in selecting the op-amp for ac applications, particularly at relatively high frequencies:

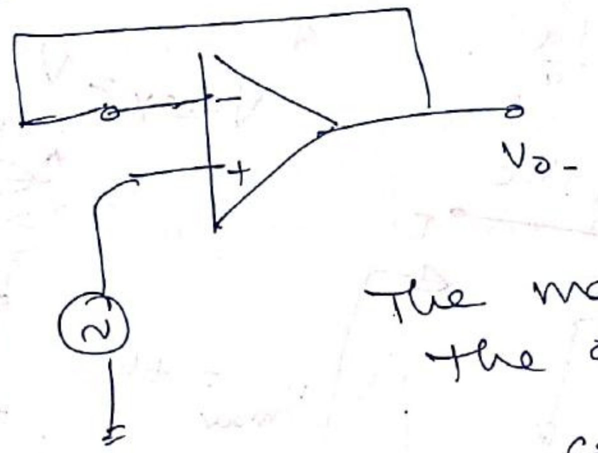
one of the drawbacks of the 741C is its low slew rate (0.5 V/μs), which limits its use in relatively high frequency applications, especially oscillators, comparators and filters. The newer op-amps - LF351, μA771, & MC34001 - which are ... have a slew

Slew Rate equation : Generally the slew rate is specified for unity gain and hence let us consider the voltage follower ckt. and let us assume that the i/p is a large amp and high freq sine wave.

The equation for i/p signal is then.

$$V_s = V_m \sin\omega t.$$

With no slew rate limitation $V_o = V_m \sin\omega t$



unity gain circuit or Voltage follower circuit.

$$\frac{dV_o}{dt} = \omega V_m \cos\omega t.$$

The maximum rate of change of the o/p occurs

$\cos\omega t = 1$ i.e.

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

$$= 2\pi f V_m \ \text{V/sec}.$$

$$S = \frac{2\pi f V_m}{10^6} \ \text{V}/\mu\text{sec}.$$

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Gain- Bandwidth product:-

The gain -band width product (GB) is the bandwidth of the op-amp when the voltage gain is 1. ~~Although~~ for the 741 op-amp it is approximately 1MHz from the open loop voltage gain versus frequency graph.

Equivalent terms for gain-bandwidth product are closed-loop bandwidth, unity gain bandwidth and small-signal bandwidth.

The newer op-amps LF351 & MC34001 have a gain-bandwidth product of 4 MHz.

Average Temperature Coefficient of Input Offset Voltage (and current):-

These parameters are also referred to as average input offset voltage (or) current drift.

The average temperature coefficient of input offset voltage is the average rate of change in input offset voltage per unit change in temperature expressed as μV/°C.

The average temperature coefficient of input offset current is the average rate of change in input offset current per unit change in temperature and is usually expressed as pA/°C.

Both of these parameters are generally given for the instrumentation and precision type op-amps. For the precision op-amp 714C, the average temperature coefficient of input offset voltage

$V_{io}/\Delta T$ = temperature $\Delta I_{io}/\Delta T$ Long

$\Delta V_{io}/\Delta T = 0.1 \mu V/^{\circ}C$ typically and the average temperature coefficient of input offset current $\Delta I_{io}/\Delta T = 12 pA/^{\circ}C$.

<u>Long-term Input offset voltage (& current) stability:-</u>

$\Delta V_{io}/\Delta t$ is the average rate of change in input offset voltage per unit of time and is generally expressed as μV/week. It is also referred to as input offset voltage drift with time. Similarly, $\Delta I_{io}/\Delta t$ is the average rate of change in input offset current per unit of time in pA/week. The precision-type op-amp 714C has $\Delta V_{io}/\Delta t$ $= 0.1 \mu V$/week typically. The value of $\Delta I_{i}/\Delta t$ is negligible for 714C.

<u>Equivalent input noise voltage (or) current:</u>

Since electrical noise is random in nature, it is expressed as a root-mean-square value. Standard industry practice is to express the noise as a power density. The equivalent input noise voltage is therefore expressed as square voltage (V^2/Hz) and the equivalent input noise current as square noise current (A^2/Hz). Using input noise voltage and input noise current versus frequency curves, the minimum amount of signal power that is necessary to overcome the noise signal and produce a measurable output signal can be determined.

As a general rule, the signal to noise ratio must be atleast larger than by a factor of 10.

Channel seperation:-

This parameter specified in the data sheets of dual and quad (four) op-amps such as the MAF772 and MA 774, respectively. It is a measure of the amount of electrical coupling between op-amps that are integrated on the same chip. Because of physical closeness of op-amps in dual & quad packages, when a signal is applied to the input of only one op-amp, some signal will appear at the output of other op-amps. The amplitude of these output signals is approximately the same and can be calculated using channel seperation and a given input signal. channel seperation is also called amplifier to amplifier coupling.

The 774/348 is a true quad 741 and has a channel seperation of -120 dB. This means that if a signal is applied to one of the op-amps, the signal at the outputs of the undriven op-amps will be atleast 120 dB (equivalent to a ratio of 10^6) below the signal output of the driven op-amp.

9.6 PARAMETER EVALUATION FOR AC & DC APPLICATIONS.

For AC applications Consider:	For DC applications Consider:
(1) Input resistance	(1) Input resistance
(2) output resistance	(2) output resistance.
(3) Large signal voltage gain	(3) Large-signal voltage gain
(4) output voltage swing	(4) Input offset voltage & input offset current
(5) Average i/p offset voltage & current drift.	(5) Average input offset voltage and current drifts.
(6) Long-term input offset voltage stability.	(6) Long-term input offset voltage stability.
(7) Gain-bandwidth product	
(8) Transient-response.	
(9) slew rate.	
(10) Equivalent i/p noise voltage & current.	

The electrical parameters are affected by mainly three factors.

a. change in supply voltage.

b. change in operating frequency.

c. change in temperature.

Supply voltage dependent parameters are,

(1) voltage gain (2) o/p voltage swing (3) i/p common mode voltage range (4) power consumption (5) input offset current.

Frequency-dependent parameters are.

(1) voltage gain.

(2) input resistance.

(3) output resistance

(4) output voltage swing.

(5) input noise voltage & noise current.

(6) common-mode rejection ratio (CMRR).

Temperature dependent parameters are.

(1) Absolute maximum power dissipation.

(2) Input bias current

(3) Input offset current

(4) power consumption

(5) input resistance.

(6) output short circuit current

(7) transient response

(8) Gain-bandwidth product.

op-am
(1) open
(2) cl

op-amp can be connected in two configurations.

(1) open-loop configuration

(2) closed-loop configuration.

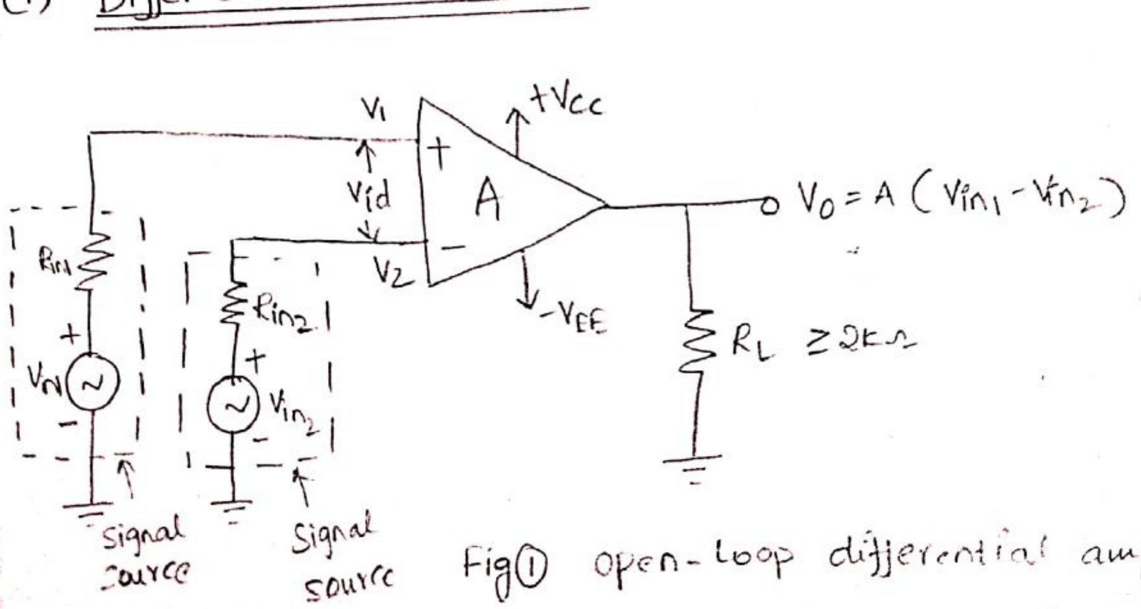
Open-loop configuration:-

The term open loop indicates that no connection either direct or via another net-work exists between the output and input terminals of an op-amp. i.e, the o/p signal is not fed back in any form as part of the input signal

when connected in open-loop configuration, the op-amp simply functions as a high-gain amplifier. Then there are 'three' modes of open-loop op-amp configuration.

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

(1) Differential amplifier:-



Fig① open-loop differential amplifier

Fig ① shows the open-loop differential amplifier in which input signals V_{in1} & V_{in2} are applied to the positive and negative input terminals.

Since the op-amp amplifies the difference between the two input signals, this configuration is called the differential amplifier.

The op-amp is a versatile device because it amplifies both ac & dc input signals. This means that V_{in1} & V_{in2} could be either ac (or) dc voltages.

The source resistances R_{in1} & R_{in2} are normally negligible compared to the input resistance (R_i). Therefore, the voltage drops across these resistors can be assumed to be zero, which then implies that $V_1 = V_{in1}$ & $V_2 = V_{in2}$

Then output voltage (V_o) becomes

$$V_o = A V_{id} = A(V_1 - V_2) = A(V_{in1} - V_{in2})$$

The output voltage is equal to the voltage gain 'A' times the difference between the two input voltages. and the polarity of the o/p voltage is dependent on the polarity of the i/p difference voltage ($V_{in1} - V_{in2}$). In open-loop configurations, gain A is commonly referred to as open-loop gain.

(2) The Inverting amplifier:-

In the inverting amplifier only one input is applied and that is to the inverting input terminal. The noninverting input terminal is grounded.

Since $V_1 = 0V$, & $V_2 = V_{in}$

o/p voltage $V_o = AV_{id} = A(V_1 - V_2) = A(0 - V_{in})$

$= -AV_{in}$

The negative sign indicates that the output voltage is out of phase w.r.t input by 180° (or) is of opposite polarity.

Thus in the inverting amplifier the input signal is amplified by gain 'A' and is also inverted at the output.

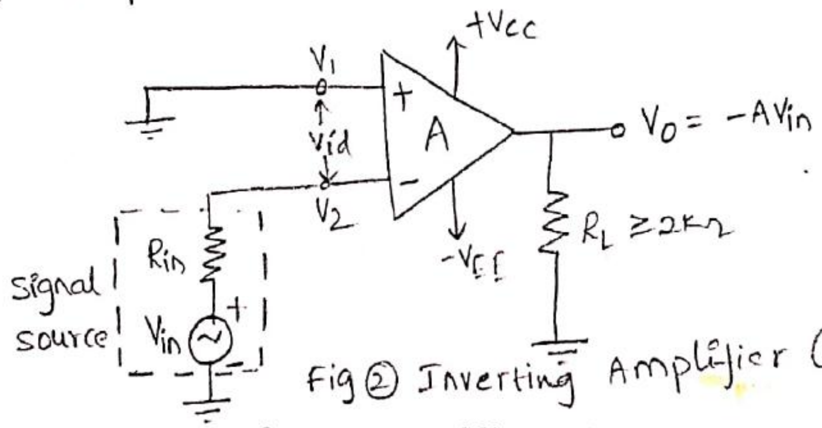


Fig ② Inverting Amplifier (open-loop)

(3) The Non-inverting amplifier:-

Fig ③ shows the open-loop noninverting amplifier. In this configuration the input is applied to the noninverting input terminal, and the inverting terminal is connected to ground.

Here, $V_1 = V_{in}$ & $V_2 = 0V$

o/p voltage $V_o = AV_{id} = A(V_1 - V_2) = A(V_{in} - 0)$

$= AV_{in}$.

This means that the output voltage is larger than the input voltage by gain 'A' and is in phase with the input signal.

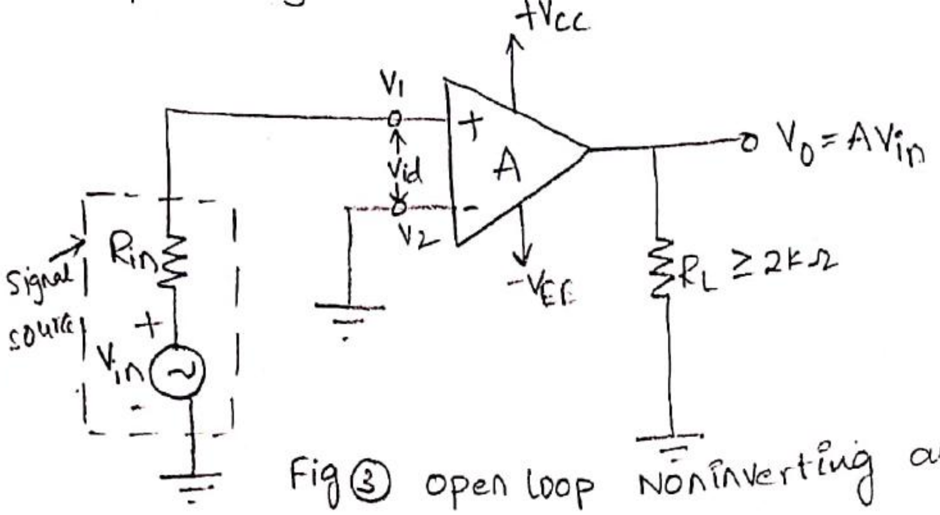


Fig ③ open loop Noninverting amplifier.

In all three open-loop configurations any input signal (difference (or) single) that is only slightly greater than zero drives the output to saturation level. This results from the very high gain of (A) of the op-amp.

Thus, when operated in open loop, the output of the op-amp is either negative (or) positive saturation (or) switches between positive & negative saturation levels. For this reason, open-loop op-amp configurations (modes) are not used in linear applications.

Problems

(1) Determine the o/p voltage in each of the following cases for the open-loop differential amplifier

(a) $V_{in1} = 5\mu V$, $V_{in2} = -7\mu V$ dc

(b) $V_{in1} = 10mV$ (rms), $V_{in2} = 20mV$ (rms)

The op-amp is a 741 with the following specifications $A = 200,000$, $R_i = 2M\Omega$, $R_o = 75\Omega$, $+V_{CC} = +15V$, $-V_{EE} = -15V$ and o/p voltage swing $= \pm 14V$.

(a) $V_0 = A V_{id} = A(V_1 - V_2) = A(V_{in1} - V_{in2})$

$= 200000 [5 \times 10^{-6} - (-7) \times 10^{-6}]$

$= 2.4V$ d.c.

(b) o/p voltage equation is valid for both ac & dc input signals. However, the restriction on ac i/p signals is that they must be of the same frequency.

$V_0 = 200{,}000 [10 \times 10^{-3} - 20 \times 10^{-3}] = -2000V$ rms.

$V_m = \sqrt{2}\, V_{rms} = \sqrt{2} \times -2000 = -2828\,V$ (peak).

Thus the theoretical value of o/p voltage $V_0 = -2000V$ rms (or) $-2828V$ (peak). However the op-amp saturates at $\pm 14V$. Therefore, the actual o/p waveform will be clipped as shown in fig (4).

The non-sinusoidal waveform is unacceptable in amplifier applications. The normal solution to this problem is to use a negative feedback.

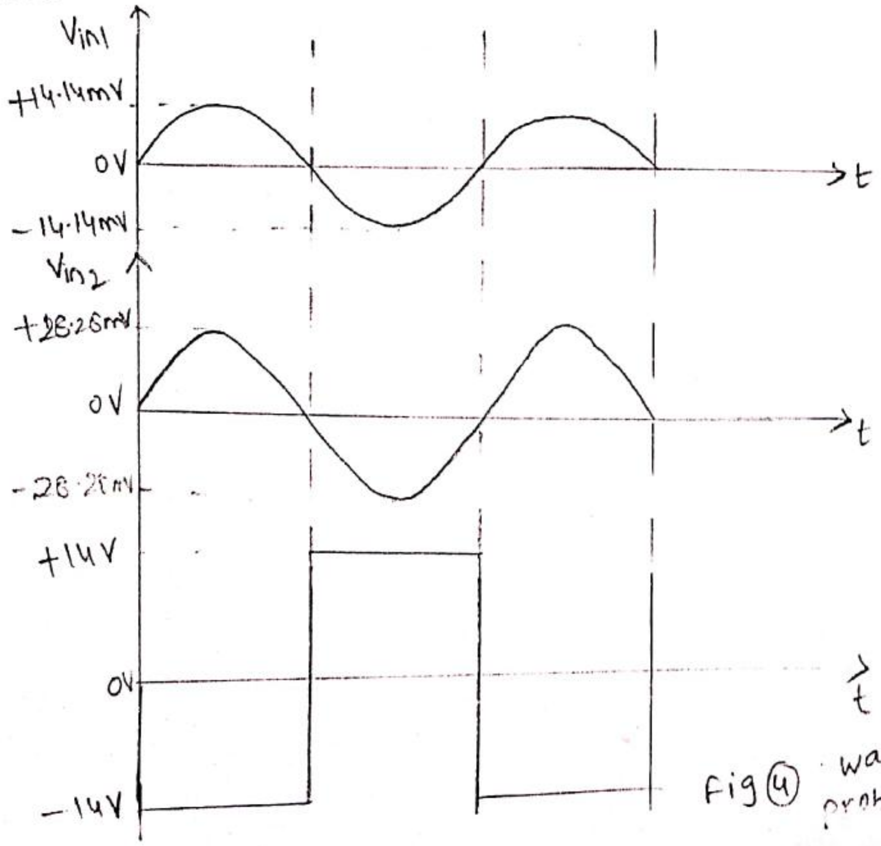


Fig (4) waveforms for problem 2 (1).

(2) Determine the output voltage for the inverting amplif[ier]
if (a) $V_{in} = 20mV$ dc

(b) $V_{in} = -50\mu V$ peak sine wave.

Assume that the op-amp is a 741.

The Bandwid[th] remains small

Ans:

(a) $V_o = -AV_{in} = -200,000 \times 20mV$

$= -4000V$ (Theoretical value)

The actual value will be a negative saturation voltage of $-14V$.

(b) $V_o = -AV_{in} = -200,000 \times -50 \times 10^{-6} = 10V$ peak sine wave

This means that the output is a sine wave, since it is less than the output voltage swing of $\pm 14V$ (or) $28V$ (peak to peak)

Disadvantages of open-loop configuration:-

(1) In open loop configurations, clipping occurs when the output attempts to exceed the saturation levels of the op-amp.

In other words, because the open-loop gain of the op-amp is very high, only the smaller signals (of order of microvolts (or) less) having very low frequency may be amplified accurately without distortion.

But this small signals are very susceptible to noise and almost impossible to obtain in labaratory.

(2) The open-loop voltage gain of the op-amp is not a constant. The voltage gain varies with changes in temperature and power supply as well as mass production techniques.

The variations in voltage gain are relatively large in open loop op-amps, which makes the open-loop op-amp unsuitable for many linear applications because

... linear applications the o/p is proportional to i/p & is of

) The Bandwidth (band of frequencies for which the gain remains constant) of most op-amps is negligibly small - almost zero.

For this reason the open-loop is impractical in ac applications.

For instance, the open-loop bandwidth of 741IC is approximately 5 Hz. However, in almost all ac applications a bandwidth larger than 5Hz is needed.

Closed loop. Configuration:-

selection as well as controlling the gain of an op-amp can be obtained by introducing a modification in the basic op-amp ckt.

This modification involves the use of feedback; i.e, an output signal is fedback to the input either directly (or) via another network.

→ An op-amp that uses feedback is called a feedback amplifier. It is also referred to as a closed-loop amplifier because the feedback forms a closed-loop between input & the output.

→ If the signal fed back is of opposite polarity (or) out of phase by 180° (or odd integer multiples of 180°) w.r.t the i/p signal, the feedback is called negative feedback.

→ An amplifier with negative feedback has a self-correcting ability against any change in output voltage caused by changes in environmental conditions.

→ Negative feedback is also known as degenerative feedback because when used it degenerates (reduces) the output voltage amplitude and in turn reduces the voltage gain.

→ If the signal fedback is in phase with the input signal, the feedback is called positive feedback.

→ In positive feedback the feedback signal aids the input signal, so it is also referred as regenerative feedback. ∴ positive feedback is necessary in oscillator circuits.

Advantages of negative feedback :

(1) stabilizes the gain
(2) Increases the bandwidth
(3) Increases the i/p impedance
(4) decreases the o/p impedance
(5) decreases harmonic (or) non-linear distortion
(6) Reduces the effect of i/p offset voltage at the o/p
(7) Reduces The effect of variations in temperature & supply voltages on the o/p of the op-amp.

Disadvantages

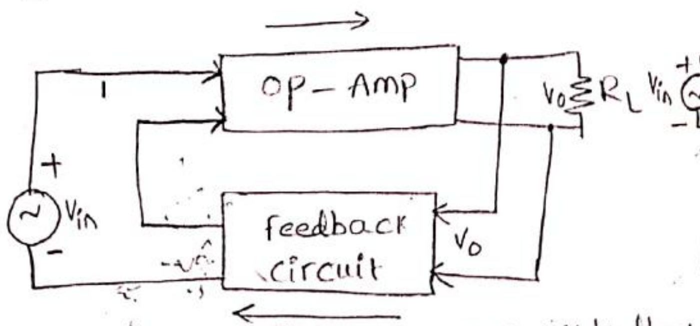
(1) Reduces voltage gain.

A closed-loop amplifier can be represented by using two blocks, one for an op-amp and another for a feedback circuit.

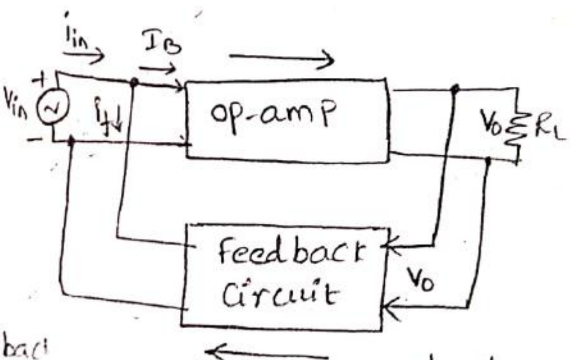
The feedback circuit can ~~be~~ take any form, depending on the intended application of the amplifier. This means, the feedback circuit may be made up of either passive components, active components or combinations of both.

There are four ways to connect these two blocks. These connections are classified according to whether the voltage (or) current is fed back to the input in series or in parallel, as follows:

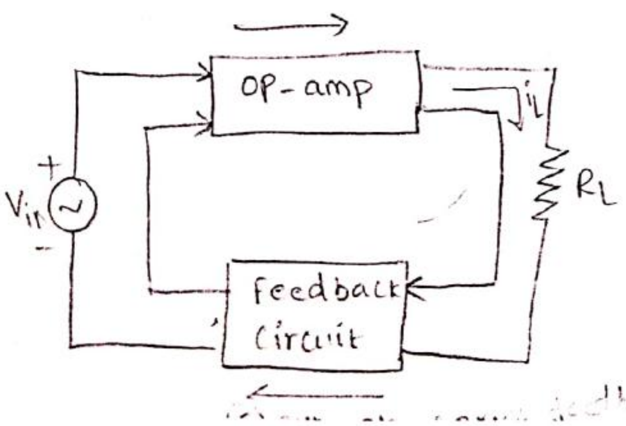
(1) voltage - series feedback
(2) voltage - shunt feedback
(3) current - series feedback
(4) current - shunt feedback

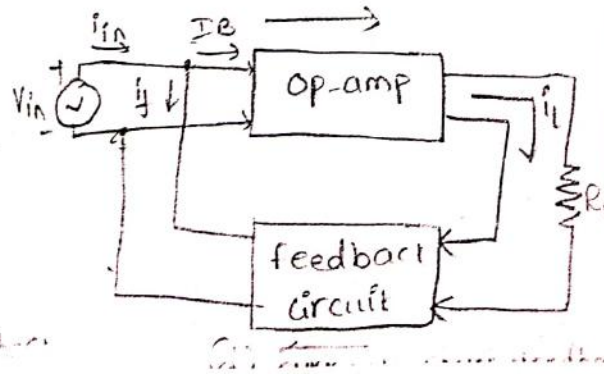


1 (a) voltage series feedback



1·(b) Voltage shunt feedback





The four types of configurations are illustrated in fig

In fig 1.ⓐ & 1.ⓑ the voltage across load resistor R_L is the input voltage to the feedback circuit. The feedback quantity (either voltage or current) is the output of feedback circuit and is proportional to the output voltage.

~~In fig ⓒ & ⓓ~~

In the current-series and current-shunt feedback circuits of fig 1.ⓒ & ⓓ, the current I_L flows into the feedback circuit. The output of the feedback circuit (either voltage or current) is proportional to the load current I_L.

In all four configurations the signal direction is from the input to output through the op-amp. On the other hand, in the ideal case the signal direction through the feedback circuit is exactly opposite: from output to input.

(1) <u>Voltage-series feedback amplifier (or)</u>
<u>Non-inverting amplifier with feed-back:-</u>

The schematic diagram of the voltage-series feedback amplifier is shown in fig. The op-amp is represented by its schematic symbol, including its large-signal voltage gain A, and the feedback circuit is composed of two resistors R_1 & R_F

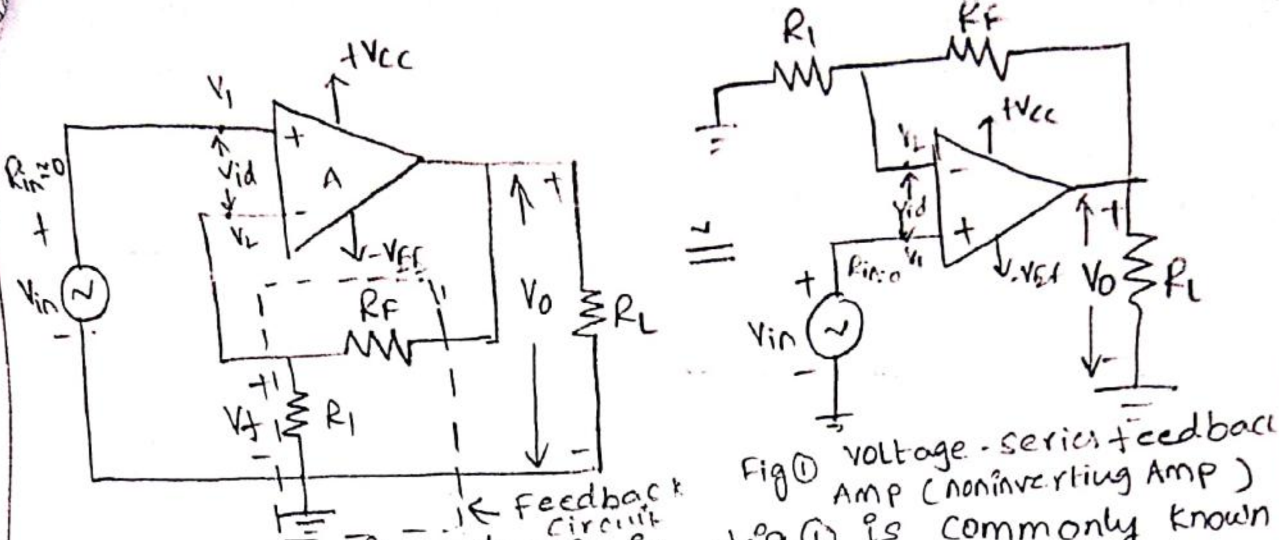


Fig ① Voltage-series feedback Amp (noninverting Amp)

The circuit shown in fig ① is commonly known as a noninverting amplifier with feedback (or closed-loop noninverting amplifier) because it uses feed-back, and the input signal is applied to the non-inverting input terminal of the op-amp.

Here,

open-loop voltage gain (or gain without feedback)

$$A = \frac{v_o}{v_{id}}$$

closed-loop Voltage gain (or gain with feedback)

$$A_F = \frac{v_o}{v_{in}}$$

Gain of the feedback circuit $B = \dfrac{V_f}{v_o}$

(1) <u>Negative feedback.</u>

By applying KVL to the i/p loop of fig

$$v_{in} - v_{id} - v_f = 0 \implies v_{id} = v_{in} - v_f \rightarrow ①.$$

where v_{in} = input voltage

v_f = feedback voltage

v_{id} = difference input voltage.

An op-amp always amplifies the difference input voltage v_{id}. This difference voltage is equal to the input voltage (v_{in}) minus the feedback voltage (V_f).

In other words, the feedback voltage always opposes the input voltage (or is out of phase by 180° w.r.t the i/p voltage); hence the feedback is said to be negative.

<u>closed loop voltage gain:-</u>

The closed loop voltage gain $(A_F) = \frac{V_o}{V_{in}}$

$$v_o = A V_{id} = A(V_1 - V_2)$$

where $V_1 = v_{in}$

$$V_2 = V_f = \frac{R_1 V_o}{R_1 + R_F} \quad \text{since } R_i >> R_1$$

Therefore

$$V_o = A\left(V_{in} - \frac{R_1 V_o}{R_1 + R_F}\right)$$

$$V_o(R_1 + R_f) = A V_{in}(R_1 + R_F) - AR_1 V_o$$

$$V_o(R_1 + R_f + AR_1) = A V_{in}(R_1 + R_F)$$

$$A_F = \frac{V_o}{V_{in}} = \frac{A(R_1 + R_F)}{R_1 + R_F + AR_1} \quad (\text{exact}) \longrightarrow (2)$$

Generally, A is very large (typically 10^5). Therefore

$$AR_1 >> (R_1 + R_F) \text{ and } R_1 + R_F + AR_1 \approx AR_1$$

Then $$A_F = \frac{V_o}{V_{in}} = 1 + \frac{R_F}{R_1} \quad (\text{Ideal}) \longrightarrow (3)$$

eqn (3) is the gain is

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eqn ③ is important because it shows that the gain of voltage series amplifier (non-inverting) is determined by the ratio of two resistors, R_1 & R_F.

for instance if a gain 11 is desired, we can then choose $R_1 = 1k\Omega$ & $R_F = 10k\Omega$ (or) $R_1 = 100\Omega$ & $R_F = 1k\Omega$.

In otherwords, in setting the gain the ratio of R_1 and R_F is important & not the absolute values of these resistors.

As a general rule, all external component values should be less than $1M\Omega$ so that they do not adversely affect the internal circuitry of the op-amp.

The gain of the feedback circuit (B) is the ratio of V_f and V_o.

$$B = \frac{V_f}{V_o}$$

$$= \frac{R_1}{R_1 + R_F} \rightarrow ④$$

By comparing eqn ③ & ④ we can conclude that

$$A_F = \frac{1}{B} \quad \text{(ideal)}. \rightarrow ⑤$$

This means that the gain of the feedback circuit is the reciprocal of the closed loop voltage gain.

In other words, for given R_1 & R_F the values of A_F & B are fixed.

The closed loop voltage gain A_F can be expressed in terms of open-loop gain (A) & feedback circuit gain B. By deviding Nr & Dr of eqn ② with R_1+R_F.

$$A_F = \frac{A\left(\frac{R_1+R_F}{R_1+R_F}\right)}{\frac{R_1+R_F}{R_1+R_F} + \frac{AR_1}{R_1+R_F}}$$

$$A_F = \frac{A}{1+AB} \rightarrow ⑥$$

where A_F = closed-loop voltage gain
A = open-loop voltage gain
B = gain of the feedback circuit
AB = loop gain.

A one-line block diagram of eqn ③ is shown in fig ②. This block diagram illustrates a standard form for representing a system with feedback and also indicates the relationship between different variables of the system.

The block-diagram helps to simplify the analysis of complex closed-loop networks, particularly if they are composed of nonresistive feedback circuits.

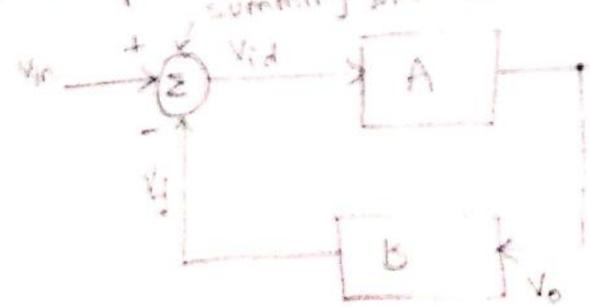

Fig ② Block diagram representation of noninverting amplifier with feedback

Difference input voltage ideally zero :-

we know that $V_o = A\,V_{id} \Rightarrow V_{id} = \frac{V_o}{A}$

Since A is large (idealy infinite)

$$V_{id} \approx 0 \longrightarrow 7(a)$$

$$V_1 \approx V_2 \text{ (ideal)} \longrightarrow 7(b)$$

Eqn 7(b) says that the voltage at the noninverting input terminal of an op-amp is approximately equal to that at the inverting input terminal provided that A is very large.

This concept is useful in the analysis of closed-loop op-amp circuits. For example, ideal closed-loop voltage gain can be obtained as follows.

Using the preceding results

$$V_1 = V_{in}$$

$$V_2 = V_f$$

$$= \frac{R_1 V_o}{R_1 + R_F}$$

substituting these values of V_1 & V_2 in eqn 7(b),

we get

$$V_{in} = \frac{R_1 V_o}{R_1 + R_F}$$

$$A_F = \frac{V_o}{V_{in}} = 1 + \frac{R_F}{R_1}$$

Input Resistance with Feedback :-

Fig (3) shows a voltage-series feedback amplifier with the op-amp equivalent circuit.

In this circuit R_i is the input resistance (open-loop) of the op-amp, and R_{iF} is the input resistance of the amplifier with feedback.

The input resistance with feedback is defined as

$$R_{iF} = \frac{v_{in}}{I_{in}}$$

$$= \frac{v_{in}}{v_{id}/R_i}$$

$$v_{id} = \frac{v_o}{A} \quad \& \quad v_o = \frac{A}{1+AB} v_{in}$$

$$v_{id} = \frac{v_{in}}{1+AB}$$

$$R_{iF} = \frac{v_{in} R_i}{v_{id}} = \frac{v_{in} R_i}{v_{in}/1+AB} = R_i(1+AB) \rightarrow ⑧$$

This means that the input resistance of the op-amp with feedback is $(1+AB)$ times that without feedback.

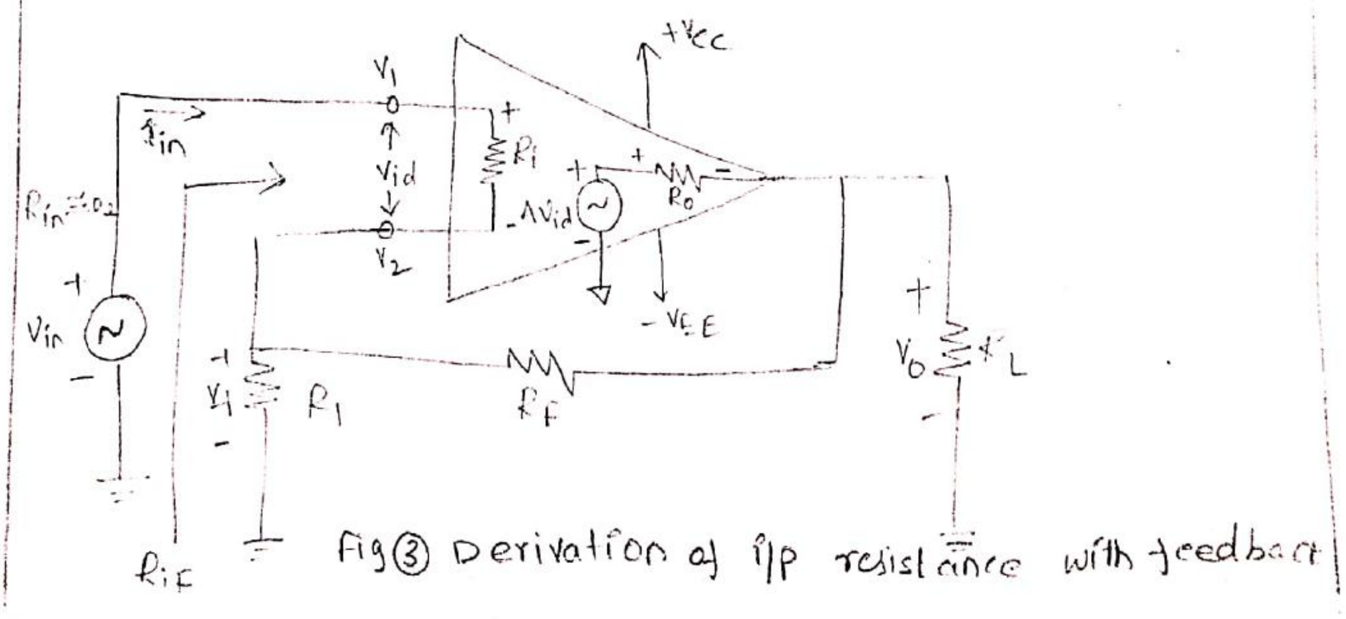

Fig ③ Derivation of i/p resistance with feedback

The current i_o can be found by writing kirchoff voltage equation for the output loop:

$$v_o - R_o i_o - A v_{id} = 0$$

$$i_o = \frac{v_o - A v_{id}}{R_o}$$

However $v_{id} = v_1 - v_2$

$$= 0 - v_f$$

$$= -\frac{R_1 v_o}{R_1 + R_F} = -B v_o$$

Therefore $i_o = \dfrac{v_o + AB v_o}{R_o} = \dfrac{v_o(1+AB)}{R_o}$

substituting the value of i_o in eqn 9(a), we get

$$R_{oF} = \frac{v_o}{v_o(1+AB)/R_o} = \frac{R_o}{1+AB} \rightarrow 9(b)$$

This result shows that the output resistance of the voltage-series feedback amplifier $1/1+AB$ times the output resistance R_o of the op-amp

That is, the output resistance of the op-amp with feedback is much smaller than the output resistance without feedback.

<u>Bandwidth with Feedback:-</u>

The bandwidth of an amplifier is defined as the band (range) of frequencies for which the gain remains constant.

Manufacturers generally specify either the gain-bandwidth product (or) supply open loop gain versus problems

(1) The 741C op-amp having the following parameters is connected as noninverting amplifier with $R_1 = 1k\Omega$ & $R_F = 10k\Omega$:

$A = 200{,}000$, $R_i = 2M\Omega$, $R_o = 75\Omega$, $f_o = 5Hz$,

supply voltages $= \pm 15V$, output voltage swing $\pm 13V$.

Compute the values of A_F, R_{iF}, R_{oF}, f_F & V_{OOT}.

Ans:- $B = \dfrac{R_1}{R_1+R_F} = \dfrac{1k}{1k+100k} = \dfrac{1}{11}$

$$1+AB = 1+\frac{200{,}000}{11} = 18{,}182.8$$

$$A_F = \frac{A}{1+AB} = \frac{200{,}000}{18{,}182.8} = 10.99$$

$$R_{iF} = R_i(1+AB) = 2\times10^6 \times 18{,}182.8 = 36.4\ G\Omega$$

$$R_{oF} = R_o/1+AB = 75/18{,}182.8 = 4.12\ m\Omega$$

$$f_F = f_o(1+AB) = 5\times 18{,}182.8 = 90.9\ kHz$$

$$V_{OOT} = \frac{\pm V_{sat}}{1+AB} = \frac{\pm 13}{18{,}182.8} = \pm 0.715\ mV$$

(2) Repeat problem (1) for voltage follower

$$B = 1$$
$$1+AB = 1+200{,}000 = 200{,}000$$

$$A_F = 1$$

$$R_{iF} = AR_i = 200{,}000 \times 2M\Omega = 400\ G\Omega$$

$$R_{oF} = \frac{R_o}{A} = \frac{75}{200{,}000} = 0.375\ m\Omega$$

$$f_F = Af_o = 200{,}000\times 5 = 1\ MHz$$

$$V_{OOT} = \frac{\pm V_{sat}}{A} = \frac{\pm 13}{200{,}000} = \pm 65\ \mu V$$

Thus, the i/p & o/p resistances of the voltage follower approches ideal values and the BW is equal to the maximum operating frequency of the op-amp $\therefore$ since $(1+AB) = A$,

VOLTAGE - SHUNT FEEDBACK AMPLIFIER:-

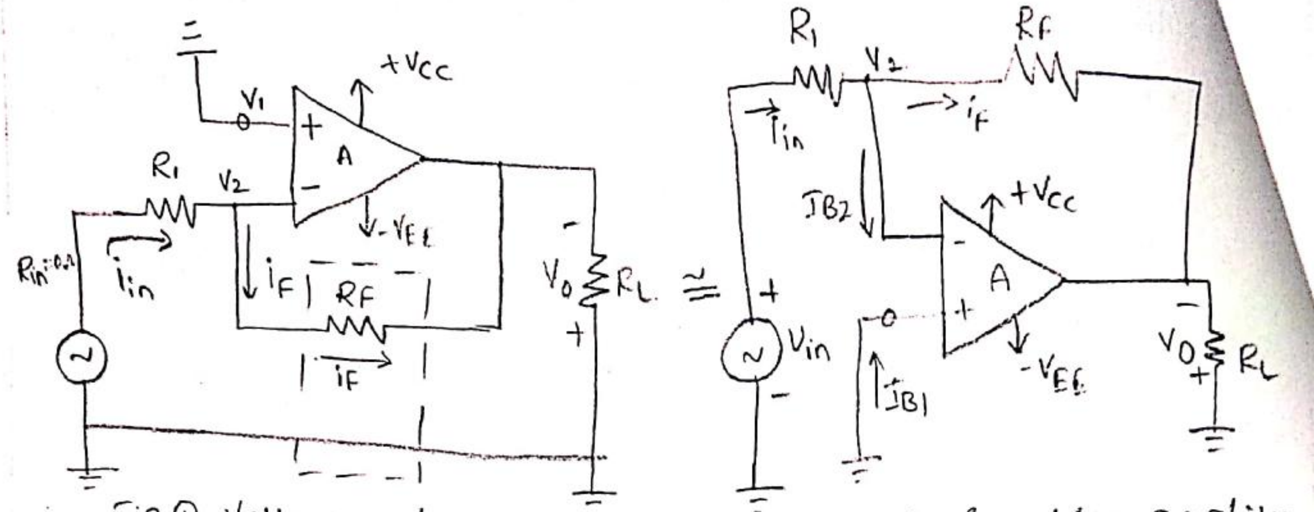

Fig ① Voltage-shunt feedback Amplifier (or inverting amplifier with feedback)

Fig ① shows the voltage - shunt feedback amplifier (or inverting amplifier with feedback) using an op- amp.

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

This arrangement forms a negative feedback because any increase in the output signal results in a feedback signal into the inverting input, causing a decrease in the output signal.

Note that the non-inverting terminal is grounded, and the feedback circuit has only one resistor R_F. However, an extra resistor R_1 is connected in series with the input signal source v_{in}.

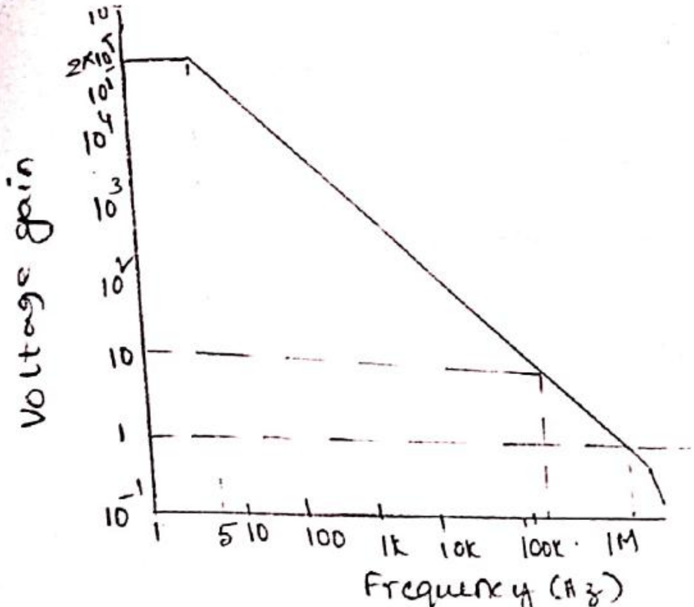

Fig ⑤ : open loop gain versus frequency curve of 741C

Fig⑤ shows the open-loop gain versus frequency curve of the 741C op-amp. From this curve for a gain of 200,000, the band width is approximately 5Hz. (or) the gain-bandwidth product is (200,000×5Hz) = 1MHz.

on the other ~~band~~ extreme, the bandwidth is approximately 1MHz when the gain is 1. Thus, the gain-bandwidth product is constant.

However, this holds true only for op-amps, like the 741 that have just ~~one~~ ~~be~~ one break frequency below unity-gain-bandwidth.

for the 741, 5Hz is the break frequency; the frequency at which the gain A is 3dB down from its value at 0Hz. we will denote it by f_o.

The frequency at which the gain equals 1 is known as the unity gain-bandwidth (UGB).

Since for an op-amp with a single break frequency f_o, the gain-bandwidth product is constant, and equal to the unity gain-bandwidth (UGB)

$$UGB = (A)(f_o) \rightarrow 10 \text{ Ⓔ}$$

where A = open-loop voltage gain

f_o: break-frequency of an op-amp.

alternatively, only for a single break-frequency op-amp.

$$UGB = (A_F)(f_F) \rightarrow 10(b)$$

where A_F: closed-loop voltage gain

f_F = bandwidth with feedback.

equating 10(a) & 10(b)

$$A f_o = A_F f_F$$

$$f_F = \frac{A f_o}{A_F} \rightarrow 10(c)$$

For the noninverting amplifier with feedback

$$A_F = \frac{A}{1+AB}$$

Substituting the value of A_F in eqn 10(c), we get

$$f_F = \frac{A f_o}{A/1+AB}$$

$$f_F = f_o(1+AB) \rightarrow 10(d)$$

Eqn 10(d) indicates that the bandwidth of the non-inverting amplifier with feedback f_F is equal to its bandwidth without feedback f_o times $(1+AB)$

If negative feedback is used, gain A decreases to $A/1+AB$; consequently, the open-loop bandwidth f_o (the break frequency) should increase to $f_o(1+AB)$

For instance, let us assume that the 741C is used as noninverting amplifier for the voltage gain (A_F) of 10

Then closed loop band width f_F will be 100KHz as follows.

$$f_F = \frac{A f_o}{A_F} = \frac{200{,}000 \times 5}{10} = 100\,KHz$$

The closed loop bandwidth can also be determined from the open-loop gain versus frequency plot. To do this we locate the closed loop voltage gain value on the gain axis and draw a line through this value parallel to the frequency axis and read the value of the closed-loop bandwidth. Using this procedure the bandwidth is approximately 100 KHz for a closed-loop gain of 10.

Total output offset Voltage with Feedback:-

In an op-amp when the input is zero, the output is also expected to be zero.

However, because of the effect of input offset voltage and current, the output is significantly larger, a result in large part of very high-open loop gain.

That is, the high gain aggravates the effect of input offset voltage and current at the output. We call this enhanced output voltage the total output offset voltage V_{OOT}.

In an open-loop op-amp the total output offset voltage is equal to either the positive (or) negative saturation voltage. The saturation voltages are specified on the data sheets as output voltage swing.

Since with feedback the gain of the noninverting 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. That is,

$$\text{Total output offset voltage with feedback} = \frac{\text{total o/p offset voltage without feedback}}{1+AB}$$

$$V_{OOT} = \frac{\pm V_{sat}}{1+AB} \rightarrow (11)$$

where $\frac{1}{1+AB}$ is always less than 1 and $\pm V_{sat}$ = Saturation voltages, the maximum voltages the output of an op-amp can reach

In an open-loop configuration even a very small voltage at the i/p of an op-amp can cause the o/p to reach maximum value ($+V_{sat}$ (or) $-V_{sat}$), for a given op-amp circuit the V_{OOT} is either positive (or) negative voltage because V_{sat} can be either positive (or) negative.

→ Negative feedback can also be used to reduce significantly the effect of noise, variations in supply voltages, and changes in temperature on the output voltage of a noninverting amplifier. Higher the value of $(1+AB)$, the smaller is the effect of noise, variations in supply voltages and changes in temperature on the output voltage of a noninverting amplifier.

→ From this analysis it is clear that the noninverting amplifier with feedback exhibits the characteristics of the perfect voltage amplifier. That is, it has very high input resistance, very low output resistance, stable voltage gain, large bandwidth, and very little (ideally zero) output offset voltage.

Voltage Follower:-

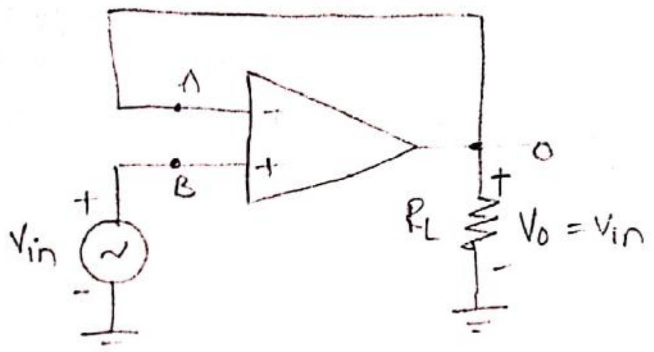

Fig ⑥ Voltage follower.

The lowest gain that can be obtained from a noninverting amplifier with feedback is '1'.

When the noninverting amplifier is configured for unity gain, it is called a voltage follower because the output voltage is equal to and in phase with the input. In other words, in the voltage follower the output follows the input.

To obtain the voltage follower from the noninverting amplifier, simply open R_1 and short R_F. The resulting circuit is shown in fig ⑥

Here The node B is at potential V_{in}. Now node A is also at the same potential as B i.e V_{in}

$$V_A = V_B = V_{in} \rightarrow ①$$

Now node 'A' is directly connected to the output

$$V_0 = V_A \rightarrow ②$$

from eqns ① & ②

$$V_0 = V_{in}$$

For this circuit, the voltage gain is unity.

Thus the output voltage V_0 is equal to the input voltage V_{in}. If V_{in} increases, V_0 also increases. If V_{in}

decreases, then Vo also decreases. Thus the o/p follows the input and hence the circuit is called voltage follower circuit. It is also called source follower, unity gain amplifier, buffer amplifier (or) isolation amplifier.

In this all the output voltage is fed back into the inverting terminal of the op-amp. the gain of the feedback circuit is 1 ($B = A_F = 1$)

$$A_F = 1$$ $\boxed{\because 1+A \approx A}$

$$R_{iF} = AR_i$$

$$R_{OF} = R_o/A$$

$$f_F = Af_o$$

$$V_{OOT} = \frac{\pm V_{sat}}{A}$$

The voltage follower is also called a noninverting buffer because when placed between two networks, it removes the loading on the first network.

<u>Advantages of Voltage follower:-</u>

(1) very large input resistance of the order of MΩ

(2) Low output impedance, almost zero, Hence it can be used to connect high impedance source to a low impedance load, as a buffer.

(3) It has large bandwidth.

(4) The output follows the input exactly without a phase shift.

Closed-Loop Voltage Gain:-

The closed loop voltage gain A_F of the voltage-shunt feedback amplifier can be obtained by writing Kirchoff's current equation at the input node "v_2" as follows:

$$i_{in} = i_F + I_{B2} \rightarrow (1)$$

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

$$i_{in} \cong i_F$$

$$\frac{v_{in} - v_2}{R_1} = \frac{v_2 - v_0}{R_F} \rightarrow (2)$$

However, $v_{id} = v_1 - v_2 = \frac{v_0}{A}$

Since $v_1 = 0$

$$v_2 = -\frac{v_0}{A}$$

Substituting this value of v_2 in eqn (2), we get

$$\frac{v_{in} + v_0/A}{R_1} = \frac{-\left(\frac{v_0}{A}\right) - v_0}{R_F}$$

$$\frac{v_{in}}{R_1} = \frac{-v_0}{AR_F} - \frac{v_0}{R_F} - \frac{v_0}{AR_1}$$

$$v_{in} = -v_0\left(\frac{R_1}{AR_F} + \frac{R_1}{R_F} + \frac{1}{A}\right)$$

$$v_{in} = -v_0\left(\frac{R_1 + AR_1 + R_F}{AR_F}\right)$$

$$A_F = \frac{v_0}{v_{in}} = -\frac{AR_F}{R_1 + R_F + AR_1} \quad (\text{exact}) \rightarrow (3)$$

The negative sign in eqn (3) indicates that the input and output signals are out of phase by 180° (or of opposite polarities).

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Let us obtain the closed loop transfer function $\frac{V_o}{V_{in}}$ of the block diagram.

$$-V_{in}K - V_f = V_{id} \rightarrow (5)$$

$$V_{id}A = V_o \rightarrow (6)$$

$$V_o B = V_f \rightarrow (7)$$

where A = open loop gain (forward path gain)

B = feedback circuit gain

K = voltage attenuation factor.

Substituting eqns (5) & (7) in eqn (6)

$$(\cancel{-V_{in}K - V_f B})\, A \cancel{=}$$

$$(-V_{in}K - V_f)A = V_o$$

$$(-V_{in}K - V_oB)A = V_o$$

$$-V_{in}AK = V_o(1+AB)$$

$$\frac{V_o}{V_{in}} = \frac{-AK}{1+AB} \rightarrow (8)$$

Now let us consider exact expression of (A_F), it is similar to (8)

$$A_F = \frac{-AR_F}{R_1+R_F+AR_1}$$

Divide numerator & Denominator by (R_1+R_F).

$$= \frac{-AR_F/R_1+R_F}{\frac{R_1+R_F}{R_1+R_F} + \frac{AR_1}{R_1+R_F}}$$

$$= \frac{-AK}{1+AB}$$

where $K = R_F/R_1+R_F$ & $B = R_1/R_1+R_F$

To derive the ideal closed-loop gain, we can use eqn ⑧ as follows:

If $AB >> 1$ then $1+AB \approx AB$ and we get

$$A_F = \frac{-AK}{AB} = \frac{-K}{B} = \frac{-R_F/R_1+R_F}{R_1/R_1+R_F} = -\frac{R_F}{R_1} \text{ (ideal)} \rightarrow (9)$$

A comparision of eqn ⑧ with the feedback eqn of noninverting amplifier indicates that in addition to the phase inversion (− sign), the closed loop gain of the inverting amplifier is K times the closed loop gain of the noninverting amplifier where $K < 1$

The reason for the one-line block diagram of the inverting amplifier with feedback is two-fold:

(1) To facilitate the analysis of the inverting amplifier

(2) To express the performance equations in the same form as those for the noninverting amplifier.

Inverting Input Terminal at Virtual Ground:-

In the inverting amplifier with feedback, the non-inverting terminal is grounded and the input signal is applied to the inverting terminal via resistor R_1. However, the difference input voltage is ideally zero, that is, the voltage at the inverting terminal (v_2) is approximately equal to that at the non-inverting terminal (v_1). In otherwords, the inverting terminal is said to be at virtual ground. This concept is extremely useful in the analysis of closed-loop inverting amplifier circuits.

In-fact, because of this phase inversion, this configuration is commonly called as an inverting amplifier with feedback.

Since the internal gain A of the op-amp is very large (ideally infinity), $AR_1 >> R_1 + R_F$. Then

$$A_F = \frac{V_o}{V_{in}} = -\frac{R_F}{R_1} \text{ (ideal)} \longrightarrow (11)$$

This eqn shows that the gain of the inverting amplifier is set by selecting a ratio of feedback resistance R_f to the input resistance R_1.

In fact, the ratio R_F/R_1 can be set to any value whatsoever, even to less than '1'. Because of this property of the gain equation, the inverting amplifier with feedback lends itself to a majority of applications as against those of noninverting amplifier.

Block diagram of inverting amplifier with feedback:-

To obtain the block diagram of the practical inverting amplifier, it is necessary to represent the current summing junction at the input terminals of an amplifier as a voltage summing junction.

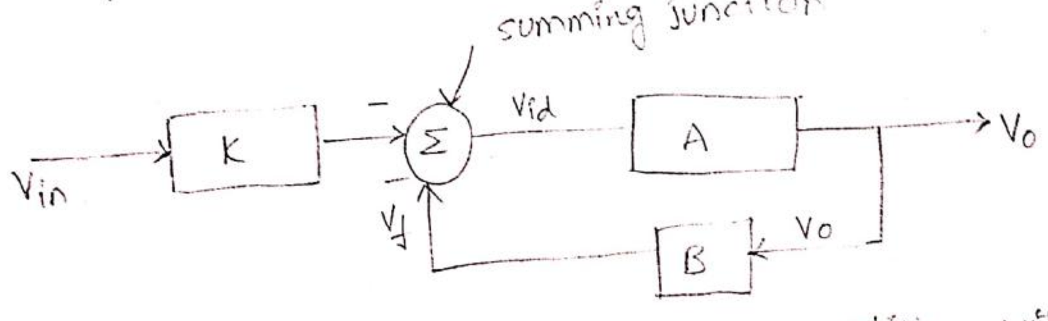


Fig (2) Block diagram of inverting amplifier with feedback using a voltage - summing junction as a ... current summing

For example, ideal closed-loop gain can be obtained using the virtual-ground concept as follows.

$$i_{in} \simeq i_F$$

$$\frac{v_{in}-v_2}{R_1} = \frac{v_2-v_0}{R_F}$$

However, $v_1 = v_2 = 0V$

Therefore, $\frac{v_{in}}{R_1} = \frac{-v_0}{R_F}$

(or

$$A_F = \frac{v_0}{v_{in}} = \frac{-R_F}{R_1} \text{ (Ideal)}.$$

Input Resistance with Feedback:-

The easiest method of finding the input resistance is to millarize the feedback resistor R_F, that is split R_F into its two miller components as shown in fig (3).

The input resistance with feedback R_{iF} is then

$$R_{iF} = R_1 + \left(\frac{R_F}{1+A} \| R_i\right) \text{ (exact)} \rightarrow (10)$$

since R_I and A are very large

$$\frac{R_F}{1+A} \| R_i \cong 0\Omega, \text{ Hence } R_{iF} = R_1 \text{ (ideal)}. \rightarrow (11)$$

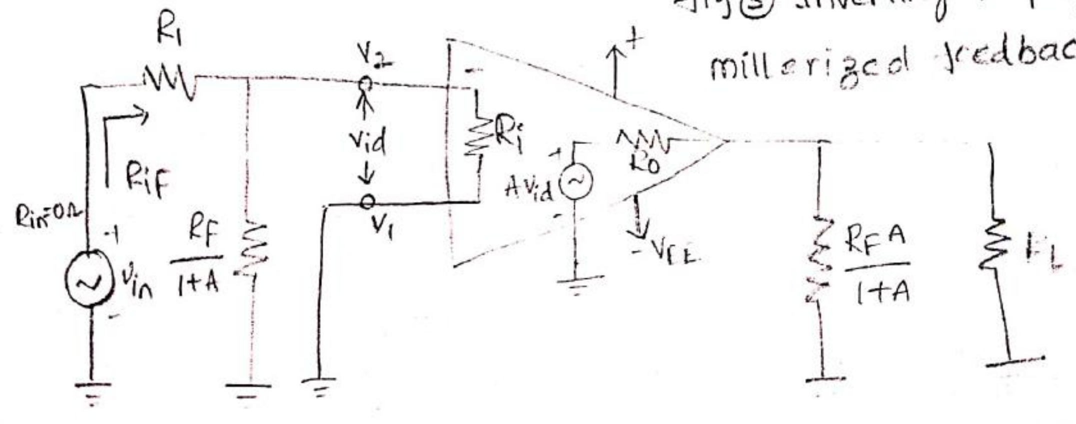


fig (3) Inverting Amplifier with millerized feedback resistor

Output Resistance with Feedback :-

The output resistance with feedback (R_{OF}) is the resistance obtained (measured) at the output terminal of the feedback amplifier.

The output resistance of the non-inverting amplifier obtained by using thevenin's Theorem, & we can do same for the inverting amplifier

Thevenin's equivalent ckt for R_{OF} of the inverting amplifier is shown in fig (4). Note that Thevenin's equivalent circuit is exactly the same as that of non inverting amplifier.

So $R_{OF} = \dfrac{R_O}{1+AB} \rightarrow (12)$

where R_O = output resistance of the op-amp

A = open-loop Voltage gain of the op-amp

B = gain of the feedback circuit.

The output resistance with feedback (R_{OF}) of the inverting amplifier is identical to that of the non-inverting amplifier.

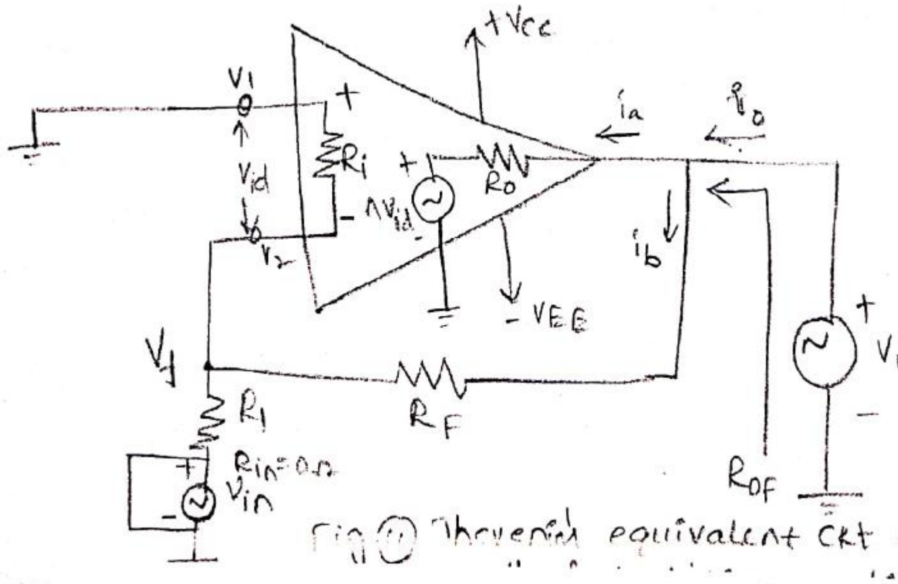


Fig (4) Thevenin's equivalent ckt for R_{OF} of

Bandwidth with Feedback:

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

The gain of the amplifier with feedback is always less than the gain without feedback.

Therefore, the bandwidth of the amplifier with feedback f_F must be larger than that without feedback.

$$f_F = f_0(1+AB) \rightarrow (13)$$

where f_0 = break frequency of the op-amp

$$= \frac{\text{Unity gain bandwidth}}{\text{open-loop voltage gain}}$$

$$= \frac{UGB}{A}$$

Substituting the value of f_0 in eqn (13), we get

$$f_F = \frac{UGB}{A}(1+AB)$$

$$f_F = \frac{(UGB)(K)}{A_F} \rightarrow (14)$$

where $K = \frac{R_F}{R_1+R_F}$ & $A_F = \frac{AK}{1+AB}$

To find the closed-loop bandwidth of the inverting amplifier, use eqn (13) if f_0 is known & use eqn (14) if unity gain-bandwidth (UGB) is given.

It is obvious that for the same closed loop gain the closed loop bandwidth for the inverting amplifier is lower than that for the noninverting amplifier by a factor of K (<1).

for example, when the closed loop gain is equal to '1', the bandwidth ~~for the non inverting amplifier~~ where will be

$f_F = UGB$ for the non-inverting amplifier.

$$A_F = \frac{AK}{1+AB} \approx \frac{AK}{AB} \approx \frac{K}{B} = 1$$

$$\frac{R_F}{R_1+R_F} = \frac{R_1}{R_1+R_F}$$

$$R_F = R_1$$

$$f_F = \frac{UGB\,K}{A_F} = \frac{UGB\,R_F}{A_F\,(R_1+R_F)} = \frac{UGB\,\cancel{R_F}}{1 \times 2\cancel{R_F}} = \frac{UGB}{2}$$

(for the inverting amplifier)

However, as the closed loop gain (A_F) approches the open-loop gain A, the difference between the noninverting amplifier bandwidths approaches zero.

As an extreme limit, when $K \approxeq 1$, the value of f_F for both the inverting & noninverting amplifiers is approximately the same.

Total output offset Voltage with Feedback:-

when the temperature and power supply voltages are fixed, the output offset voltage is a function of the gain of an op-amp.

However, the gain of the op-amp with feedback is always less than that without feedback.

The output offset voltage with feedback V_{OOT} must always be smaller than that without feedback.

$$\left(\text{Total o/p offset Voltage with feedback}\right) = \frac{\text{total o/p offset voltage without feedback}}{1+AB}$$

$$V_{OOT} = \frac{\pm V_{sat}}{\text{[illegible]}}$$

equal
mplifier

where $\pm V_{sat}$ = saturation voltages

A = open-loop voltage gain of the opamp

B = gain of the feedback circuit

$$B = \frac{R_{f1}}{R_1 + R_f}$$

The output offset voltage of the op amp without feedback can be either $+V_{sat}$ (or) $-V_{sat}$ because of its very high voltage gain A, which is typically on the order of 10^5.

Note that the V_{OOT} for the inverting amplifier is same as that of the noninverting amplifier. This is because, when the input signal V_{in} is reduced to zero, both inverting and noninverting amplifiers result in the same circuit.

→ Because of the negative feedback, the effect of noise, variations in supply voltage and changes in temperature on the output voltage of the inverting amplifier are significantly reduced.

Special cases of Inverting amplifier:-

(1) current-to-voltage converter

(2) Inverter.

Current to voltage converter:-

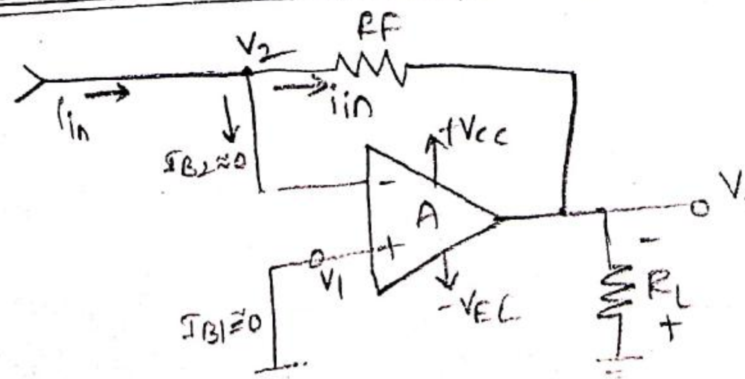


Fig ⑤ current to voltage converter

Let us consider the ideal voltage-gain of the inverting amplifier,

$$\frac{v_o}{v_{in}} = \frac{-R_F}{R_1}$$

$$v_o = -\left(\frac{v_{in}}{R_1}\right) R_F$$

However, since $v_1 = 0V$ & $v_1 = v_2$

$$\frac{v_{in}}{R_1} = i_{in}$$

$$v_o = -i_{in} R_F \rightarrow (16)$$

This means that if we replace the v_{in} and R_1 combination by a current source i_{in} ~~the~~ as shown in fig (5), the output voltage v_o becomes proportional to the input current i_{in}.

In other words circuit in fig (5) converts the input current into a proportional output voltage.

The most common uses of the current to voltage converter is in sensing current from photo detectors and in digital-to-analog converter applications.

Inverter:-

If we need an output signal equal in amplitude but opposite in phase to that of the input signal, we can use the inverter.

The inverting amplifier works as an inverter if $R_1 = R_F$. The equations of inverting amplifier can be applied to inverter by substituting $(A/2)$ for $(1+AB)$, since $B = \frac{1}{2}$.

oblems:-

For the inverting amplifier, $R_1 = 470\Omega$ & $R_F = 4.7K\Omega$. Assume that the op-amp is the 741 having the ~~same~~ specifications $A = 200{,}000$, $R_i = 2M\Omega$, $R_0 = 75\Omega$, $f_0 = 5Hz$, supply voltages $= \pm 15V$, output voltage swing $= \pm 13V$.

Compute the values of A_F, R_{IF}, R_{OF}, f_F & V_{OOT}.

Ans:- $K = \frac{R_F}{R_1 + R_F} = \frac{4.7K}{470 + 4.7K} = \frac{1}{1.1}$

$$B = \frac{R_1}{R_1 + R_F} = \frac{470}{470 + 4.7K} = \frac{1}{11}$$

$$1 + AB = 1 + \left(200000 \times \frac{1}{11}\right) = 18{,}182.8$$

$$A_F = \frac{-AK}{1+AB} = \frac{(200000)(1/1.1)}{18{,}182.8} = -10.$$

$$R_{IF} = R_1 + \left[\frac{R_F}{1+AB} \parallel R_i\right] = \left[470 + \left(\frac{4.7k}{18182.8} \parallel 2\times10^6\right)\right] = 470\Omega.$$

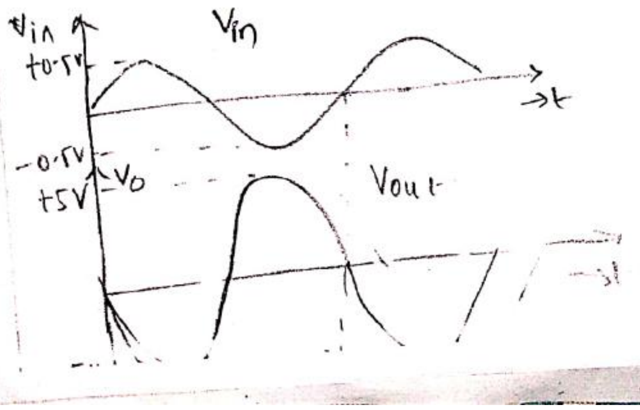
$$R_{OF} = \frac{R_0}{1+AB} = \frac{75}{18{,}182.8} = 4.12m\Omega$$

$$f_F = \frac{UGB\,K}{A_F} = \frac{f_0 A K}{A_F} = \frac{5 \times 200{,}000 \times 1/1.1}{10} = 100k\,Hz$$

$$V_{OOT} = \frac{\pm V_{sat}}{1+AB} = \frac{\pm 13V}{18{,}182.8} = \pm\ 0.715mV.$$

(2) For the inverting amplifier of above example, determine the value of output voltage if the input is a 1-V peak to peak sine wave at 1KHz. Also sketch the o/p waveform. Assume that V_{OOT} is zero.

$$v_0 = -A_F v_{in} = -(10)(1) = -10V \text{ peak to peak}.$$



Comparision of Noninverting & inverting amplifiers:

Parameter	Non-inverting amplifier	Inverting amplifier
(1) closed loop voltage gain	$A_F = \frac{A(R_1+R_F)}{R_1+R_F+AR_1}$ (exact) $= 1+\frac{R_F}{R_1}$ (Ideal)	$A_F = \frac{-AR_F}{R_1+R_F+AR_1}$ (exact) $= \frac{-R_F}{R_1}$ (ideal)
(2) Block diagram representation (A_F)	$A_F = \frac{A}{1+AB}$	$A_F = \frac{-AK}{1+AB}$
(3) Attenuation factor	$K=1$	$K = \frac{R_F}{R_1+R_F}$
(4) Gain of the feedback ckt	$B = \frac{R_1}{R_1+R_F}$	$B = \frac{R_1}{R_1+R_F}$
(5) input resistance with feedback	$R_{iF} = R_i(1+AB)$	$R_{iF} = R_1 + \left(\frac{R_F}{1+A} \parallel R_i\right)$ (exact) $\approx R_1$ (ideal)
(6) output resistance with feedback	$R_{oF} = \frac{R_o}{1+AB}$	$R_{oF} = \frac{R_o}{1+AB}$
(7) Bandwidth	$f_F = f_o(1+AB)$ $= \frac{UGB}{A_F}$	$f_F = \cancel{UGB}\, f_o(1+AB)$ $= \frac{UGB(K)}{A_F}$
(8) Total output offset voltage	$V_{ooT} = \frac{\pm V_{sat}}{1+AB}$	$V_{ooT} = \frac{\pm V_{sat}}{1+AB}$
(9) special cases	Voltage follower	current to voltage converter & Inverter.
(10) Block diagram	—	—
(11) ckt diagram.	—	—

Differential Amplifier with three op-Amps:-

The advantages of the two differential amplifiers (Variable voltage gain and very high input resistance) Can be combined in a single differential amplifier. To achieve this desirable combination, three op-amps must be Used. as shown in fig (4).

Voltage gain:-

The differential amplifier op-amp of fig (4) consists of two stages. The first stage is composed of op-amps A_1 & A_2, while the second stage is formed by op-amp A_3.

Therefore, to find the overall voltage gain A_D of the amplifier, the voltage gain of each stage must be determined.

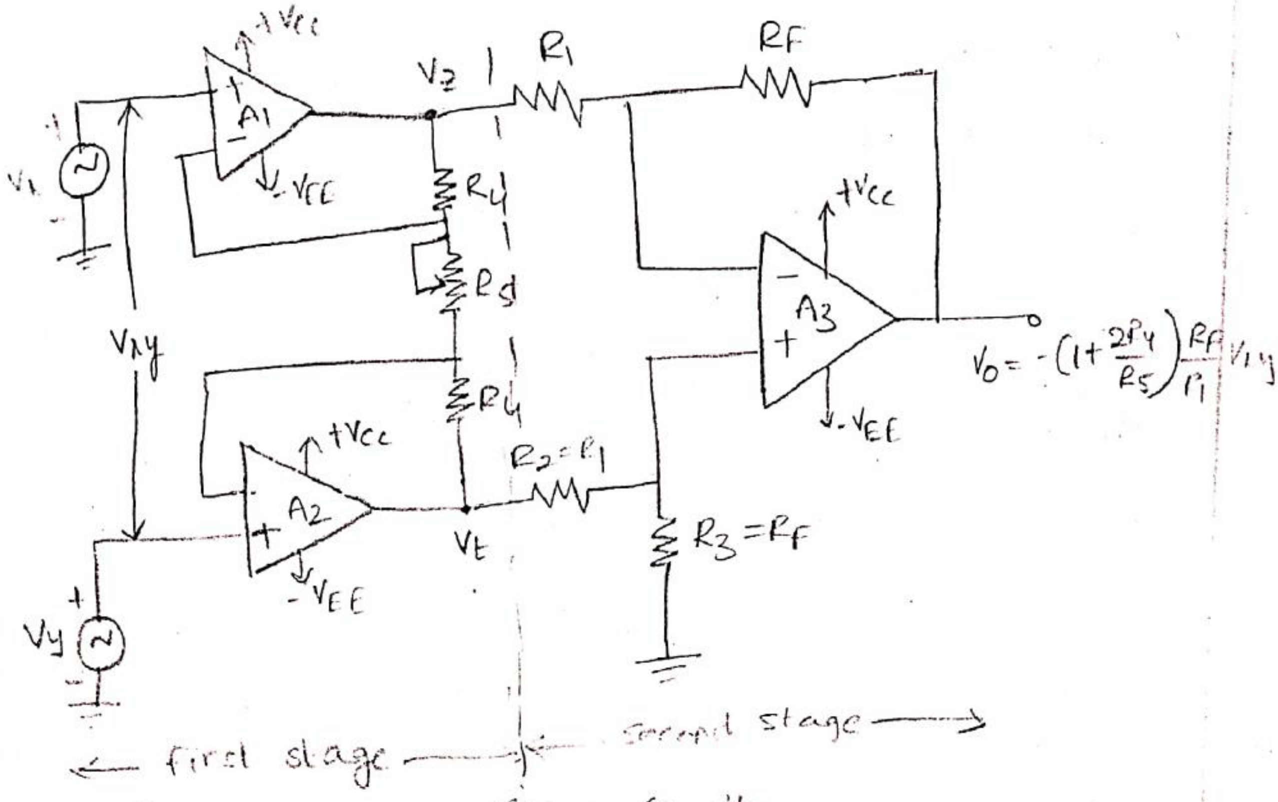


Fig (4) Differential amplifier with three op-amps

$$V_{zt}\left(1-\frac{R_4}{R_4+R_5}\right)=\frac{2R_4+R_5}{R_4+R_5}V_{xy}$$

$$\frac{V_{zt}}{V_{xy}} = \frac{2R_4+R_5 / R_4+R_5}{R_5 / R_4+R_5}$$

$$\frac{V_{zt}}{V_{xy}} = \frac{2R_4+R_5}{R_5}$$

The gain of the second stage is

$$\frac{V_o}{V_{zt}} = \frac{-R_F}{R_1}$$

The overall voltage gain is

$$A_D = \frac{V_o}{V_{xy}} = \frac{V_o}{V_{zt}} \times \frac{V_{zt}}{V_{xy}} = -\frac{R_F}{R_1}\times\left(\frac{2R_4+R_5}{R_5}\right)$$

(or) $$A_D = \frac{V_o}{V_{xy}} = -\left(1+\frac{2R_4}{R_5}\right)\frac{R_F}{R_1}$$

Remember that the gain can be changed by varying potentiometer R_5. Of course, R_5 should never be set to zero (or) infinity.

If R_5 is set to zero, the voltage gain eqn becomes indeterminant, whereas if R_5 is set to infinity (open R_5) the first stage acts as a voltage follower.

Input resistance:-

The input resistance R_{iF} of the differential amplifier is the same as the i/p resistance of the first stage, that is, the resistance determined at input V_x & V_y looking into the circuit with the other

Closed Loop Differential amplifiers :-

Differential amplifier with negative feedback can be classified according to the no. of op-amps used. They are

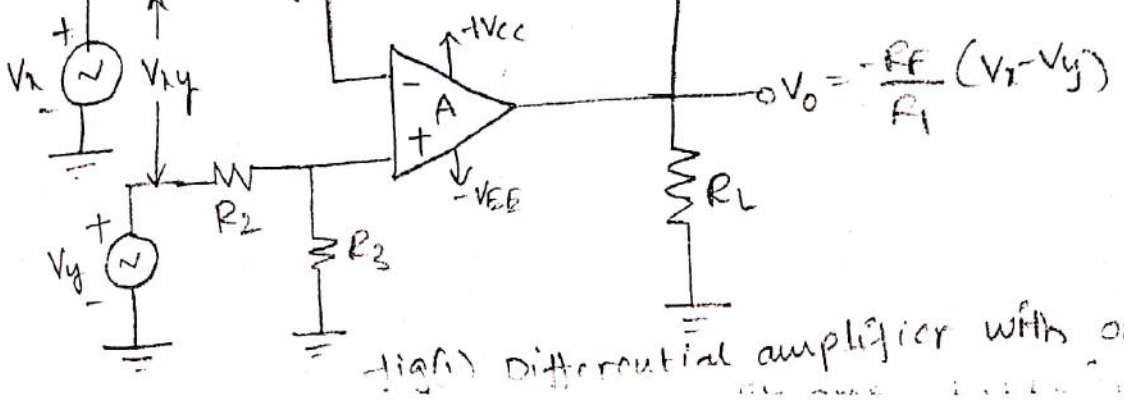
1. Differential amplifier with one op-amp
2. Differential amplifier with two op-amps
3. Differential amplifier with three op-amps

The differential amplifiers are used in instrumen-tation and industrial applications to amplify the differences between two i/p signals such as the outputs of the wheat-stone bridge circuits.

Differential amplifiers are preferred in these applications because they are better able to reject common-mode (noise) voltages than single-input circuits such as inverting & non-inverting amplifiers. They also present a balanced i/p impedance.

Differential Amplifier with one-op-amp :-

Fig (1) shows the differential amplifier with one op-amp. The differential amplifier is a combination of inverting and non-inverting amplifiers.



fig(1) Differential amplifier with one

when V_x is reduced to zero the circuit is a noninverting amplifier, where as the circuit is an inverting amplifier when input V_y is reduced to zero.

Voltage gain:-

The ckt shown in fig ① has two inputs, V_x and V_y. we will use superposition Theorem in order to establish the relationship between input and output.

when $V_y = 0V$, the configuration becomes an inverting amplifier: hence the output due to V_x is

$$V_{ox} = \frac{-R_F}{R_1}(V_x) \rightarrow ①$$

similarly, when $V_x = 0V$, the configuration is a noninverting amplifier having a voltage-divider network composed of R_2 and R_3 at the noninverting input. Therefore

$$V_1 = \frac{R_3 (V_y)}{R_2 + R_3}$$

and the output due to V_y is

$$V_{oy} = \left(1 + \frac{R_F}{R_1}\right) V_1$$

$$= \left(1 + \frac{R_F}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right) V_y$$

since $R_1 = R_2$ & $R_F = R_3$

$$V_{oy} = \left(\frac{R_F}{R_1}\right) V_y \rightarrow ②$$

Thus from eqn ①&②, the net output voltage is

$$V_o = V_{ox} + V_{oy} = \frac{-R_F}{R_1} V_x + \frac{R_F}{R_1} V_y$$

$$= \frac{-R_F}{R_1}(V_x - V_y) = \frac{-R_F}{R_1}(V_{xy})$$

or the voltage gain

$$A_D = \frac{V_0}{V_{xy}} = \frac{-R_F}{R_1} \rightarrow (3)$$

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

Input resistance:-

The input resistance R_{iF} of the differential amplifier is the resistance determined looking into either one of the two input terminals with other grounded.

Therefore, with $V_y = 0V$, the ckt in fig (1) is an inverting amplifier, the input resistance of which is

$$R_{iFx} \cong R_1 \rightarrow (4)$$

Similarly, with $V_x = 0V$, the differential amplifier becomes a noninverting amplifier whose input resistance can be written as.

$$R_{iFy} \cong (R_2 + R_3) \rightarrow (5)$$

from equs (4) & (5), it is obvious that the input resistance seen by the signal sources V_x and V_y are not the same. This inequality can be corrected and both input resistances can be made equal if we modify the basic differential amplifier of fig (1) as shown in fig (4).

However, to perform properly, both R_1 & $(R_2 + R_3)$ can be made much larger than the source resistances so that loading of signal sources doesn't occurs.

If we need a variable gain; we can use the differential amplifier of fig ②.

In this circuit $R_1 = R_2$, $R_f = R_3$ and the potentiometer $R_p = R_4$. Therefore depending on the position of the wiper in R_p, voltage gain can be varied from the closed loop gain of $-\frac{2R_F}{R_1}$ to the open loop gain of A.

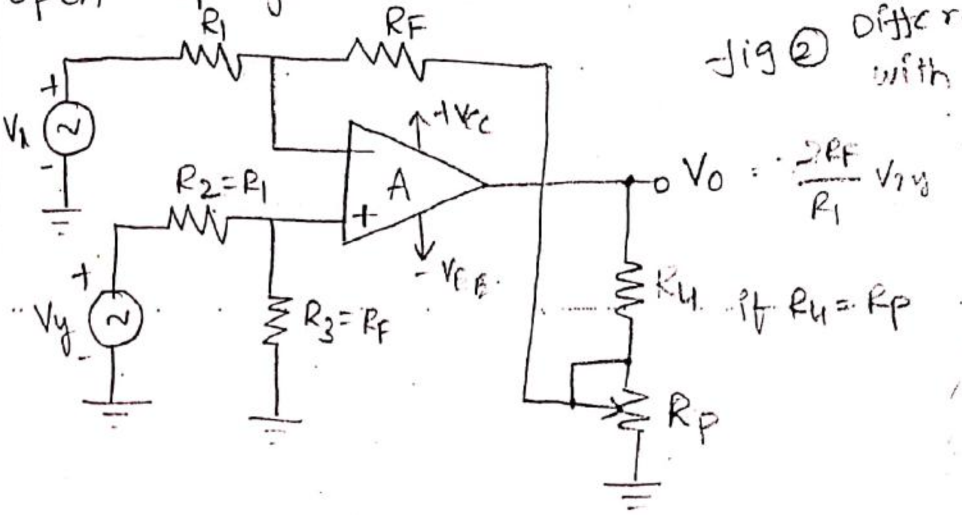


fig ② Differential Amp with variable gain

problem

In the ckt of fig(1) $R_1 = R_2 = 1k\Omega$, $R_F = R_3 = 10k\Omega$, and the op-amp is a 741C

(a) what are the gain & input resistance of the amplifier

(b) calculate the output voltage V_o if $V_x = 2.7V$ PP and $V_y = 3V$ sine waves at 100 Hz

(a) $A_D = -\frac{R_F}{R_1} = \frac{-10k}{1k} = -10$

$R_{IFx} \cong R_1 = 1k\Omega$

$R_{IFy} \cong R_2 + R_3 = 1k + 10k \cong 11k\Omega$.

(b) $V_o = -A_D V_{xy} = -A_D(V_x - V_y)$

$= -10(2.7 - 3V)$

$= 3V$ PP sine wave at 100Hz