UNIT – 4

Operational Amplifiers and its Applications

INTRODUCTION

Op-Amp (operational amplifier) is a direct coupled multistage voltage amplifier with an extremely high gain. Opamp is basically an amplifier available in the IC form. The word "operational" is used because the amplifier can be used to perform a variety of mathematical operations such as addition, subtraction, integration, differentiation etc.

Figure 4.1 below shows the symbol of an Op-Amp.

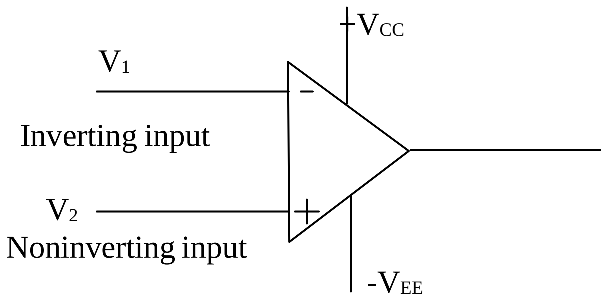


Fig.4.1 Symbol of Op-Amp

It has two inputs and one output. The input marked "-" is known as Inverting input and the input marked "+" is known as Non-invertinginput.If a voltage V_i is applied at the inverting input (keeping the non-inverting input at ground) as shown below.

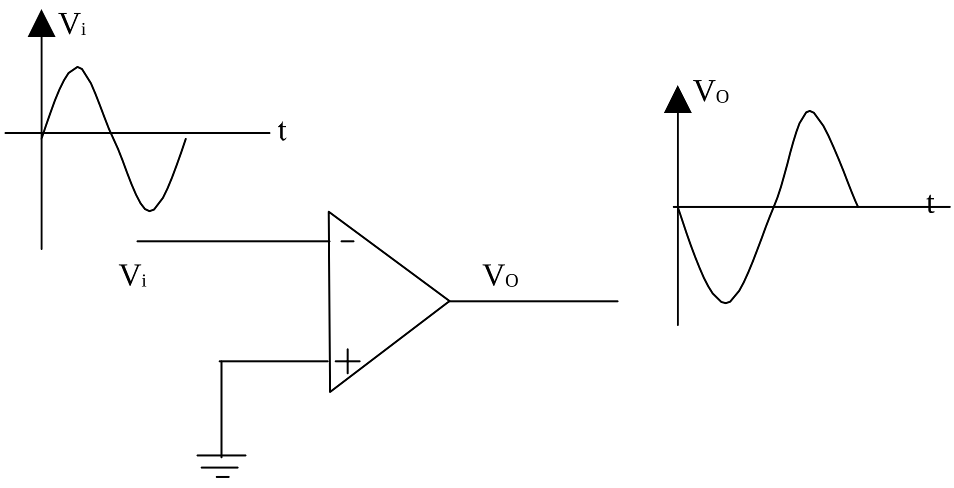


Fig.4.2 Op-amp in inverting mode

The output voltage $V_O = -AV_i$ is amplified but is out of phase with respect to the input signal by 180^0. If a voltage V_i is fed at the non-inverting input (Keeping the inverting input at ground) as shown below.

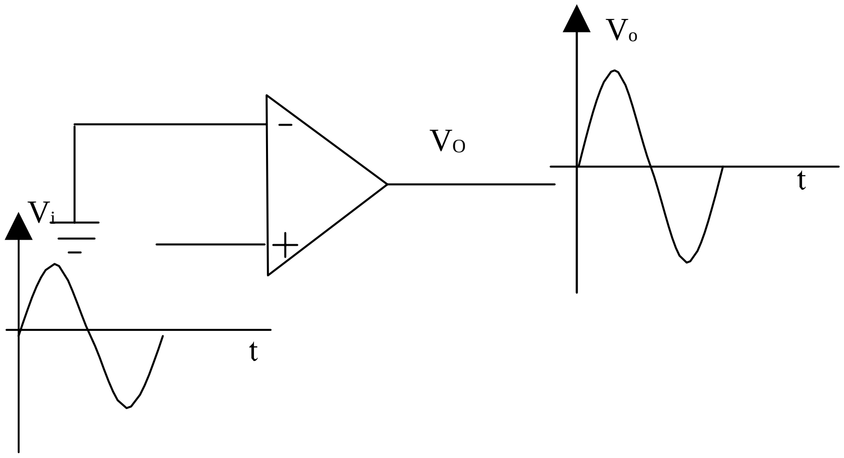


Fig 4.3 Op-Amp in Non-inverting mode

The output voltage $V_o = AV_i$ is amplified and in-phase with the input signal.

If two different voltages V_1 and V_2 are applied to an ideal Op-Amp asshown below.

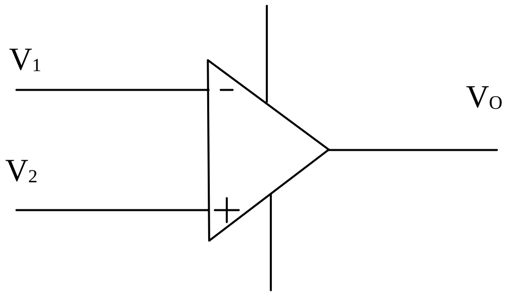


Fig.4.4 Ideal Op-Amp

The output voltage will be $V_o = A(V_1 – V_2)$

i.e the difference of the two voltages is amplified. Hence an Op-Amp is also called as a High gain differential amplifier.

Characteristics of an Ideal Op-Amp

An ideal Op-Amp has the following characteristics.

1. Infinite voltage gain (ie $A_V = \infty$)
2. Infinite input impedance ($R_i = \infty$)
3. Zero output impedance($R_o = 0$)
4. Infinite Bandwidth (B.W. = ∞)

5. Infinite Common mode rejection ratio (ie CMRR =∞)

6. Infinite slew rate (ie S=∞)

7. Zero power supply rejection ratio (PSRR =0)ie output voltage is zero when power supply V_{CC} =0

8. Zero offset voltage(ie when the input voltages are zero, the output voltage will also be zero)

9. Perfect balance (ie the output voltage is zero when the input voltages at the two input terminals are equal)

10. The characteristics are temperature independent.

Typical Values of Op-amp [Specifications]

Parameter	Ideal	Typical or Practical Value
Voltage Gain [A_v]	∞	$2*10^5$
Output Impedance	0	75Ω
Input Impedance	∞	2MΩ
Input Offset	0	2mV
CMRR	∞	90dB
Slew Rate	∞	0.5V/µs
Bandwidth	∞	1MHz
PSRR	0	30µV/V
Input Bias Current	0	80nA

Definitions

1. **Slew rate(S):** It is defined as " The rate of change of output voltage per unit time"

$$SR = \frac{dV_o}{dt} \ volts/\mu \sec$$

$$SR = f_{max}\, 2\, \Pi\, V_m$$

Ideally slew rate should be as high as possible. But its typical value is s=0.5 V/µ-sec.

2. Common Mode Rejection Ratio(CMRR): It is defined as " The ratio of differential voltage gain to common-mode voltage gain".

$$CMRR = \frac{Ad}{Acm}$$

3. Open Loop Voltage Gain (AV): It is the ration of output voltage to input voltage in the absence of feed back. Its typical value is $2*10^5$

4. Input Impedance (R_i): It is defined as "The impedance seen by the input(source) applied to one input terminal when the other input terminal is connected to ground".

$$Ri \approx 2M\Omega$$

5. Output Impedance (R_O): It is defined as " The impedance given by the output (load) for a particular applied input".

$$Ro \approx 75\Omega$$

Concept of Virtual ground

We know that, an ideal Op-Amp has perfect balance (ie output will be zero when input voltages are equal).

Hence when output voltage Vo = 0, we can say that both the input voltages are equal ie V1= V2.

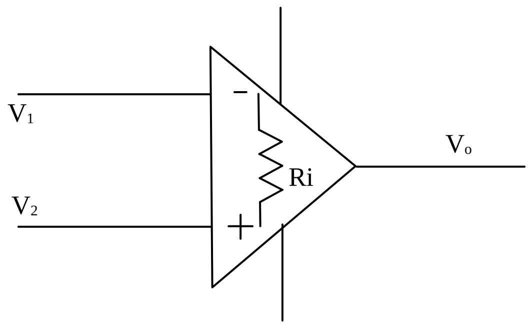


Fig. 4.5a Concept of Virtual ground

Since the input impedances of an ideal Op-Amp is infinite ($Ri = \infty$). There is no current flow between the two terminals. Hence when one terminal (say V2) is connected to ground (ie V2 = 0) as shown.

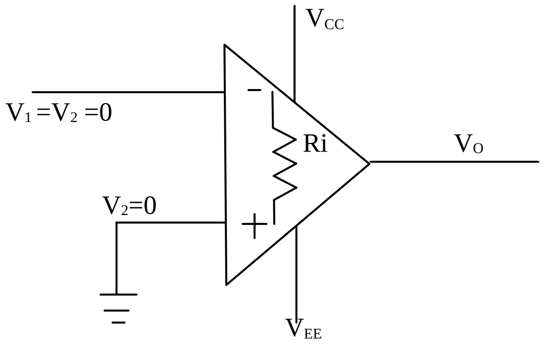
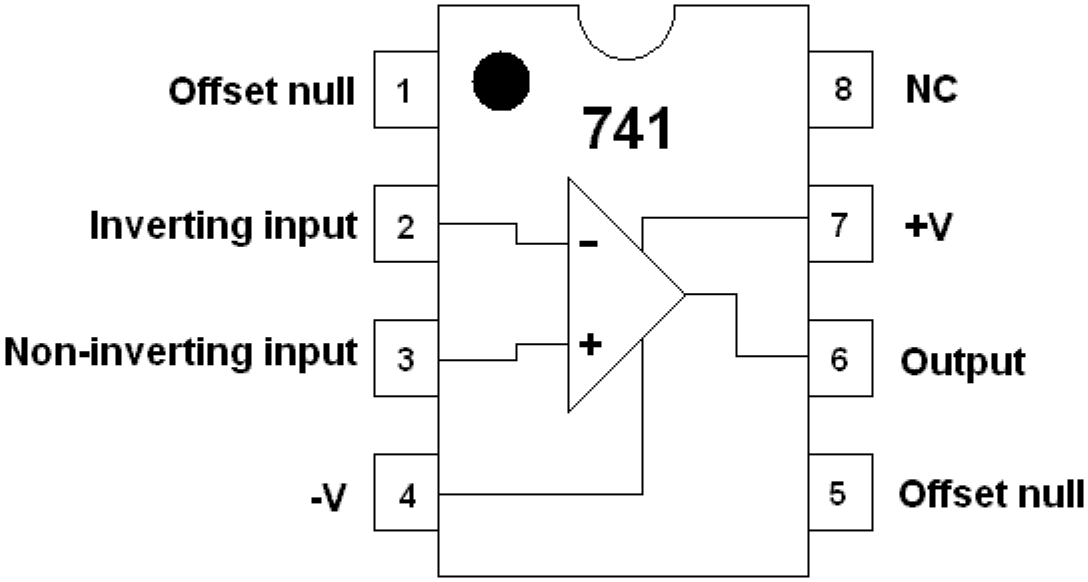


Fig. 4.5b Concept of Virtual ground

Then because of virtual ground V_1 will also be zero

Pin Configuration of IC 741



1. **Offset Null** - Rarely used. It can be used to to adjust for small errors in the two inputs so zero volts in gives zero volts out.
2. **Inverting Input** - If this voltage **goes up**, the output voltage will go **DOWN** unless the Op Amp is already saturated.
3. **Non-Inverting Input** - If this voltage **goes up**, the output voltage will go **UP** unless the Op Amp is already saturated.
4. **The minus supply** - Sometimes this is connected to zero volts (ground). Sometimes it's connected to a voltage between -5V and -18V or more for a few specialised op amps.
5. **Offset Null** - Rarely used. It can be used to to adjust for small errors in the two inputs so zero volts in gives zero volts out.
6. **The Output** - In an ideal Op Amp, the maximum and minimum output voltage is equal to the power supply voltages.
   In a real life Op Amp, these voltages are 2 to 3 Volts less.
7. **The plus supply** - Voltages from +5V to +18V are common.
   There are specialist and more expensive Op Amps with a higher voltage ratings.
8. **No Connection** - This pin is not used

Applications of Op-Amp

An Op-Amp can be used as

1. Inverting Amplifier
2. Non-Inverting Amplifier
3. Voltage follower
4. Adder (Summer)
5. Integrator
6. Differentiator
7. Difference Amplifier(Subtractor)
8. Comparator
9. Schmitt Trigger
10. Instrumentation Amplifier

1. **Inverting Amplifier**

An inverting amplifier is one whose output is amplified and is out of phase by 180^0 with respect to the input

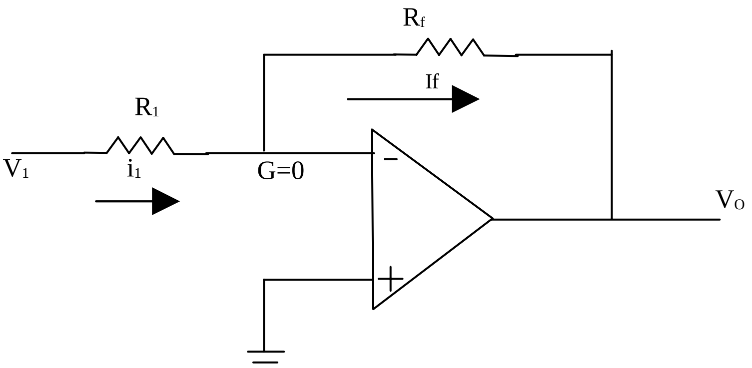


Fig 4.6 Inverting Amplifier

The point "G" is called virtual ground and is equal to zero.

Inverting Op-amp

- Input Signal V_i is applied to the inverting input terminal through resistor R_1.
- Non inverting terminal is grounded.
- The feedback from output is given to the inverting terminal through R_f.

$V_d = V_2 - V_1 = V_o = 0$

From the concept of Virtual ground,

$V_1 = V_2 = 0$

Due to high input impedance of Op-amp, current flowing into inverting input terminal is zero. Thus same current flows through R_1 and R_f.

$I_1 = I_F$ (1)

By KCL we have

$$I_1 = \frac{V\_ - V_1}{R_1} = \frac{V_i}{R_1} \text{------------------}(2)$$

$$I_f = \frac{V_1 - V_0}{R_f} = \frac{-V_0}{R_f} \text{------------------}(3)$$

From (1),(2) and (3),

$$\frac{V_i}{R_1} = \frac{-V_0}{R_f}$$

$$A_v = \frac{V_o}{V_i} = \frac{-R_f}{R_1}$$ --------------- Gain for Inverting Op-amp

Where $\frac{R_f}{R_1}$ is the gain of the amplifier and negative sign indicates that the output is inverted with respect to the input.

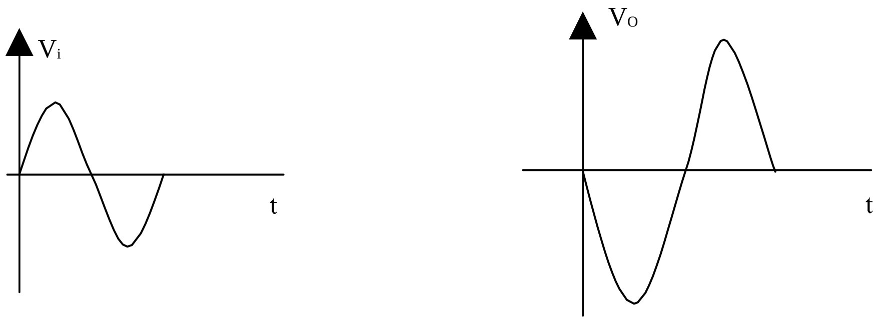


Fig 4.7 Waveforms of Inverting Amplifier

2. Non- Inverting Amplifier

A non-inverting amplifier is one whose output is amplified and is in-phase withthe input.

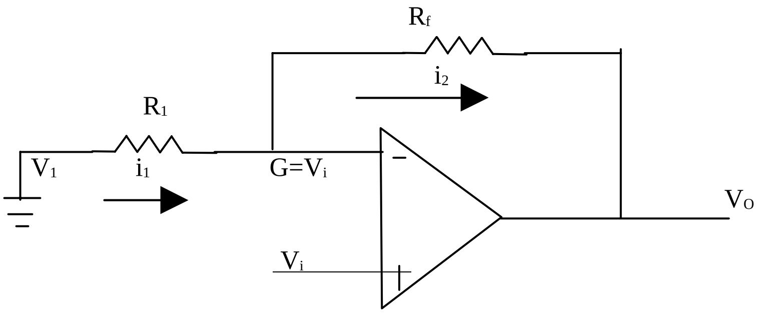


Fig 4.8 Non Inverting Amplifiers

Non Inverting Op-amp

- Input Signal V_i is applied to the non - inverting input terminal.
- Inverting terminal is grounded through resistor R_1.
- The feedback from output is given to the inverting terminal through R_f.

$V_2 = V_i$...(1)

Due to virtual ground,

V_1=V_2 (2)

V_i=V_1=V_2

Due to high input impedance of Op-amp, current flowing into inverting input terminal is zero. Thus same current flows through R_1 and R_f.

$I_1 = I_F$--(3)

$I_1 = \frac{0-V_1}{R_1} = \frac{-V_i}{R_f}$-------------------(4)

$I_f = \frac{V_1 - V_0}{R_f} = \frac{V_i - V_0}{R_f}$-------------------(5)

Using (3),equating (4) and(5),

$$\frac{-V_i}{R_1} = \frac{V_i - V_o}{R_f}$$

$$\frac{V_0}{R_f} = V_i \left[\frac{1}{R_1} + \frac{1}{R_f}\right]$$

$$\frac{V_0}{V_i} = R_f \left[\frac{1}{R_1} + \frac{1}{R_f}\right]$$

$\boldsymbol{A_v = \frac{V_0}{V_i} = 1 + \frac{R_f}{R_1}}$----------------Gain for non inverting Op-amp

3. Voltage follower

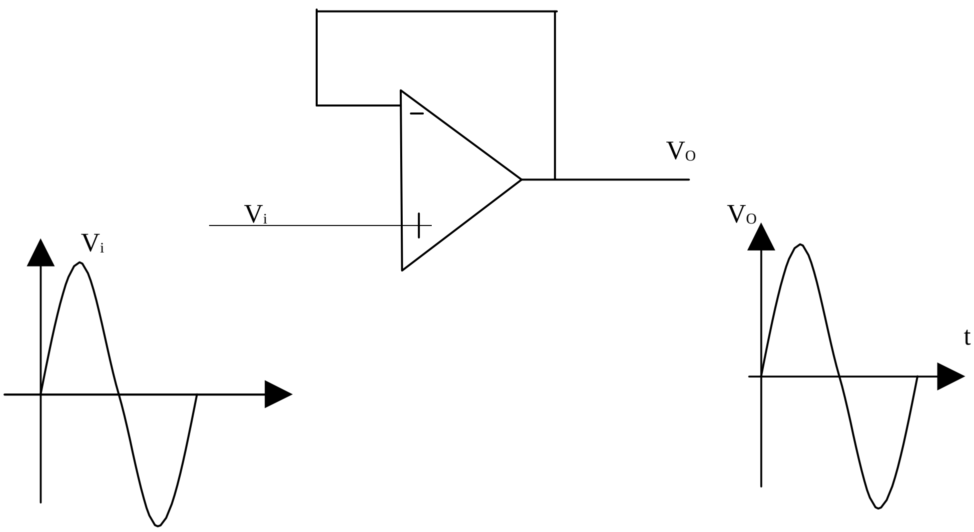


Fig. 4.9 Voltage follower

Voltage follower is one whose output is equal to the input. The voltage follower configuration shown above is obtained by short circuiting “Rf”and open circuiting “R1” connected in the usual non-inverting amplifier.Thus all the output is fed back to the inverting input of the op-Amp

Consider the equation for the output of non-inverting amplifier

When Rf = 0 short

circuiting R1= ∞

open circuiting

- Input Signal V_i is applied to the non - inverting input terminal.

$V_2=V_i$ (1)

- Inverting terminal is directly connected to the output..

$V_0=V_1$ (2)

From (1) and (2)

$V_0=V_i$

$$A_v = \frac{V_0}{V_i} = 1$$

Feedback factor for Voltage Follower

β =1

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

Since β =1

$A_f = \frac{A}{1+A}$ ---------------- Gain for Voltage Follower

Error =$\left[1 - \frac{A}{1+A}\right]$ x 100%

Therefore the output voltage will be equal and in-phase with the input voltage. Thus voltage follower is nothing but a non-inverting amplifier with a voltage gain of unity.

4. Summer(Inverting Adder)

Inverting adder is one whose output is the inverted sum of the constituentinputs

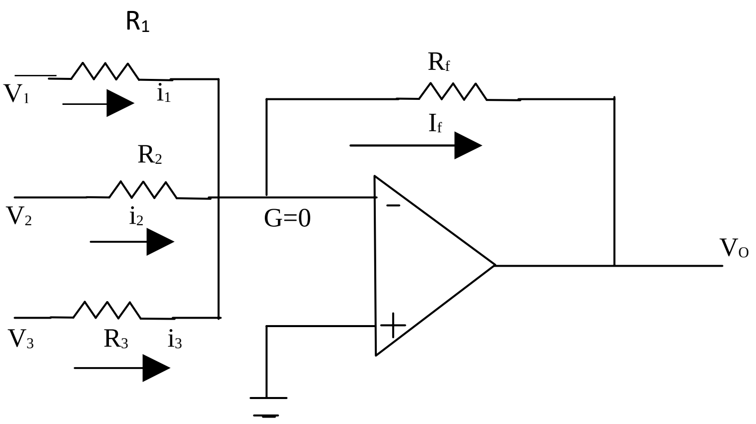


Fig 4.10 Summer (Inverting Adder)

Since non inverting terminal is grounded,

$V_B = 0$

And

$V_A = V_B = G = 0$ [Virtual Ground]

$$I_1 = \frac{V_1 - V}{R_1} = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2 - V_A}{R_2} = \frac{V_2}{R_2}$$

$$I_3 = \frac{V_3 - V}{R_3} = \frac{V_3}{R_3}$$

$$I_f = \frac{V_A - V_o}{R_f} = \frac{-V_o}{R_f}$$

Applying KCL at node A

$$I_f = I_1 + I_2 + I_3$$

$$\frac{-V_o}{R_f} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$V_o = [\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3]$$

If $R_f = R_1 = R_2 = R_3$

$$\boldsymbol{V_O = -[V_1 + V_2 + V_3]}$$

Hence it can be observed that the output is equal to the inverted sum of the inputs.

5. Integrator

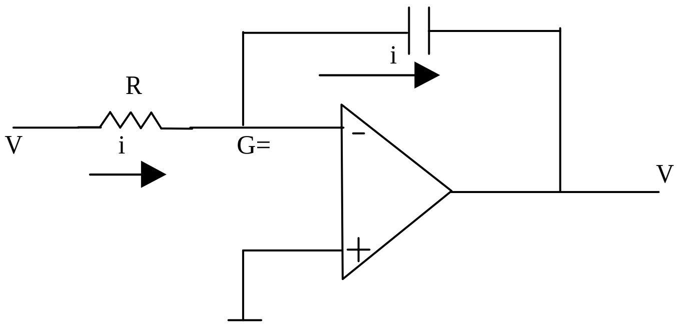


Fig 4.11a. Integrator Circuit

V_2=V_1 = 0 [Virtual Ground]

$$I_1 = I_F$$

$$I_1 = \frac{V_i - V_1}{R} = \frac{V_i}{R}$$

$$I_f = C\frac{d}{dt}(V_1 - V_o) = -C\frac{dV_o}{dt}$$

Since $I_1 = I_F$,

$$\frac{V_i}{R} = -C\frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = \frac{-1}{RC}V_i$$

Integrate both the sides to t

$$V = \frac{-1}{RC}\int_0^t V_i\,dt + V(0)$$

$V_o(0)$ is the initial voltage on capacitor at t=0,which is a constant.

$\boldsymbol{V_o = \frac{-1}{RC}\int_0^t V_i\,dt}$------------Output Voltage for Integrator

Output is -1/RC times the integral of input. There is phase shift of 180 degree between input and output.RC is called the time constant of integrator. The main advantage of integrator is large time constant. Due to large effective capacitance, time constant is very large and thus a perfect integration results due to such circuits.

6. Differentiator

A differentiator is one whose output is the differentiation of the input

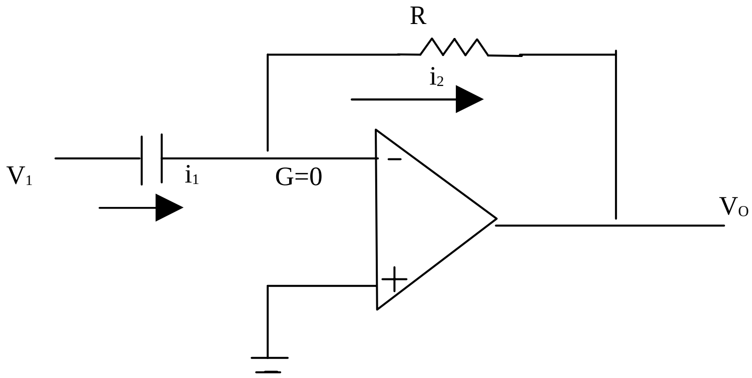


Fig 4.11b. Differentiator Circuit

$$V_1 = V_2 = 0 \text{ [Virtual Ground]}$$

$$I_1 = I_F$$

$$I_1 = C\frac{d}{dt}(V_i - V_1) = C\frac{dV_i}{dt}$$

$$I_f = \frac{V_1 - V}{R} = \frac{-V_o}{R}$$

$$C\frac{dV_i}{dt} = \frac{-V_o}{R}$$

$$\boldsymbol{V_o = -RC\frac{dV_i}{dt}}$$ ------------ Output Voltage of Differentiator.

Output is -RC times the differential of input. There is phase shift of 180 degree between input and output. The main advantage of differentiator is small time constantis required for differentiation.

7. Difference Amplifier [Sub tractor]

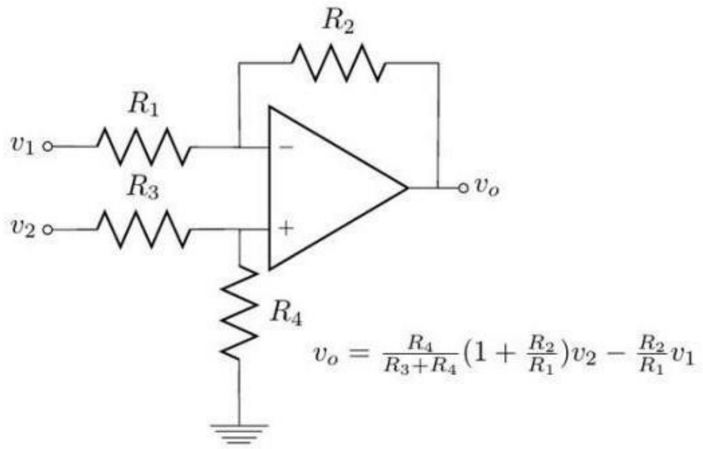


Fig 4.12 Difference Amplifier circuit

Circuit is a combination of inverting and non-inverting amplifier.R1 ,R2 and Op-amp constitutes inverting amplifier for V_{i1}.R1,R2 and Op-amp constitutes inverting amplifier for V_{R4} .V_{R4} is derived from Thevenin's Theorem.

V_{R4} is obtained from the voltage divider of V_{i2} by R3 and R4

To understand circuit operation consider the output produced by each input when the other input is zero.

CASE 1 :- V_{i2} = 0

V_{01} = V x Gain of inverting Op-amp

$V_{01} = V_{i1}\ X\ [\frac{-R_2}{R_1}]$---------(1)

CASE 2 :- V_{i1} = 0

V_{02} = V x Gain of Non-inverting Op-amp

$V_{02} = V_{R4}\ X\ [1+\frac{R_2}{R_1}]$---------(2)

$V_{R4} = \frac{V_{i2} X R_4}{R_3+R_4}$ [Thevenin's Voltage]------(3)

Substitute (3) in (2),

$V_{02} = \frac{V_{i2} X R_4}{R_3+R_4}\ X\ \frac{R_1+R_2}{R_1}$

With R3=R1 and R4=R2

$V_{02} = V_{i2}\ X\ [\frac{R_2}{R_1}]$---------(4)

When both inputs are present ,

Apply the Superposition principle,

$$V_O = V_{01} + V_{02}$$

$$= V_{i1}\ X\left[\frac{-R_2}{R_1}\right] + V_{i2}\ X\left[\frac{R_2}{R_1}\right]$$

$$V_O = \left[\frac{R_2}{R_1}\right][V_{i1} - V_{i2}]$$

When R2=R1,

$\boldsymbol{V_O = [V_{i2} - V_{i1}]}$-----output is proportional to the difference b/w 2 inputs.

Consider when inputs are equal [Common mode]

$V_{i1} = V_{i2} = V_{cm}$ =>V_O=0

$$V_O = V_{01} + V_{02}$$

$$0 = V_{cm}\ X\left[\frac{-R_2}{R_1}\right] + V\left[\frac{R_4}{R_3+R_4}\right] X\left[\frac{R_1+R_2}{R_1}\right]$$

On simplifying, we get

$$\boldsymbol{\frac{R_2}{R_1} = \frac{R_4}{R_3}}$$

Hence output voltage for difference amplifier can be,

$$V_O = \left[\frac{R_2}{R_1}\right][V_{i2} - V_{i1}] = \left[\frac{R_4}{R_3}\right][V_{i2} - V_{i1}]$$

8.Instrumentation Amplifier

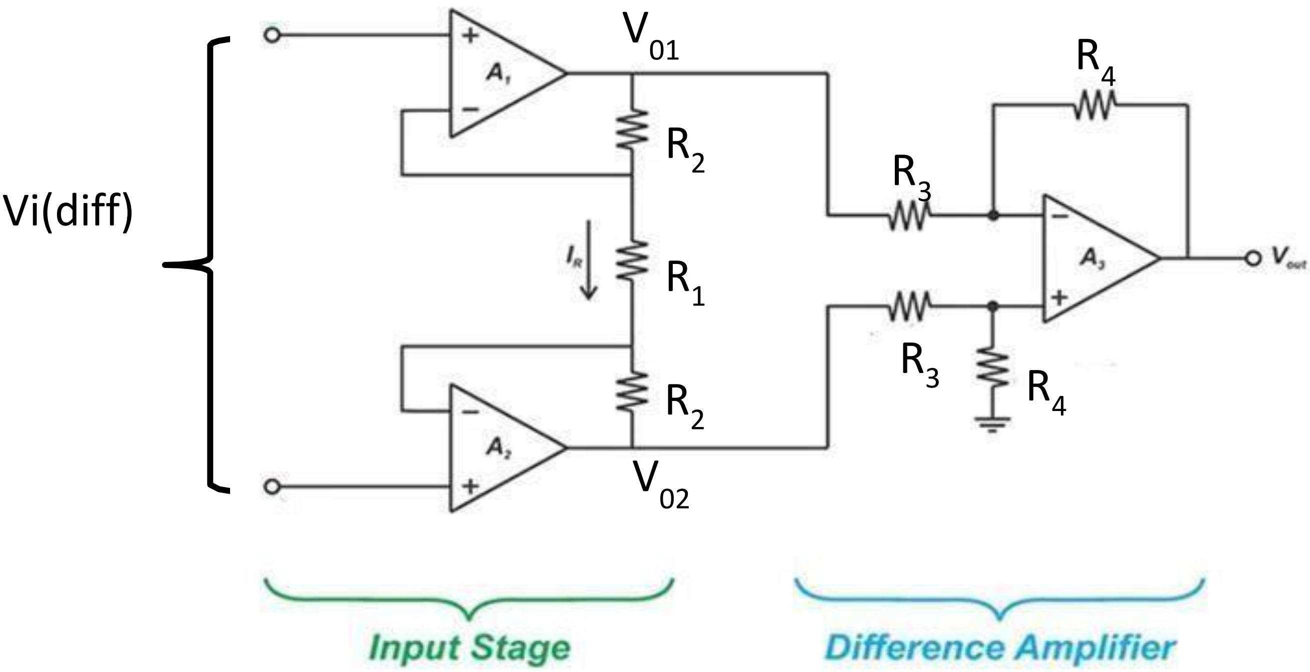


Fig 4.13 Instrumentation amplifier circuit

Gain of Non Inverting Op-amp = $1 + \frac{R_2}{R_1}$

Gain of 1st Op-amp [A1] = $1 + \frac{R_2}{R_1}$

Gain of 2nd Op-amp [A2] = $1 + \frac{R_2}{R_1}$

$$V_{idiff} = [V_{i2} - V_{i1}]$$

$V_{01} = V_{i1}\ X\ [1 + \frac{R_2}{R_1}]$--------(1)

$V_{02} = V_{i2}\ X\ [1 + \frac{R_2}{R_1}]$--------(2)

$$V_{odiff} = [V_{02} - V_{01}]$$

$V_{odiff} = 1 + \frac{R_2}{R_1}[V_{i2} - {}_{i1}]$-------(3)

$V_{odiff}$is the i/p to the difference amplifier A3.

$V_{0diff} = V_{idiff}\ X\ [1 + \frac{R_2}{R_1}]$---------(4)

We know

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

$$V_O = [\frac{R_4}{R_3}]\ [V_{02} - V_{01}]$$

$$V_O = [\frac{R_4}{R_3}]\ V_{0diff}$$

Using (4)

$$V_O = [\frac{R_4}{R_3}]\ [1 + \frac{R_2}{R_1}]\ V_{idiff}$$

Overall differential gain is

$$\mathbf{A_d} = \frac{\boldsymbol{V_O}}{\boldsymbol{V_{idiff}}} = [\frac{\boldsymbol{R_4}}{\boldsymbol{R_3}}]\ [\mathbf{1} + \frac{\boldsymbol{R_2}}{\boldsymbol{R_1}}]$$

9.Schmitt Trigger

Schmitt Trigger circuit is a fast operating voltage level detector.When the input voltage arrives at a level determined by circuit components, the output voltage switches rapidly between its max positive level and its max negative level.The input voltage Vi is applied to inverting input terminal and the feedback voltage goes to non-inverting input.The waveform shows that o/p switches rapidly from positive saturation (+Vosat) voltage to negative saturation (-Vosat) when the input exceeds a certain positive level. This is called

Upper Trigger Point.(UTP).Output switches from low to high when the input goes below a negative trigger point is Lower Trigger Point(LTP).

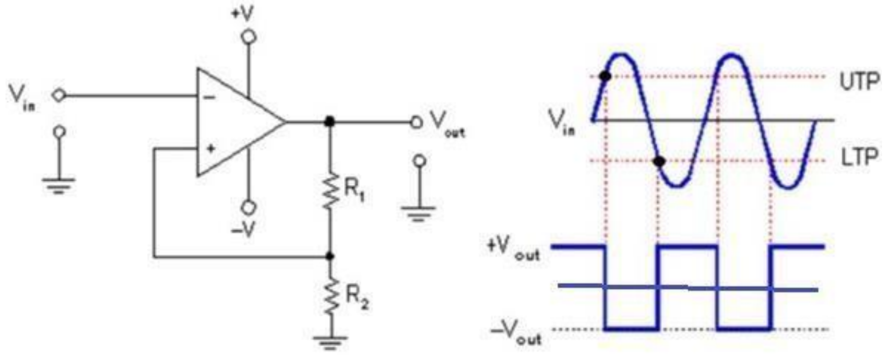


Fig 4.14 Schmitt Trigger

Feedback factor(β) = $\frac{R1}{R1+Rf}$

UTP is given by,

V_{UT} = UTP = $(+V_O)\frac{R1}{R1+Rf}$ = $+V_O$ X β

(OR)

V_{UT} = UTP = $(V_{CC})\frac{R1}{R1+Rf}$ = $+V_{CC}$ X β

LTP is given by,

V_{LT} = LTP = $(-V_O)\frac{R1}{R1+Rf}$ = $-V_O$ X β

(OR)

V_{LT} = LTP = $(-V_{EE})\frac{R1}{R1+Rf}$ = $-V_{EE}$ X β

Hysteresis = UTP – LTP

$\mathbf{V_H = V_{UT} - V_{LT}}$

$V_H = +V_O$ X β – ($-V_O$ X β)

$V_H = V_{CC}$ X β – ($-V_{EE}$ X β)

$\mathbf{V_H = V_{CC}\frac{R_1}{R_1+R_f} - (-V_{EE}\frac{R_1}{R_1+R_f})}$

Graph of Input-Output Characteristics of Schmitt Trigger(Hysteresis Loop)

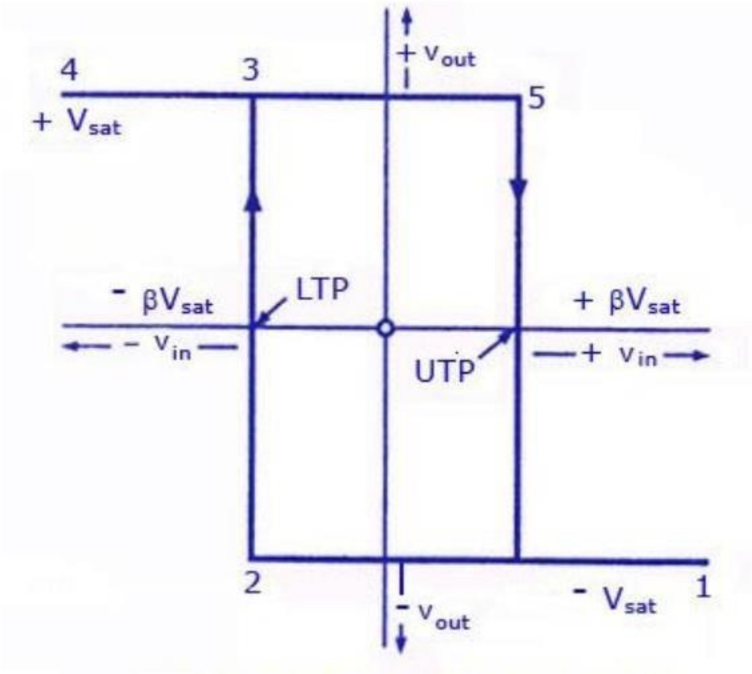


Fig 4.15 Input Output Characteristics of Schmitt Trigger

Conditions:

- **Positive cycle, At point 1: Vo<LTP, Vi=+Vosat**
- **At point 2: Vo>LTP, Vi=+Vosat**
- **At point 3: Vo=UTP, Vi=+Vosat**
- **At point 4: Vo=UTP, Vi= switches from +Vosat to –Vosat**
- **Negative cycle, At point 5: Vo>UTP, Vi= -Vosat**
- **At point 6: Vo=LTP, Vi= -Vosa**
- **At point 1: Vo<LTP, Vi=+Vosat(switches from -Vosat to +Vosat)**

10. Comparator

The comparator is an electronic decision making circuit that makes use of operational amplifiers very high gain in its open-loop state, that is, there is no feedback resistor. The Op-amp comparator compares one analogue voltage level with another analogue voltage level, or some preset reference voltage, V_{REF} and produces an output signal based on this voltage comparison. In other words, the op-amp voltage comparator compares the magnitudes of two voltage inputs and determines which is the largest of the two.

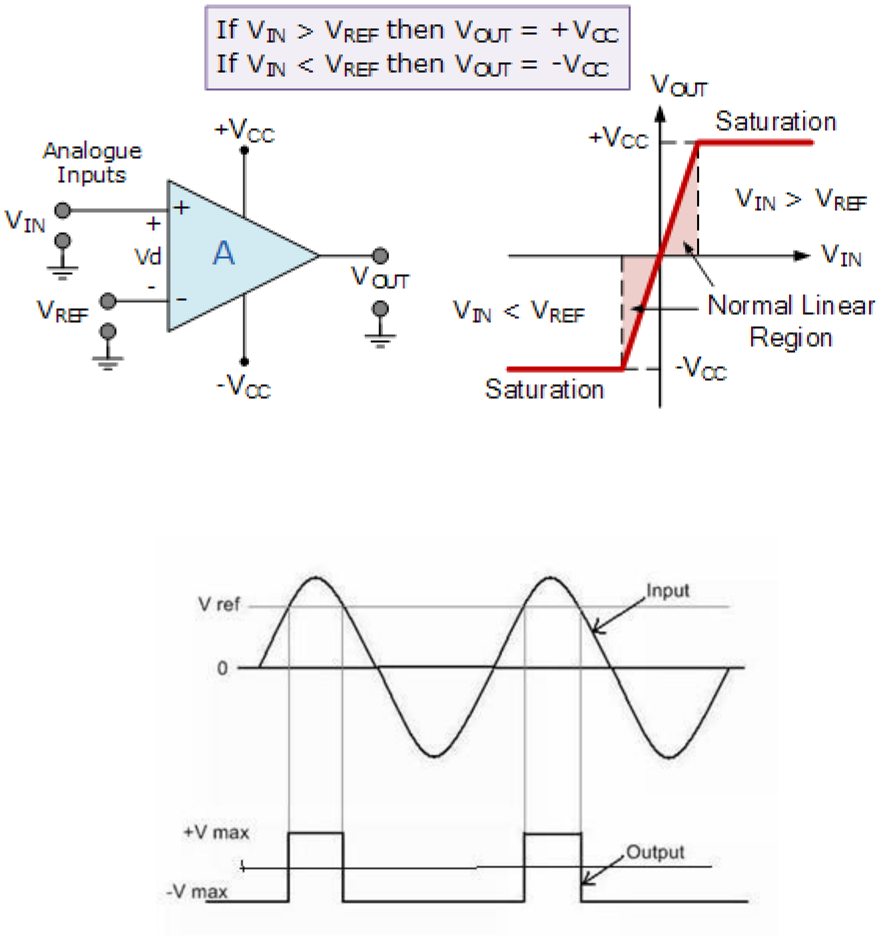


Fig 4.16 Comparator circuit and waveform