UNIT – II

Operational Amplifiers and Applications: Introduction to Op-Amp, Differential Amplifier Configurations, CMRR, PSRR, Slew Rate; Block Diagram, Pin Configuration of 741 Op-Amp, Characteristics of Ideal Op-Amp, Concept of Virtual Ground; Op-Amp Applications - Inverting, Non-Inverting, Summing and Difference Amplifiers, Voltage Follower, Comparator, Differentiator, Integrator.

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2.1 BASICS OF DIFFERENTIAL AMPLIFIER

The Differential amplifier is a basic building block of the op-amp. The function of the differential amplifier is to amplify difference in between two input signals. Let us consider 2 emitter-biased circuits as shown in the figure.

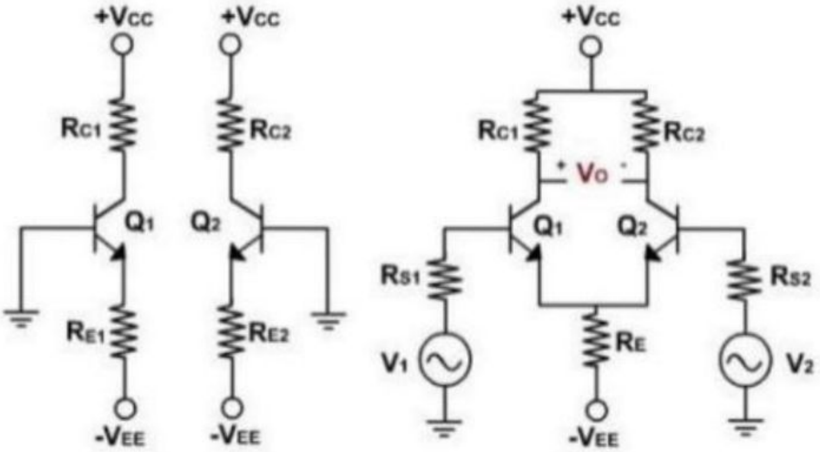


Figure 2.1: Basic Differential Amplifier

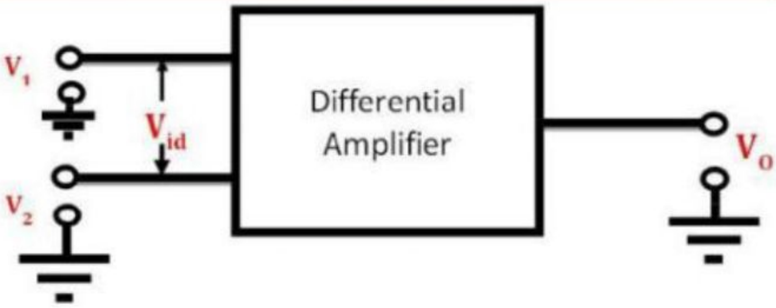
The 2 transistors Q_1 and Q_2 have the same characteristics. The resistances of circuits are equal, that is R_{E1} = R_{E2}, $R_{C1} = R_{C2}$ and magnitude of $+V_{CC}$ is equal to magnitude of $-V_{EE}$. These voltages are measured with respect to the ground.

To make a differential amplifier, two circuits are connected as shown in the figure. The two $+V_{CC}$ and $-V_{EE}$ supply terminals are made common as they are same. The two emitters are also connected and parallel combination of R_{E1} and R_{E2} is replaced by the resistance R_E. The two input signals V_1 & V_2 are applied at base of Q_1 and at base of Q_2. The output voltage is taken between the two collectors. The collector resistances are equal and hence denoted by $R_C = R_{C1} = R_{C2}$.

Ideally, output voltage is zero when the two inputs are equal. When V_1 is greater than V_2 output voltage with the polarity shown appears. When V_1 is less than V_2, output voltage has the opposite polarity.

Differential Amplifier

The differential amplifier amplifies the difference between two input voltage signals. Hence it is also called difference amplifier. The need for differential amplifier in many physical measurements arises where response from d.c to many megahertz is required. It is also the *basic input stage of an integrated amplifier.*



The output signal in a differential amplifier is proportional to the difference between the two input signals.

$$V_o \alpha (V_1 - V_2)$$

Where,

V_1 & V_2 – Two input signals

V_o – Single ended output Each signal is measured with respect to the ground.

Modes of operation of Differential Amplifier

There are two modes of operations of differential amplifier

- Differential mode operation
- Common mode operation

Differential mode operation

Two input signals are of **same magnitude** but **opposite polarity** are used (180^0 out of phase)

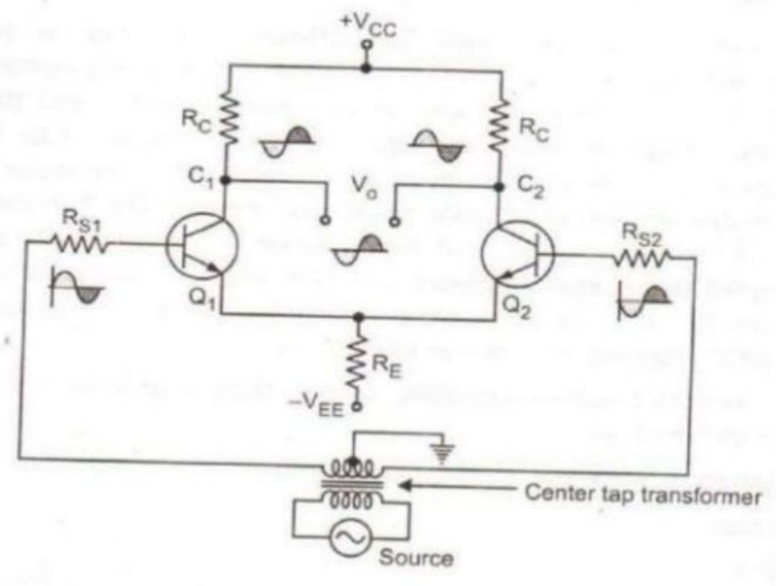


Figure 2.2: Differential Mode Operation

Assume sine wave on base of Q_1 is +Ve going signal while on the base of Q_2 –Ve going signal

- An amplified –Ve going signal will appear at collector of Q1
- An amplified +ve going signal will appear at collector of Q_2
- Due to +ve going signal of base of Q_1, current increases in R_E & hence a +ve going wave is developed across R_E

- Due to -ve going signal of base of Q2, -ve going wave is developed across R_E because of emitter follower action of Q2
- So, signal voltages across R_E, due to effect of Q1 &Q2 are equal in magnitude &180^0 out of phase- due to matched transistors. Hence the two signals cancel each other & there is no signal across R_E. No AC signal flows through it
- V_o= +10-(-10)= 20
- V_o is difference voltage in two signals

Differential Gain (A_d):

The output voltage **$V_o \alpha (V_1 - V_2)$**

$$V_0 = A_d (V_1 - V_2)$$

Where,

A_d is the **constant of proportionality**.

A_d is the gain with which differential amplifier amplifies the difference between two input signals.

Hence it is known as '***differential gain of the differential amplifier***'.

$$Ad = \frac{V_O}{V_d}$$

V_1-V_2= Difference of two voltage

Generally, differential gain is expressed in decibel (dB) as

$$A_d = 20 \log_{10} (Ad) \text{ in dB}$$

Common Mode Operation

Two input signals are of **equal in magnitude** and **same phase** are used

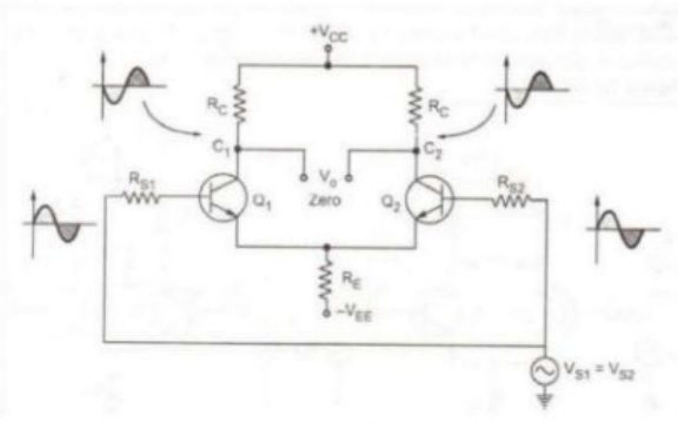


Figure 2.3: Common Mode operation

- Two input signals are of equal in magnitude and same phase are used
- In phase signal develops in phase signal voltages across R_E
- Hence R_E carries a signal current & provides **-ve feedback**
- This –ve feedback decreases AC in signal voltages of equal magnitude will appear across two collectors of Q1 &Q2
- Vo= 10-10=0 Negligibly small. Ideally it should be zero

Common Mode Gain (Ac)

If we apply two input voltages which are equal in all the respect to the differential amplifier i.e $V_1=V_2$ then ideally the output voltage $V_O= (V_1-V_2) A_d$, must be zero.

But the output voltage of the practical differential amplifier not only depends on the difference voltage but also depends on the average common level of the two inputs. Such an average level of the two input signals is called common mode signal denoted as V_{cm}.

$$V_{cm} = \frac{V_1 + V_2}{2}$$

Practically, the differential amplifier produces the output voltage proportional to such common mode signal. The gain with which it amplifies the common mode signal to produce the output is called common mode gain of the differential amplifier denoted as A_c.

$\mathbf{V_o = A_c V_c}$ Where A_c is the common mode gain.

Therefore, there exists some finite output for $V_1 = V_2$ due to common mode gain Ac.

Hence the total output of any differential amplifier can be given as,

$$\mathbf{V_o = A_d V_d + A_c V_c}$$

For an ideal differential amplifier, the differential gain A_d must be infinite while the common mode gain must be zero. This ensures zero output for $V_1=V_2$.

But due to mismatch in the internal circuitry, there is some output available for $V_1=V_2$ and gain Ac is not practically zero. The value of such common mode gain Ac is very small while the value of the differential gain Ad is always very large.

Common Mode Rejection Ratio (CMRR):

The ability of a differential amplifier to reject a common mode signal is defined by a ratio called '***Common Mode Rejection Ratio***' denoted as CMRR.

CMRR is defined as the ***ratio of the differential voltage gain A_d to common mode gain A_c*** and is expresses in dB.

$$CMRR = 20\,log\left|\frac{A_d}{A_c}\right| dB$$

Ideally the common mode voltage gain is zero; hence the ideal value of CMRR is infinite. For a practical differential amplifier Ad is large and Ac is small hence the value of CMRR is also very large.

2.2 DIFFERENTIAL AMPLIFIER CONFIGURATIONS

The differential amplifiers are of the various configurations. The 4 differential amplifier configurations are given as follows:

1. The Dual input, balanced output differential amplifier.
2. The Dual input, unbalanced output differential amplifier.
3. The Single input balanced output differential amplifier.
4. The Single input unbalanced output differential amplifier.

Here V_1& V_2 are input voltages and the difference between them is called **"Differential Input Voltage"**. It is very essential that the transistors Q_1& Q_2 match perfectly for proper functioning of the differential amplifier. The differential input voltage gets amplified and appears as the output voltage V_0 across the collector terminals C_1& C_2.

If the output is measured between C_1& C_2 it is termed as **Balanced Output**. If the output is measured between either of the collector terminals and ground, it is termed as **Unbalanced Output**.

On observing phase relationship between output (V_0) and inputs (V_1& V_2), V_0& V_1 are in phase and V_0& V_2 are 180° out of phase. Hence B_1 at which input signal V_1 is applied is called "Non-Inverting Input Terminal" and is at which input signal V_2 applied is called "Inverting Input Terminal".

$\therefore V_0 = A(V_1 - V_2)$

Where A - Gain of the amplifier.

If B_2 is grounded i.e., $V_2 = 0$, $V_0 = AV_1$

If B_1 is grounded i.e., $V_1 = 0$, $V_0 = -AV_2$.

Dual Input Balanced Output Differential Amplifier Configuration

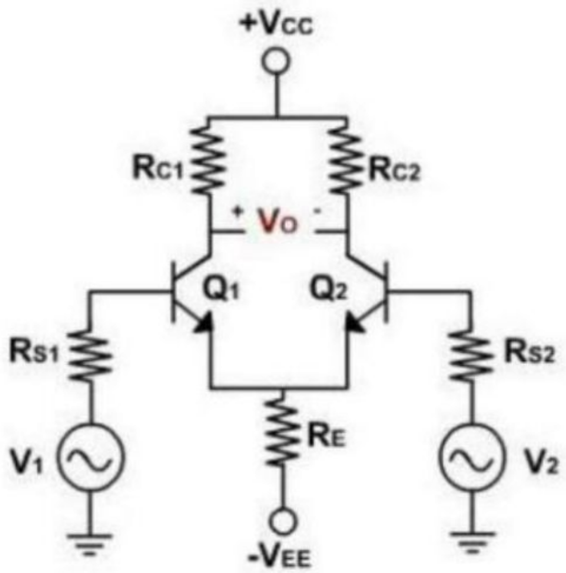


Figure 2.4: Dual Input Balanced Output Differential Amplifier

The two input signals V_1 and V_2 are applied to the bases B_1 and B_2 of transistors Q_1 and Q_2. The output V_O is measured between the two collectors C_1 and C_2, which are at the same DC potential. Because of the equal dc potential at the two collectors with respect to ground, the output is referred to as a balanced output.

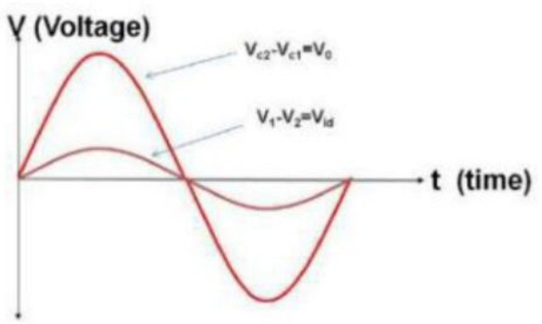


Figure 2.5: Input and Output waveforms of DIBO Differential Amplifier

Inverting and Non-Inverting inputs

In the differential amplifier circuit, the input voltage V_1 is called the "non inverting input" because a positive voltage V_1 acting alone produces a positive output voltage. Similarly, the positive voltage V_2 acting alone produces a negative output voltage; hence V_2 is called inverting input. The base terminal B_1 to which V_1 is applied as the non-inverting input terminal and the base terminal B_2 is called the inverting input terminal.

Dual - Input Unbalanced Output Differential Amplifier

Here two input signals are used; the output is measured at only one of the two collectors with respect to ground. The output is referred as an unbalanced output because the collector at which the output voltage is measured is at some finite DC potential with respect to ground.

In other words, there is some DC voltage at the output terminal without any input signal applied. The output is measured at collector of Q_2 with respect to ground.

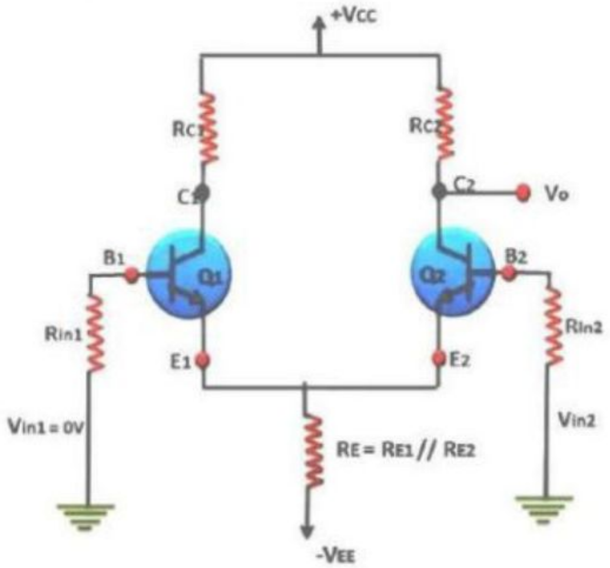


Figure 2.6: Dual Input Unbalanced Output Differential Amplifier

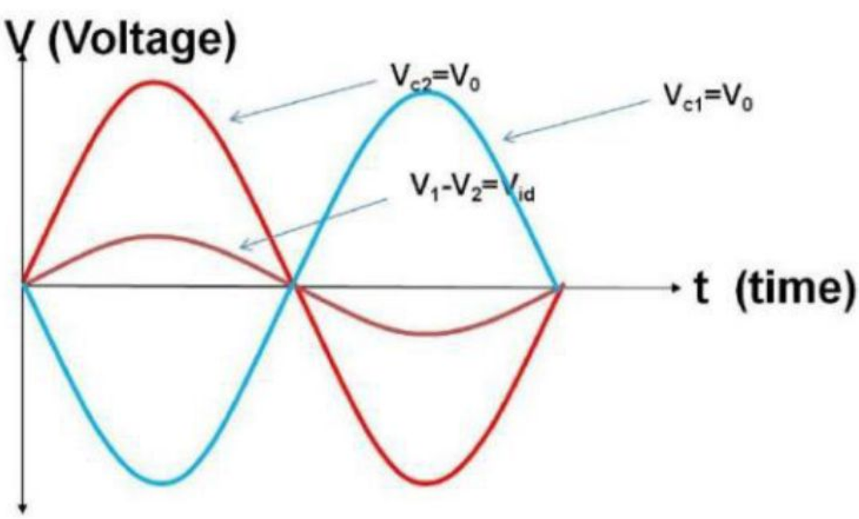


Figure 2.7: Input and output waveforms of Dual Input Unbalanced Output Differential Amplifier

Single Input Balanced Output Differential Amplifier

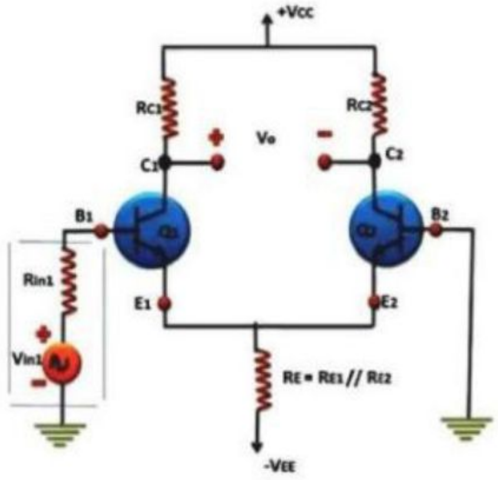


Figure 2.8: Single Input Balanced Output Differential Amplifier

Here the output is applied to the base of transistor Q_1 and the output is measured between the two collectors which are at the same DC potential. Hence the output is said to be balanced output.

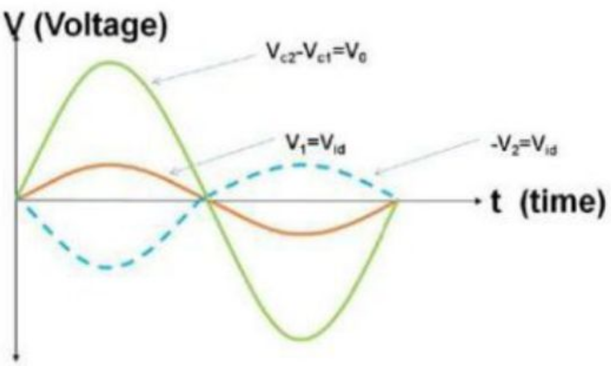


Figure 2.9: Input and output waveforms of Single Input Balanced Output Differential Amplifier

Single Input Unbalanced Output Differential Amplifier

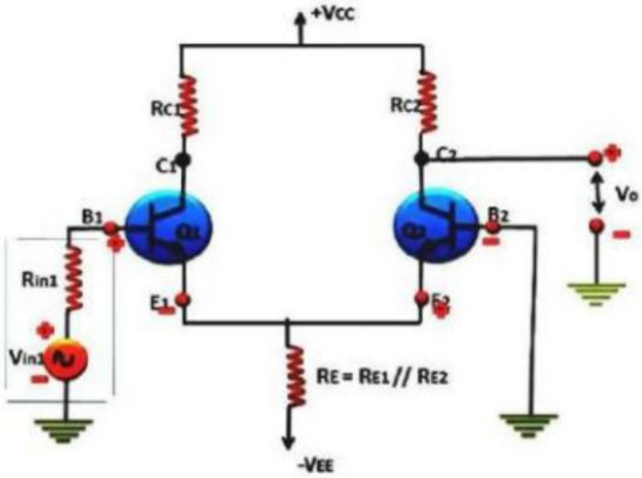


Figure 2.10: Single Input Unbalanced Output Differential Amplifier

Here the output is applied to the base of transistor Q_1 and the output is measured at collector 2 terminals which are at the same DC potential. Hence the output is said to be unbalanced output.

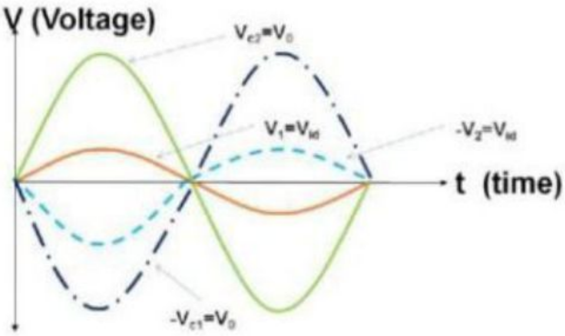


Figure 2.11: Input and output waveforms of Single Input Unbalanced Output Differential Amplifier

2.3 INTRODUCTION TO OPERATIONAL AMPLIFIERS

An Op-Amp is a direct coupled high gain amplifier usually consists of one or more differential amplifiers and usually followed by a level translator and an output stage. The output stage is generally a push pull complementary symmetric pair. An op-amp is available as a single IC package.

Op-Amp is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for performing mathematical operations such as addition, subtraction, multiplication, differentiation and integration 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.

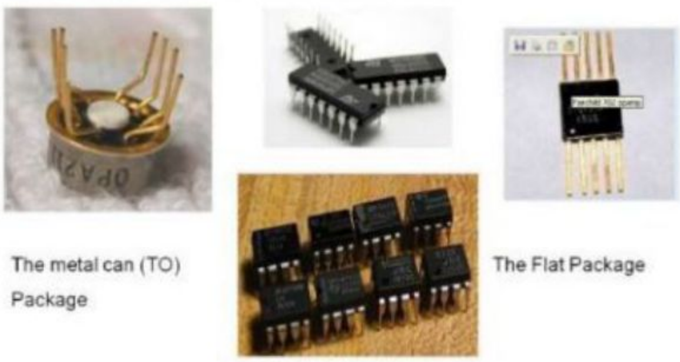
Packages:

There are three popular packages available:

1. The metal can (TO) Package
2. The Dual-in-line Package
3. The flat package or flat pack.

Op-Amp packages may certain single, two (dual) or four (quad) Op-Amps

Typical Packages have 8 terminals, 10 terminals and 14 terminals.



The metal can (TO) Package

The Flat Package

The Dual-in-Line (DIP) Package

Figure 2.12: IC Packages

Circuit Symbol

The circuit symbol of an Op-Amp is a triangular as shown in figure.

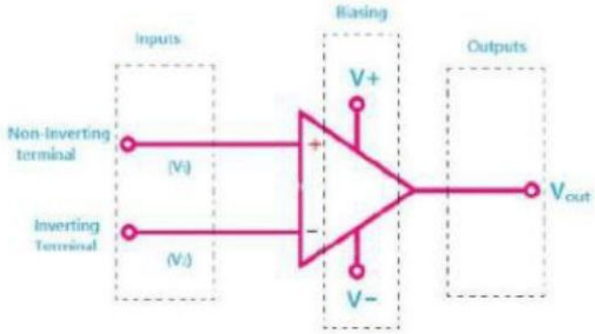


Figure 2.13: Schematic of Op-Amp

The V^+ and V^- power supply terminals are connected to two DC Voltage sources. It has two input terminals and one output terminal. The two inputs of the operational amplifier are called Non-Inverting terminal and Inverting terminal. The Non-Inverting terminal is indicated by the **'plus (+)'** sign and the Inverting terminal is indicated by **'minus (-)'** sign. When there is no feedback path from the output to the input of the Op Amp then the A is called open loop gain. So the output will be $\mathbf{V_{out} = A(V_1\text{-}V_2)}$

Suppose one input signal to the Non-Inverting terminal and the Inverting terminal is grounded. In this case, the output will be $\mathbf{V_{out} = A(V1\text{-}V_2) = A(V_1\text{-}0) = A{*}V_1}$

From this equation, the amplified output signal is in the same phase as the input signal.

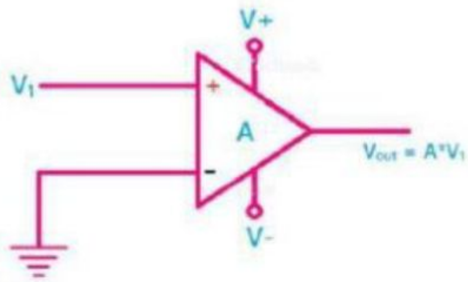


Figure 2.14: Non inverting amplifier

If he input signal to the Inverting terminal and the Non-Inverting is grounded then the output signal will be

$\mathbf{V_{out} = A(V_1\text{-}V_2) = A(0\text{-}V_2) = A{*}\text{-}V_2 = \text{-}AV_2}$

From this equation, the amplified output signal having a 180° phase with respect to the input signal.

As when we applied the input signal that terminal the output signal is inverted that is why it is called Inverting terminal.

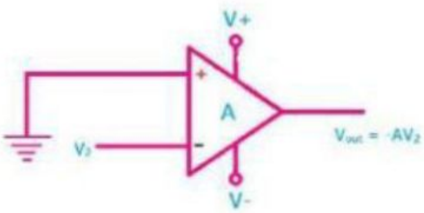


Figure 2.15: Inverting amplifier

Equivalent circuit of an Op-amp

The equivalent circuit is useful in analysing the basic operating principles of op-amps and in observing the effect of feedback arrangements.

For the circuit, the output voltage is

$V_o = AV_{id} = A(V_1 - V_2)$

Where A = large signal voltage gain

V_{id} = differential input voltage

V_1 and V_2 are the voltages at non-inverting and inverting input terminals respectively.

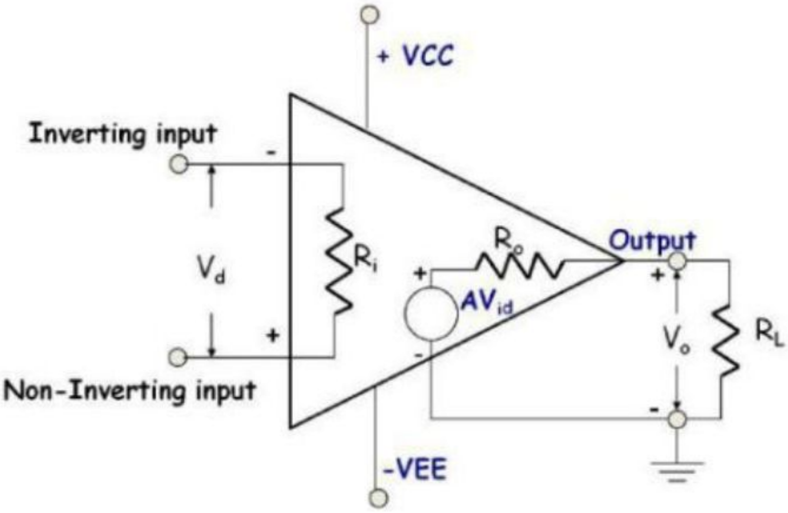


Figure 2.16: Equivalent circuit of Op-amp

The output voltage V_0 is directly proportional to the algebraic difference between the two input voltages. Hence the polarity of the output voltage depends on the polarity of the difference voltage.In the figure the output voltage V_o is plotted against differential input voltage $V_{id,}$ keeping the gain constant.However, the output voltage cannot exceed the positive and negative saturation voltages.

Voltage Transfer Curve

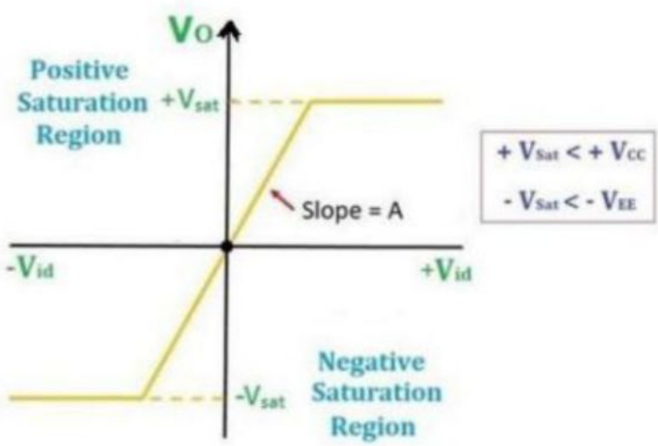


Figure 2.17: Ideal Voltage Transfer Curve

$+V_{sat}$---→Positive Saturation Voltage ($+V_{sat} < +V_{CC}$)

$-V_{sat}$----→Negative Saturation Voltage ($-V_{sat} < -V_{EE}$)

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 voltages and that thereafter output voltage remains constant.

2.4 BLOCK DIAGRAM OF OP-AMP

An op-amp is a multistage amplifier; it is represented as shown in figure.

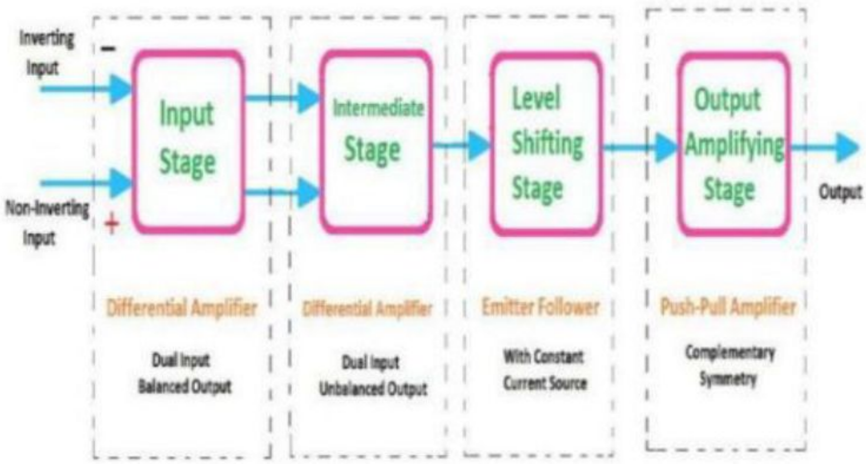


Figure 2.18: Block Diagram of a Typical Op-Amp

The input stage is a dual input balanced output differential amplifier. This stage generally provides most of the voltage gain of the amplifier and also establish the input resistance of the op-amp.

The intermediate stage is usually another differential amplifier, which driven by the output of the first stage. In most of the amplifiers the intermediate stage is dual input unbalanced output differential amplifier. Because direct coupling is used, the dc voltage at the output of the intermediate stage is well above ground potential.

So generally level translator (shifting) circuit is used after the intermediate stage to shit the dc level at the output of the intermediate stage downward to zero volts with respect to ground. The final stage is a push pull complementary output stage. The output 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 impedance.

Input Stage:

- Generally, for any circuit loading effect on sources is one of the major problems. To avoid this, the input impedance of input stage will be taken as high.
- Input stage consists of two input terminals (inverting & non-inverting) & also requires low output impedance.
- All such requirements are achieved by using the Dual Input Balanced Output differential amplifier.

- This Differential amplifier consists of high input impedance and it amplifies the difference of the two applied inputs.
- This stage provides most of the voltage gain of the amplifier.

Intermediate Stage:

- It is another differential amplifier with Dual Input balanced Output configuration. For an op-amp the overall gain requirement is very high.
- The main function of the intermediate stage is to provide an additional voltage gain required. Practically it is a chain of cascaded amplifiers called multistage amplifier.

Level Translating Stage:

- In Op-amp all the stages are directly coupled to each other. As the op-amp amplifies dc signals also, the coupling capacitors are not used to cascade the stages.
- Hence the Quiescent voltage level of previous stage gets applied as the input to the next stage. Hence stage by stage dc level increases well above the ground potential.
- Such high dc voltage level may drive the transistors into saturation.
- This further may cause distortion in the output due to clipping.
- This may limit the maximum output voltage swing without distortion. Hence before the output stage it is necessary to bring such a high dc level to zero.
- The level shifter stage brings the dc level down to ground potential when no signal is applied at the input terminals.
- The buffer is usually an emitter follower provides high input impedance to prevent the loading of the high gain stage.

Output Stage:

Generally, the output stage requires

- ✓ low output impedance
- ✓ Large ac output voltage swing
- ✓ High current sourcing & sinking capability

The Push-pull complimentary amplifier meets all these requirements and used as an output stage.

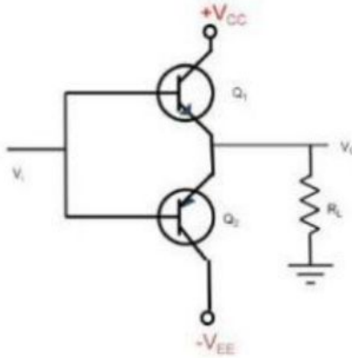


Figure 2.19: Output stage

2.5 DC CHARACTERISTICS

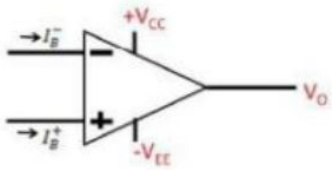
An ideal op-amp draws no current from the source and its response is also independent of temperature. However, a real op-amp does not work this way. Current is taken from the source into the op-amp inputs. These non-ideal dc characteristics that add error components to the dc output voltage are:

Input Bias current:

In an ideal op-amp, we assumed that no current is drawn from the input terminals. However, practically, input terminals do conduct a small value of dc current to bias the input transistors. The base currents entering into the inverting and non-inverting terminals are shown as I_B^- and I_B^+ respectively. Even though both the transistors are identical, I_B^- and I_B^+ are not exactly same.

The input bias current I_B is the average of the current entering the input terminals of a balanced amplifier

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



Input offset current:

The input transistors 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} and can be written as

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

Input offset voltage:

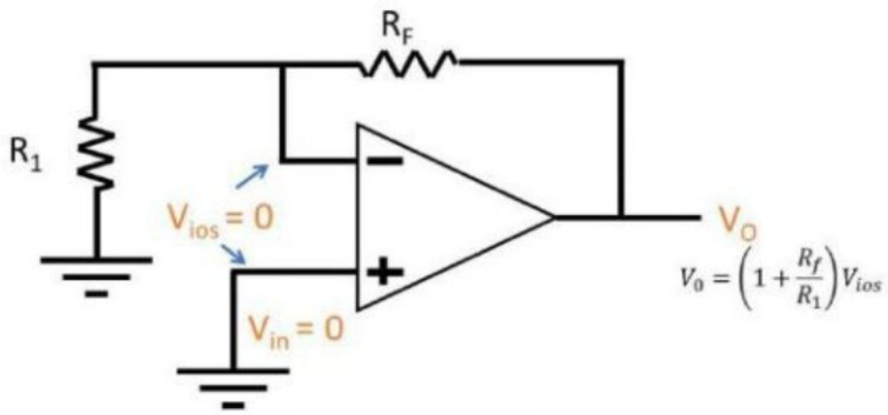


Figure 2.20: Non-Inverting amplifier

In spite of the use of the compensating techniques discussed above, the output voltage may still not be zero with zero input voltage. This is due to unavoidable imbalance inside the op-amp and one may have to apply a small amount of voltage at the input terminals to make output voltage zero. This voltage is known as input offset voltage V_{ios}.

Thermal drift

The op-amp parameters input offset voltage V_{ios}, input bias current I_b and input offset current I_{ios} are not constant but vary with the factors.

1. Temperature
2. Supply voltage changes
3. Time

Bias current, offset current and offset voltage change with temperature. A circuit capability carefully null at 25^0C may not remain so when the temperature rises to 35^0C. This is called drift. Forced air cooling may be used to stabilize the temperature.

The thermal drift is used to identify such changes and it is defined as the average rate of change of input offset voltage per unit change in temperature.

Thermal drift in Input offset voltage drift= $\frac{\Delta V_{ios}}{\Delta T}$ Units μV/°C

Thermal drift in Input bias current= $\frac{\Delta I_B}{\Delta T}$ Units nA/°C

Thermal drift in Input offset current= $\frac{\Delta I_{os}}{\Delta T}$ Units nA/°C

Power Supply Rejection Ratio (PSRR)

The Power Supply Rejection Ratio is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. It is also called Power Supply Sensitivity (PSS) or Supply Voltage Rejection Ratio (SVRR). Now if V_{EE} is constant due to certain in V_{CC}, there is change in input offset output voltage then PSRR is defined as

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{CC}} \because constant\ V_{EE}\ Unit - mV$$

For a fixed V_{CC}, if there is change in V_{EE} then

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{EE}} \because constant\ V_{CC}\ Unit - mV$$

Common Mode Rejection Ratio (CMRR)

It can be defined as the ratio of the differential voltage gain (A_d) to the common mode voltage gain A_{cm}.

$$CMRR = \frac{A_d}{A_{cm}}$$

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

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

Where V_{ocm}= common mode output voltage

V_{cm}=common mode input voltage

A_{cm}= common mode voltage gain

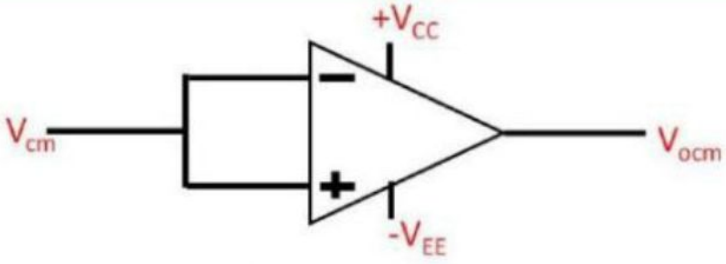


Figure 2.21: Common mode operation

Slew Rate:

The maximum rate of change of the output voltage in response to a step input voltage is the **slew rate** of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

For a step input, the slope on the output is inversely proportional to the upper critical frequency. Slope increases as upper critical frequency decreases.

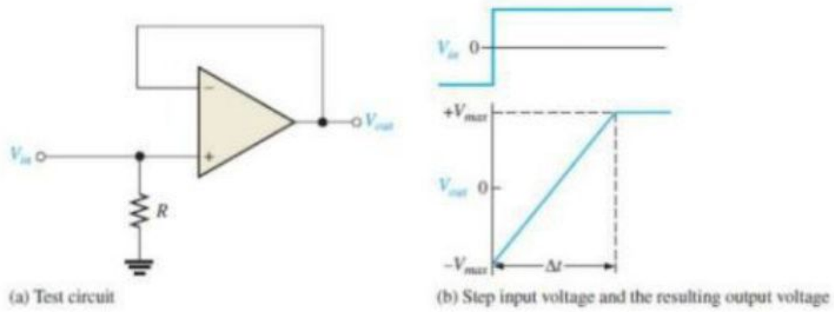


Figure 2.22: concept of slew rate

The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit. A certain time interval, Δt, is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied. The slew rate is expressed as:

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/μs).

2.6 PIN CONSTRUCTION OF 741 OP-AMP

The operational amplifier comes in form of IC. The IC no. of Op-Amp is 741. The internal block diagram of **IC 741**

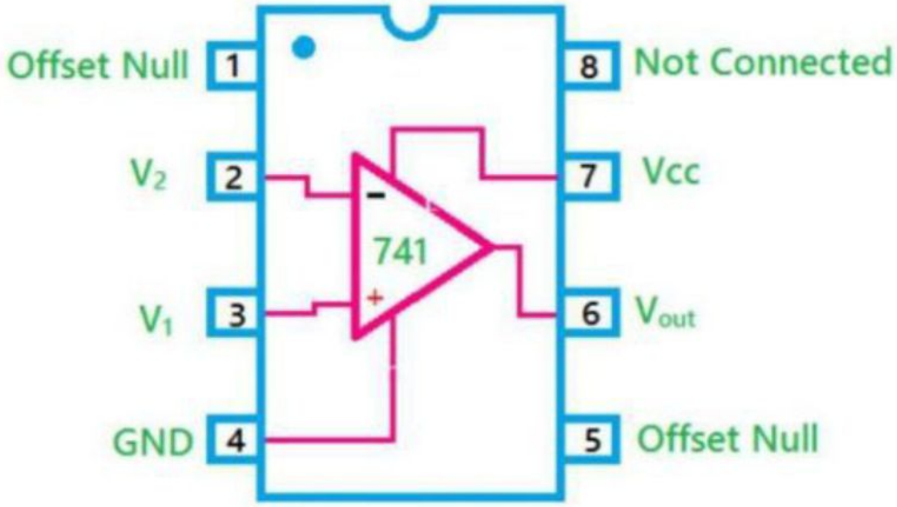


Figure 2.23: Pin diagram of Op-Amp

IC 741 is an 8-pin Op-Amp IC. The 8 pins are,

Pin 1: Offset Null

Pin 2: Inverting terminal for giving input signal.

Pin 3: Non-Inverting terminal for giving input signal.

Pin 4: Ground terminal to provide power supply or biasing to the Op-Amp

Pin 5: Offset Null

Pin 6: Output pin to connect the load and feedback path.

Pin 7: Vcc or Positive pin to provide power supply.

Pin 8: Not connected to the internal circuit.

The different Op-amp ICs has a different specification.

2.7 IDEAL CHARACTERISTICS OF OP-AMP

An ideal OP-amp would exhibit the following electrical characteristics:

- Infinite voltage gain A.
- Infinite input resistance R_i so that almost any signal source can drive it and there is no loading of the preceding stage.
- Zero output resistance R_o so that output can drive an infinite number of other devices.
- Zero output voltage when input voltage is zero.
- Infinite Bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation.
- Infinite Common Mode Rejection Ratio so that the output common mode noise voltage is zero.
- Infinite slewrate so that output voltage changes occur simultaneously with input voltage changes.

2.8 VIRTUAL GROUND

In opamps **the term virtual ground means that the voltage at that particular node is almost equal to ground voltage** (0V). It is **not** physically connected to ground. This concept is very useful in analysis of opamp circuits and it will make a lot of calculations very simple.

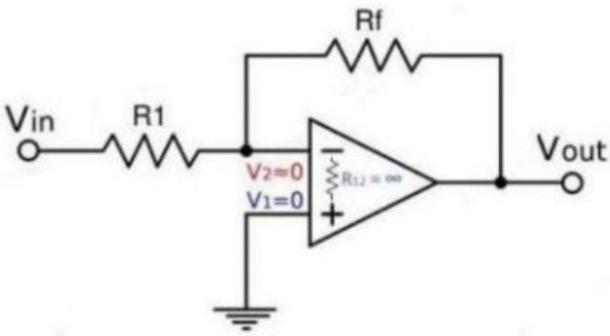


Figure 2.24: Schematic of Op-Amp

- **Gain = Vo/Vin**

As gain is infinite, **Vin = 0**

- Vin = V2 – V1

In the above circuit V1 is connected to ground, so V1 = 0. Thus V2 also will be at ground potential.

- **V2 = 0**

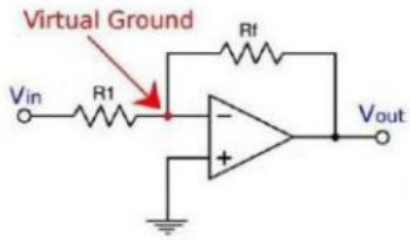


Figure 2.25: Schematic of Op-Amp

2.9 APPLICATIONS OF OP-AMP

There are many useful applications of Op-Amp. Some applications of Op-Amp are given below,

1. A very important application of the Op-Amp is amplification. The Op-Amp is used as Inverting amplifier, Non-Inverting amplifier.
2. The Op-Amp is used as Voltage Follower.
3. The Op-Amp is used as Comparator.
4. The Op-Amps sometimes used as audio preamplifier which used before the power amplifier in the audio system.
5. The Operational amplifier is also used as Active Filter.
6. The other important application of operational amplifier is Oscillator. The Op-Amp can produce the oscillating signal of any desired frequency and waveforms.

7. The operational amplifiers are used for convert waveforms that means we can convert a sine wave into square wave using an Op-Amp.
8. By using operational amplifier we can convert the analog signal into digital signal.
9. The conversion of the digital signal into analog signal also be possible by the Op-Amp.

Inverting amplifier

The output voltage V_O is fed back to the inverting input terminal through the R_f-R_1 network where Rf is the feedback resistor. Input signal V_{in} (ac or dc) is applied to the inverting input terminal through R_1 and non-inverting terminal of op-amp is grounded.

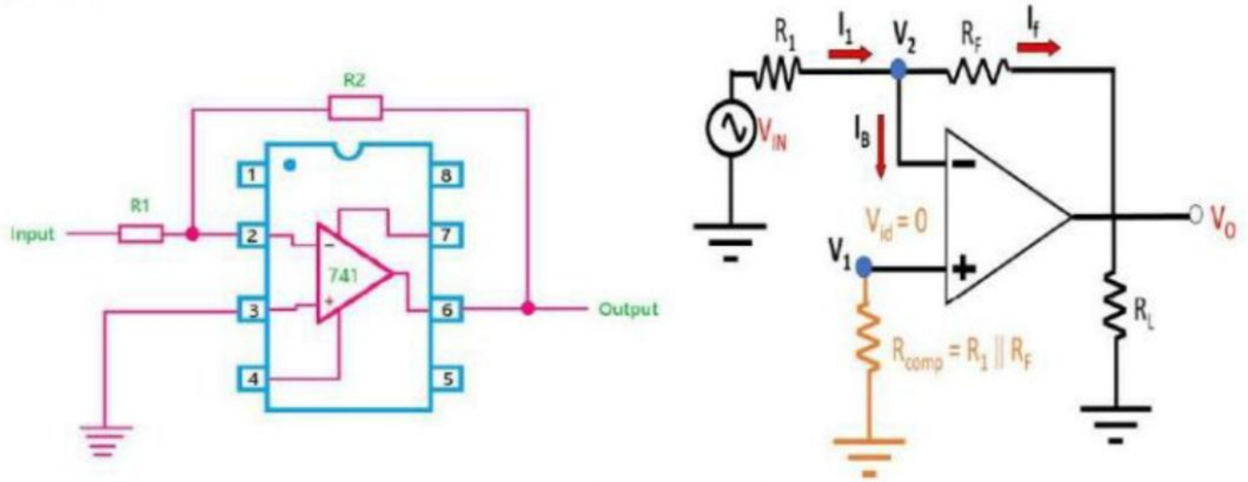


Figure 2.26: Inverting amplifier

Analysis: For simplicity assume an ideal op-amp V_{id}=0. Apply KCL at node V_2

$$I_1 = I_f + I_B$$

But I_B=0

$$I_1 = I_f$$

$$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_O}{R_f}$$

From virtual ground concept V_{id}=0V so V_1=V_2=0

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_O}{R_f}$$

$$V_O = \frac{-R_f}{R_1} V_{in}$$

The closed loop gain of inverting amplifier

$$A_f = \frac{V_O}{V_{in}} = \frac{-R_f}{R_1}$$

The negative sign indicates a phase shift of 180^0 between V_{in} and V_O. Also, since inverting input terminal is at virtual ground, the effective input impedance is R_1.

Non-Inverting Amplifier

If a signal (ac or dc) is applied to the non-inverting input terminal and the circuit amplifies without inverting the input signal. Such a circuit is called non-inverting amplifier. It may be noted that it is also a negative feedback system as output is being fed back to the inverting input terminal.

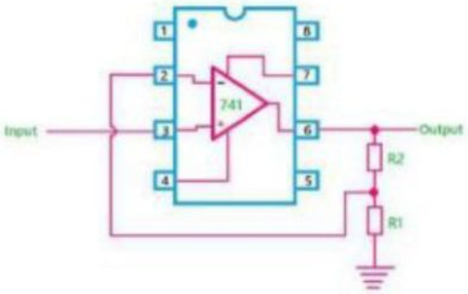
Analysis: For simplicity assume an ideal op-amp $V_{id}=0$. Apply KCL at node V_2

$$I_1 = I_f + I_B$$

But $I_B=0$

$$I_1 = I_f$$

$\frac{0-V_2}{R_1} = \frac{V_2-V_O}{R_f}$



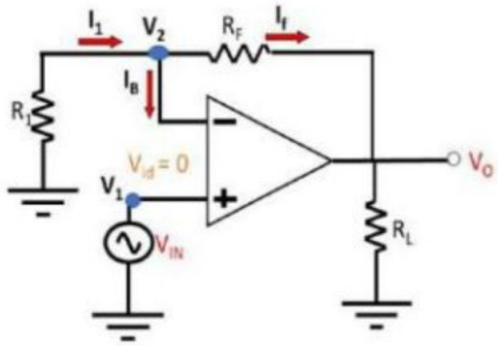


Figure 2.27: Non-Inverting Amplifier

From virtual ground concept $V_{id}=0V$ so $V_1=V_2$ and $V_1=V_{in}$

$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_O}{R_f}$$

$$\frac{-V_{in}}{R_1} + \frac{-V_{in}}{R_f} = \frac{-V_O}{R_f}$$

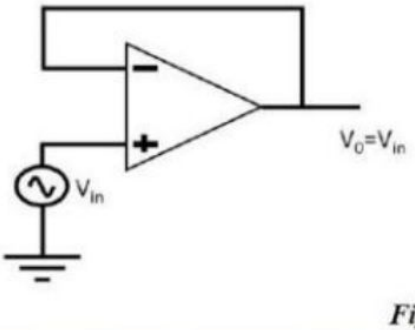
$$-V_{in}\left(\frac{R_1 + R_f}{R_1 R_f}\right) = \frac{-V_O}{R_f}$$

$$\frac{V_O}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Thus, for non-inverting amplifier the voltage gain,

$$A_f = \frac{V_O}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Voltage follower



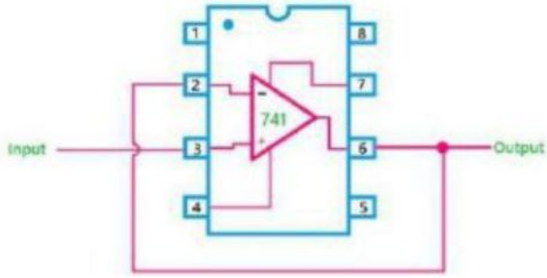


Figure 2.28: Voltage follower

When the non-inverting 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.

$$R_1 \rightarrow \text{open circuited} \rightarrow \infty$$

$$R_f \rightarrow \text{short circuited} \rightarrow 0$$

$$A_f = \frac{V_0}{V_{in}} = \left(1 + \frac{R_f}{R_1}\right) = \left(1 + \frac{\infty}{0}\right) = 1$$

$$V_0 = V_{in}$$

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

Summing, Scaling and Averaging Amplifiers

The inverting, Non-inverting and differential amplifier configurations are used in applications as

- Summing amplifiers
- Scaling amplifiers
- Averaging amplifiers

Inverting summing amplifier

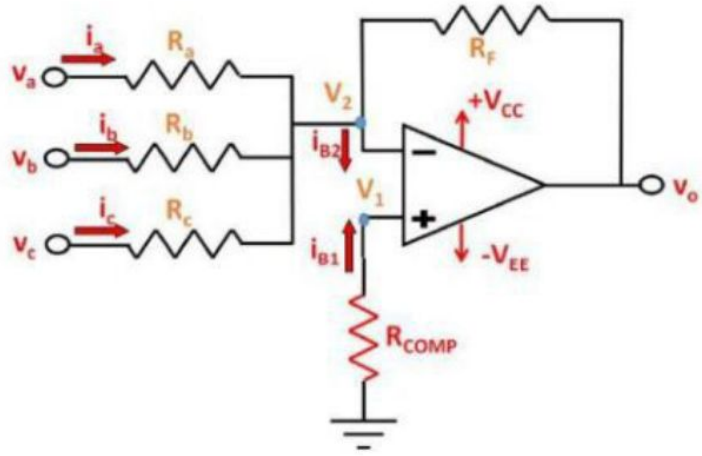


Figure 2.29: Inverting summing amplifier

Inverting configuration with three inputs V_a, V_b, V_c and R_a, R_b, R_c are the input resistances. Rf is the feedback resistance. Depending on the relation between R_a,R_b, R_c, R_f circuit can be summing, scaling or averaging amplifier.

The voltage at node 'V_2' is zero as the non-inverting input terminal is grounded. The nodal equation by KCL at node 'a' is

$$I_a + I_b + I_c = I_B + I_F$$

$$\frac{V_a - V_2}{R_a} + \frac{V_b - V_2}{R_b} + \frac{V_c - V_2}{R_c} = \frac{V_2 - V_o}{R_f}$$

Since R_i and A of op-amp are ideally infinity I_B=0, V1=V2=0

$$\frac{V_a}{R_a}+\frac{V_b}{R_b}+\frac{V_c}{R_c}+\frac{V_0}{R_f}=0$$

$$V_0=-\left(\frac{R_f}{R_a}V_a+\frac{R_f}{R_b}V_b+\frac{R_f}{R_c}V_c\right)$$

Thus, the output is an inverted, weighted sum of the input.

Summing Amplifier

If $R_a = R_b = R_c = R$ above equation becomes

$$V_0=-\frac{R_f}{R}(V_a+V_b+V_c)$$

If output voltage is equal to the negative sum of all the inputs times the gain of the circuit R_f/R then it is called summing amplifier.

In the special case, when $R_a = R_b = R_c = R_f$ we have the output voltage is equal to negative sum of all input voltages.

$$V_0=-(V_a+V_b+V_c)$$

Differential amplifier

Differential amplifier is a combination of inverting and non-inverting amplifiers. That is, when V_x is reduced to zero the circuit is a non-inverting amplifier, whereas the circuit is an inverting amplifier when input V_y is reduced to zero.

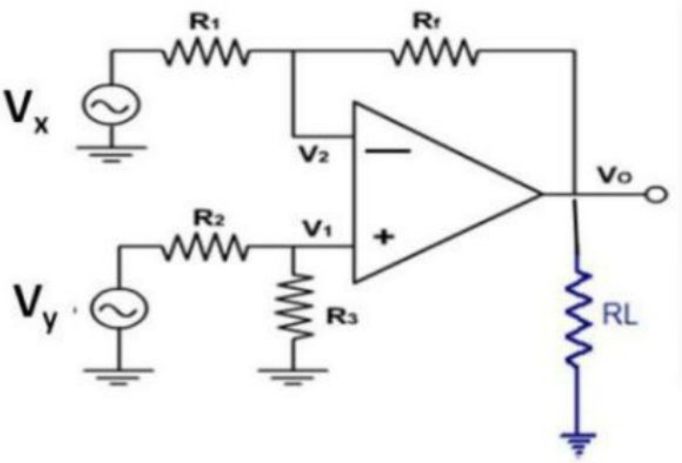


Figure 2.30: Differential amplifier with one op-amp

Voltage gain

Use the super position theorem in order to establish the relationship between inputs and outputs.

When V_y=0, the configuration comes an inverting amplifier. The output due to V_x only

$$\therefore V_{01}=\frac{-R_f}{R_1}V_x$$

When V_x=0, the configuration comes an non-inverting amplifier. The output due to V_y only

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

$$\therefore V_{02} = (1 + \frac{R_f}{R_1})V_y \frac{R_3}{R_2 + R_3}$$

If $R_1 = R_2$ & $R_f = R_3$ then

$$\therefore V_{02} = (\frac{R_1 + R_f}{R_1})V_y \frac{R_f}{R_1 + R_f}$$

$$\therefore V_{02} = \frac{R_f}{R_1} V_y$$

The net output voltage $V_0 = V_{01} + V_{02}$

$$V_0 = \frac{-R_f}{R_1} V_x + \frac{R_f}{R_1} V_y$$

$$= \frac{-R_f}{R_1}(V_x - V_y)$$

The voltage gain $A_D = \frac{V_0}{V_x - V_y} = \frac{-R_f}{R_1}$

The gain of the differential amplifier is the same as that of the inverting amplifier.

Differentiator

Differentiator or differentiation amplifier, the circuit peroms the mathematical operation of differentiation, that is, the output waveform is the derivative of the input waveform. The differentiator may be constructed from a basic inverting amplifier if an input resistor R_1 is replaced by a capacitor C_1.

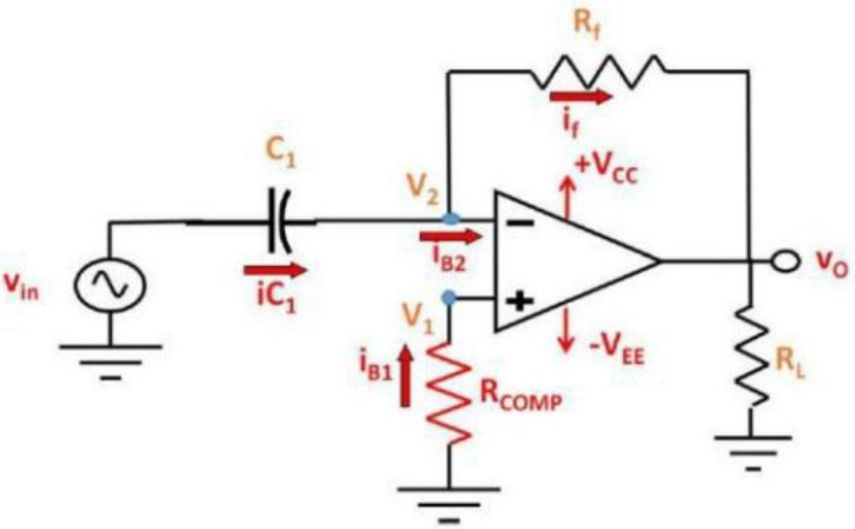


Figure 2.31: Differentiator

The expression for the output voltage can be obtained rom KCL equation written at node V_2 as follows:

$$I_c = I_f + I_B$$

Since $I_B \cong 0$ and $V_1 = V_2 \cong 0$ and A is very large. Therefore

$$I_C = I_f$$

$$C\frac{d}{dt}(V_{in}-V_2)=\frac{V_2-V_O}{R_f}$$

$$C\frac{d}{dt}(V_{in}-0)=\frac{0-V_O}{R_f}$$

$$C\frac{d}{dt}V_{in}=\frac{-V_O}{R_f}$$

$$V_O=-R_fC\frac{d}{dt}V_{in}$$

Thus, the output voltage V_o is a constant $-R_fC_1$ times the derivative of the input voltage V_{in} and the circuit is a differentiator. The minus sign indicates an 180^0 phase shift of the output waveform V_O with respect to the input signal.

Integrator

A circuit in which the output voltage waveform is the integral of the input voltage waveform is the integrator or the integration amplifier. Such a circuit is obtained by using a basic inverting amplifier configuration if the feedback resistor R_f is replaced by a capacitor C_f. The expression for the output voltage V_o can be obtained by writing KCL at node V_2.

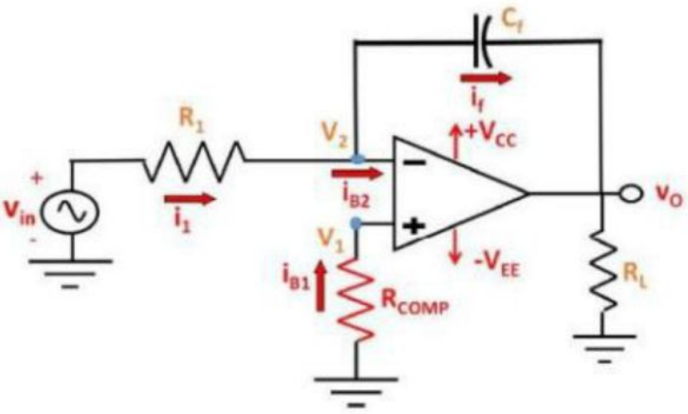


Figure 2.32: Integrator

$$I_1=I_B+I_F$$

But I_B=0 and V_1=V_2=0, so

$$I_1=I_F$$

The current flowing through the feedback capacitor C is given as

$$I_F=C\frac{d}{dt}(V_2-V_O)=C\frac{d}{dt}(0-V_O)$$

$$=-C\frac{d}{dt}V_O$$

$$I_1=\frac{V_{in}-V_2}{R_1};V_2=0$$

$$I_1=\frac{V_{in}}{R_1}$$

The output voltage can be obtained by integrating both sides with respect to time

$$\therefore \frac{V_{in}}{R_1} = -C\frac{d}{dt}V_O$$

$$V_O = -\frac{1}{R_1 C}\int V_{in}dt + C$$

Where C is the integration constant and is proportional to the values of the output voltage Vo at time t=0 seconds. Here above equation indicates that the output voltage is directly proportional to the negative integral of the input voltage and inversely propotional to the time constant R_1C_f.

Basic Comparator

A comparator compares a signal voltage on one input of an op-amp with a known voltage called the reference voltage on the other input.

Non-Inverting Comparator

A fixed reference voltage V_{ref} is applied to the (-) input, and the other time varying signal voltage Vin is applied to the (+) input, then the circuit is called the non-inverting comparator. When Vin is less than V_{ref}, the output voltage V_O is $-V_{sat}$ ($-V_{EE}$) because the voltage at the (-) input is higher than that at the (+) input. When V_{in} is greater than V_{ref}, the (+) input becomes positive with respect to the (-) input and V_O goes to $+V_{sat}$ ($+V_{CC}$).

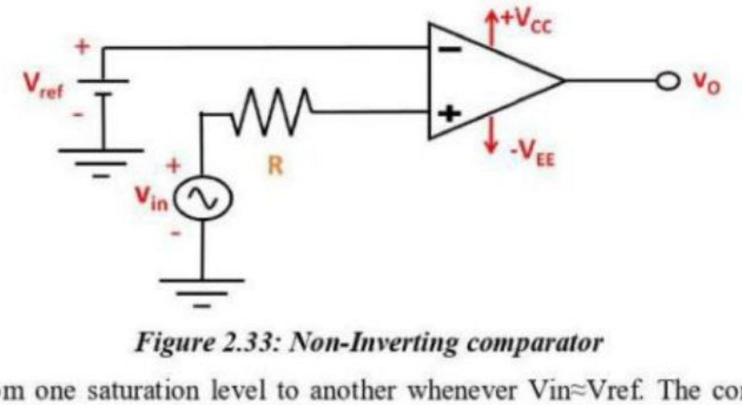


Figure 2.33: Non-Inverting comparator

Thus, V_O changes from one saturation level to another whenever Vin≈Vref. The comparator is a type of analog to digital converter. At any given time, the VO waveform shows whether Vin is greater or less than Vref. The comparator is sometimes also called a voltage level detector because, for a desired value of Vref, the voltage level of the input Vin can be detected.

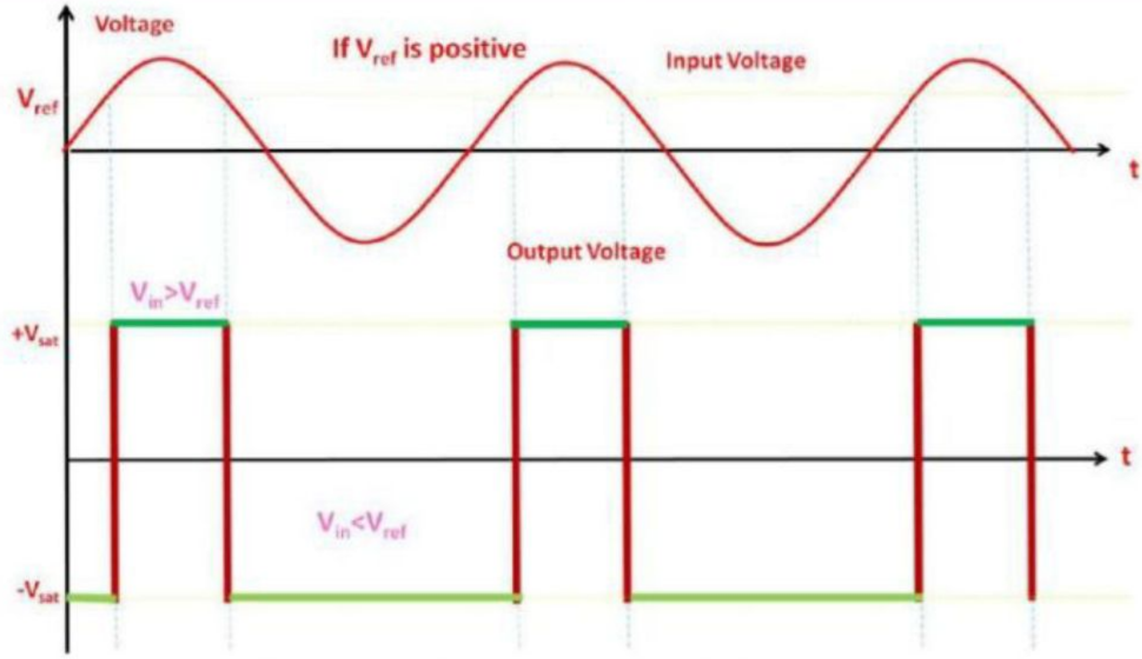


Figure 2.34: Input and output waveforms of Non-Inverting comparator

If the reference voltage Vref is negative with respect to ground, with sinusoidal signal applied to the (+) input, the output waveform shown in figure.

When $V_{in}>V_{ref}$ $\quad V_O=+V_{sat}$

$V_{in}<V_{ref}$ $\quad V_O=-V_{sat}$

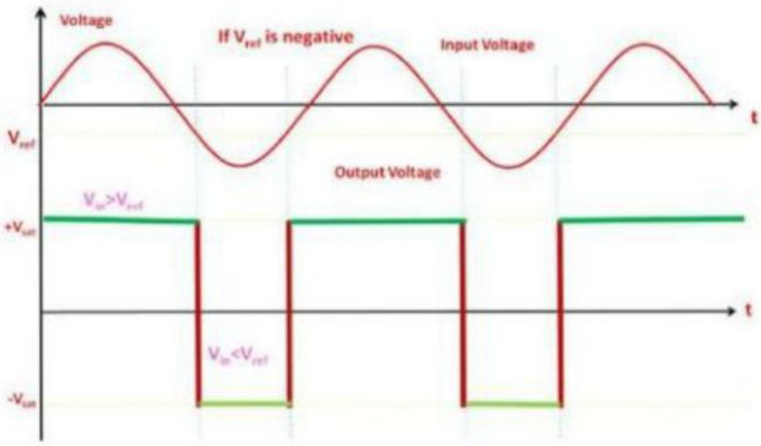


Figure 2.35: Input and output waveforms of Non-Inverting comparator

Inverting Comparator

An inverting comparator in which the reference voltage Vref is applied to the (+) input and Vin is applied to the (-) input.

When $V_{in}>V_{ref}$ $\quad V_O=-V_{sat}$

$V_{in}<V_{ref}$ $\quad V_O=+V_{sat}$

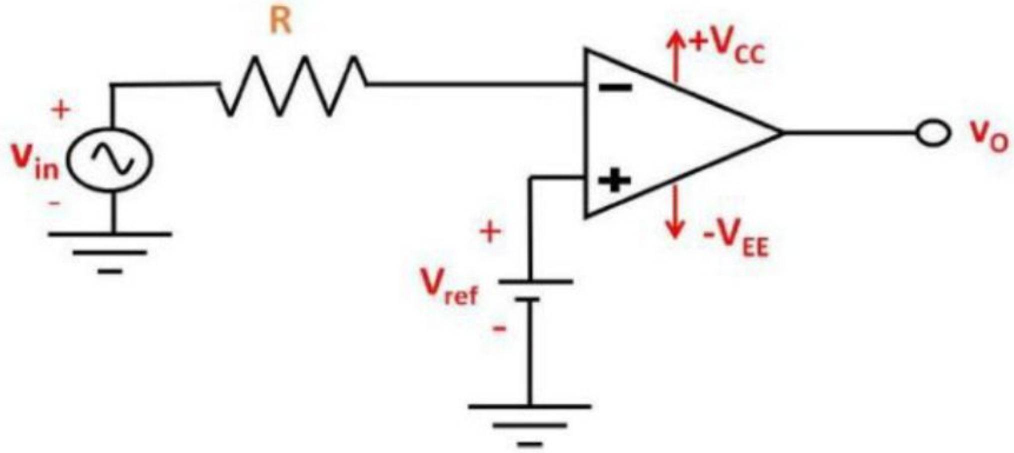


Figure 2.36: Inverting comparator

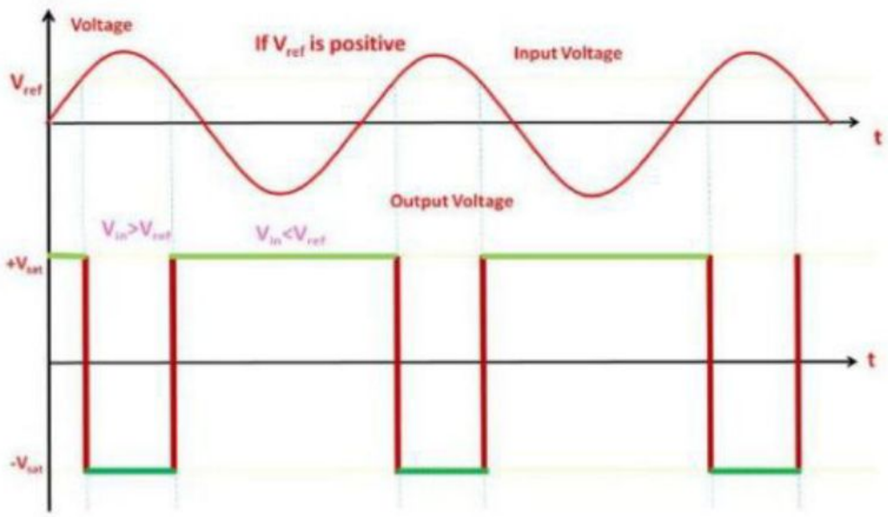


Figure 2.37: Input and output waveforms of Inverting comparator

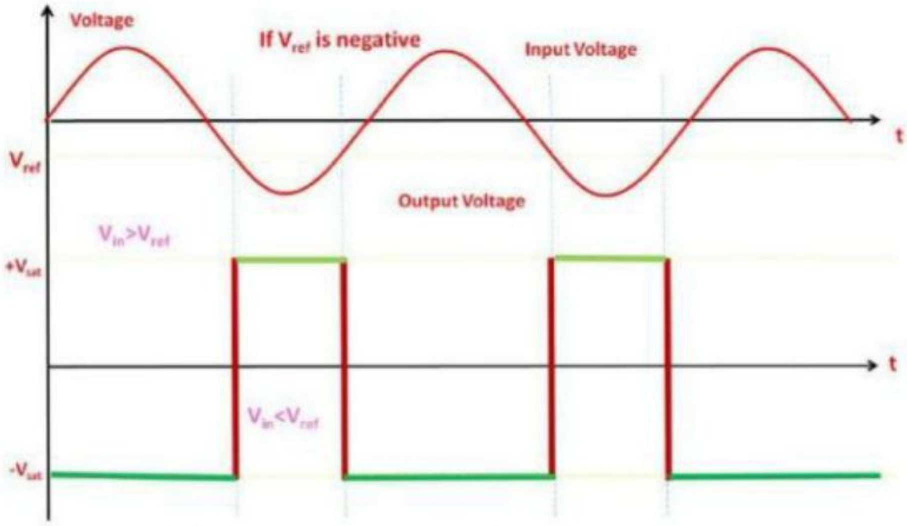


Figure 2.38: Input and output waveforms of Inverting comparator

Model Questions

1. What is a differential amplifier? Explain balanced and unbalanced output in differential amplifier.
2. Explain the operating modes of differential amplifier.
3. Define an op-amp. Explain the ideal characteristics of an op-amp.
4. Organize the op-amp with block diagram representation and explain the functionality of each block.
5. Draw the diagram of basic integrator and derive the equation for its output voltage.
6. Define the terms input offset voltage, input offset current, common mode rejection ratio, large signal voltage gains and slew rate.
7. Draw the diagram of basic differentiator and derive the equation for its output voltage.
8. Derive the expressions for output voltage of an inverting and non-inverting operational amplifier.
9. What is an op-amp? Explain the operation of non-inverting comparator
10. Derive the expression for 3 input summing amplifier with circuit diagram.
11. Derive the expression for difference amplifier with circuit diagram.
12. Design an inverting and non inverting amplifier with gain of 5.
13. Design an inverting amplifier with a gain of -5 and an input resistance of 10 KΩ.