

# **HANDBOOK ON OPAMP**

**An Introduction**

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Reference: NPTEL Lectures

**DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING**



**The operation amplifier:**

An operational amplifier is a direct coupled high gain amplifier consisting of one or more differential (OPAMP) amplifiers and followed by a level translator and an output stage. An operational amplifier is available as a single integrated circuit package.

The block diagram of OPAMP is shown in **fig. 1**.

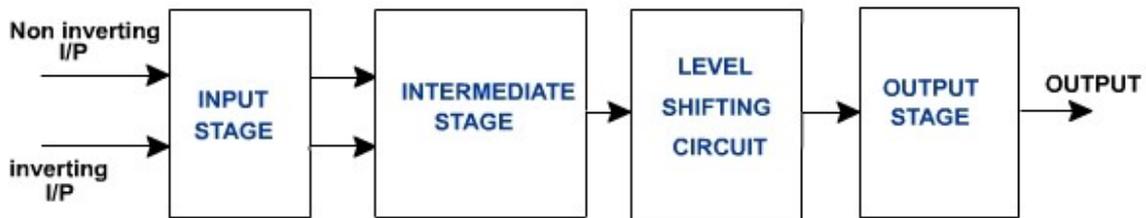


Figure 1

The input stage is a dual input balanced output differential amplifier. This stage provides most of the voltage gain of the amplifier and also establishes the input resistance of the OPAMP. The intermediate stage of OPAMP is another differential amplifier which is driven by the output of the first stage. This is usually dual input unbalanced output.

Because direct coupling is used, the dc voltage level at the output of intermediate stage is well above ground potential. Therefore level shifting circuit is used to shift the dc level at the output downward to zero with respect to ground. The output stage is generally a push pull complementary amplifier. The output stage increases the output voltage swing and raises the current supplying capability of the OPAMP. It also provides low output resistance.

**Level Translator:**

Because of the direct coupling the dc level at the emitter rises from stages to stage. This increase in dc level tends to shift the operating point of the succeeding stages and therefore limits the output voltage swing and may even distort the output signal.

To shift the output dc level to zero, level translator circuits are used. An emitter follower with voltage divider is the simplest form of level translator as shown in **Fig. 2**.

Thus a dc voltage at the base of Q produces 0V dc at the output. It is decided by  $R_1$  and  $R_2$ . Instead of voltage divider emitter follower either with diode current bias or current mirror bias as shown in **Fig. 3** may be used to get better results. In this case, level shifter, which is common collector amplifier, shifts the level by 0.7V. If this shift is not sufficient, the output may be taken at the junction of two resistors in the emitter leg.

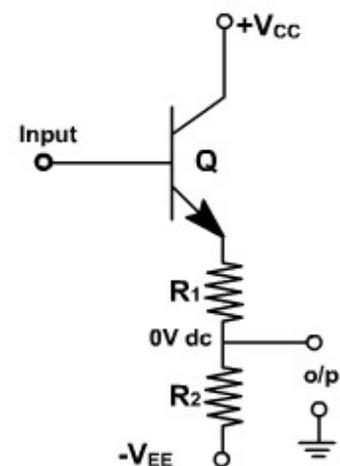


Fig. 2

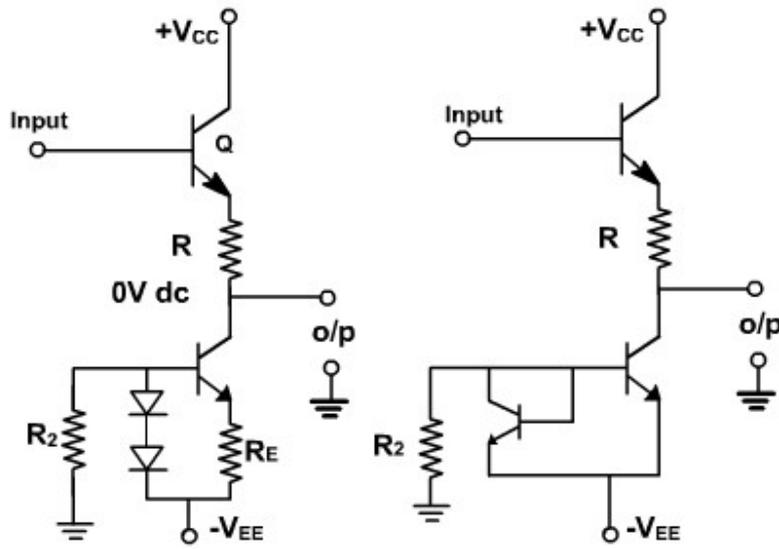


Fig. 3

Fig. 4, shows a complete OPAMP circuit having input different amplifiers with balanced output, intermediate stage with unbalanced output, level shifter and an output amplifier.

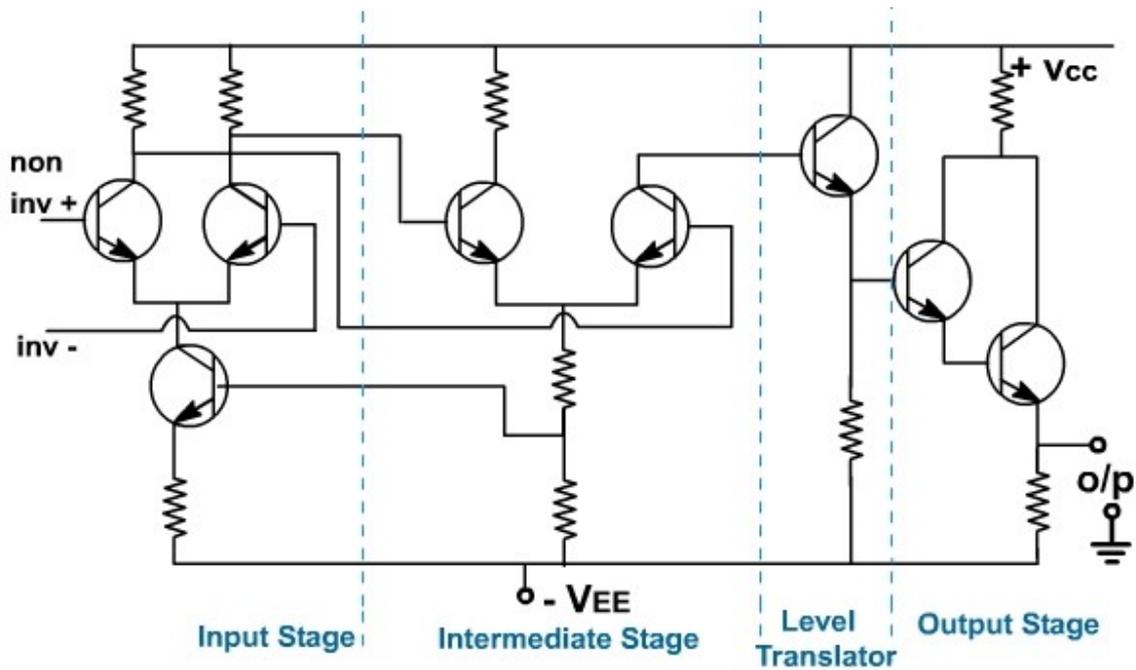
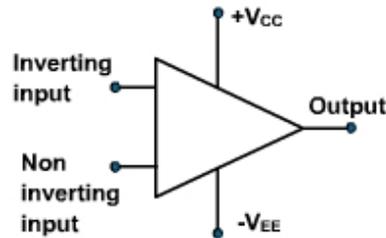


Fig. 4

## Practical Operational Amplifier

The symbolic diagram of an OPAMP is shown in [fig. 1](#).



741c is most commonly used OPAMP available in IC package. It is an 8-pin DIP chip.

### Parameters of OPAMP:

The various important parameters of OPAMP are follows:

#### 1. Input Offset Voltage:

Input offset voltage is defined as the voltage that must be applied between the two input terminals of an OPAMP to null or zero the output [fig. 2](#), shows that two dc voltages are applied to input terminals to make the output zero.

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

$V_{dc1}$  and  $V_{dc2}$  are dc voltages and  $R_s$  represents the source resistance.  $V_{io}$  is the difference of  $V_{dc1}$  and  $V_{dc2}$ . It may be positive or negative. For a 741C OPAMP the maximum value of  $V_{io}$  is 6mV. It means a voltage  $\pm 6$  mV is required to one of the input to reduce the output offset voltage to zero. The smaller the input offset voltage the better the differential amplifier, because its transistors are more closely matched.

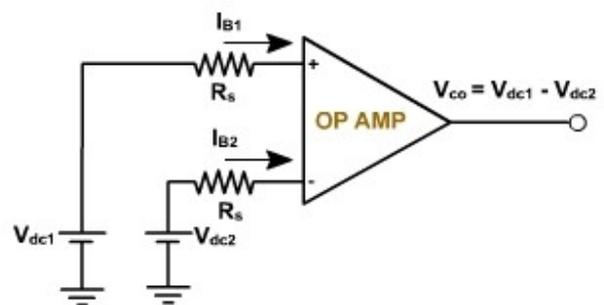


Fig. 2

#### 2. Input offset Current:

The input offset current  $I_{io}$  is the difference between the currents into inverting and non-inverting terminals of a balanced amplifier.

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

The  $I_{i0}$  for the 741C is 200nA maximum. As the matching between two input terminals is improved, the difference between  $I_{B1}$  and  $I_{B2}$  becomes smaller, i.e. the  $I_{i0}$  value decreases further. For a precision OPAMP 741C,  $I_{i0}$  is 6 nA

### 3. Input Bias Current:

The input bias current  $I_B$  is the average of the current entering the input terminals of a balanced amplifier i.e.

$$I_B = (I_{B1} + I_{B2}) / 2$$

For 741C  $I_{B(max)} = 700$  nA and for precision 741C  $I_B = \pm 7$  nA

### 4. Differential Input Resistance: ( $R_i$ )

$R_i$  is the equivalent resistance that can be measured at either the inverting or non-inverting input terminal with the other terminal grounded. For the 741C the input resistance is relatively high 2 M $\Omega$ . For some OPAMP it may be up to 1000 G ohm.

### 5. Input Capacitance: ( $C_i$ )

$C_i$  is the equivalent capacitance that can be measured at either the inverting and noninverting terminal with the other terminal connected to ground. A typical value of  $C_i$  is 1.4 pf for the 741C.

### 6. Offset Voltage Adjustment Range:

741 OPAMP have offset voltage null capability. Pins 1 and 5 are marked offset null for this purpose. It can be done by connecting 10 K ohm pot between 1 and 5 as shown in [fig. 3](#).

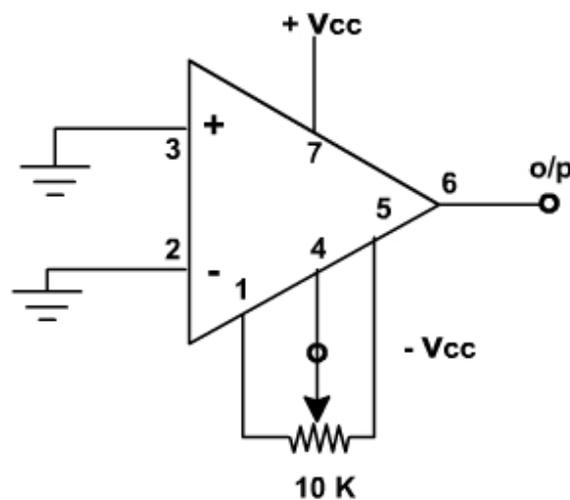


Fig. 3

By varying the potentiometer, output offset voltage (with inputs grounded) 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 10 K pot. For the 741C the offset voltage adjustment range is  $\pm 15$  mV.

### 7. Input Voltage Range :

Input voltage range is the range of a common mode input signal for which a differential amplifier remains linear. It is used to determine the degree of matching between the inverting and noninverting input terminals. For the 741C, the range of the input common mode voltage is  $\pm 13$ V maximum. This means that the common mode voltage applied at both input terminals can be as high as +13V or as low as -13V.

### 8. Common Mode Rejection Ratio (CMRR).

CMRR is defined as the ratio of the differential voltage gain  $A_d$  to the common mode voltage gain  $A_{CM}$

$$CMRR = A_d / A_{CM}$$

For the 741C, CMRR is 90 dB typically. The higher the value of CMRR the better is the matching between two input terminals and the smaller is the output common mode voltage.

### 9. Supply voltage Rejection Ratio: (SVRR)

SVRR is the ratio of the change in the input offset voltage to the corresponding change in power supply voltages. This is expressed in mV / V or in decibels, SVRR can be defined as

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

Where  $\Delta V$  is the change in the input supply voltage and  $\Delta V_{io}$  is the corresponding change in the offset voltage.

For the 741C,  $SVRR = 150 \mu V / V$ .

For 741C, SVRR is measured for both supply magnitudes increasing or decreasing simultaneously, with  $R_3 \leq 10K$ . For some OPAMPS, SVRR is separately specified as positive SVRR and negative SVRR.

### 10. Large Signal Voltage Gain:

Since the OPAMP amplifies difference voltage between two input terminals, the voltage gain of the amplifier is defined as

$$\text{Voltage gain} = \frac{\text{Output voltage}}{\text{Differential input voltage}}$$
$$A = \frac{V_o}{V_{id}}$$

Because output signal amplitude is much larger than the input signal the voltage gain is commonly called large signal voltage gain. For 741C the voltage gain is 200,000 typically.

### 11. Output voltage Swing:

The ac output compliance PP is the maximum unclipped peak to peak output voltage that an OPAMP can produce. Since the quiescent output is ideally zero, the ac output voltage can swing positive or negative. This also indicates the values of positive and negative saturation voltages of the OPAMP. The output voltage never exceeds these limits for a given supply voltages  $+V_{CC}$  and  $-V_{EE}$ . For a 741C it is  $\pm 13$  V.

### 12. Output Resistance: ( $R_o$ )

$R_o$  is the equivalent resistance that can be measured between the output terminal of the OPAMP and the ground. It is 75 ohm for the 741C OPAMP.

### The ideal OPAMP :

An ideal OPAMP would exhibit the following electrical characteristics.

1. Infinite voltage gain  $A_d$
2. Infinite input resistance  $R_i$ , so that almost any signal source can drive it and there is no loading of the input source.
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 signals from 0 to infinite 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.

There are practical OPAMPs that can be made to approximate some of these characteristics using a negative feedback arrangement.

### Equivalent Circuit of an OPAMP:

[Fig. 5](#), shows an equivalent circuit of an OPAMP.  $v_1$  and  $v_2$  are the two input voltage voltages.  $R_i$  is the input impedance of OPAMP.  $A_d V_d$  is an equivalent Thevenin voltage source and  $R_o$  is the Thevenin equivalent impedance looking back into the terminal of an OPAMP.

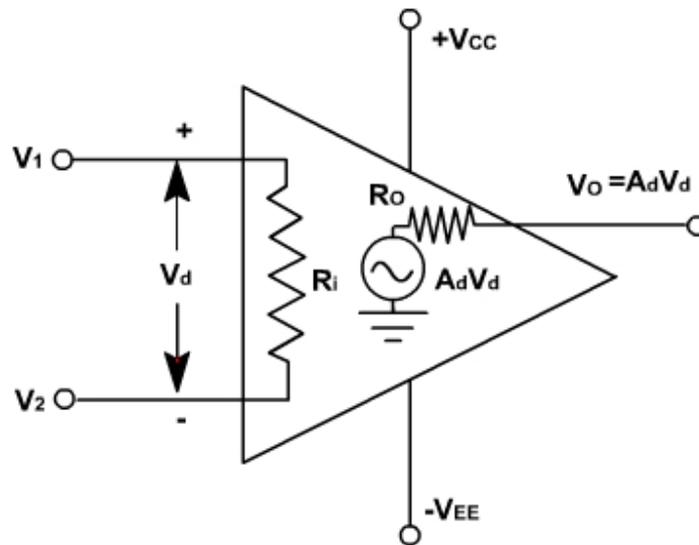


Fig. 5

This equivalent circuit is useful in analyzing the basic operating principles of OPAMP and in observing the effects of standard feedback arrangements

$$v_o = A_d (v_1 - v_2) = A_d v_d.$$

This equation indicates that the output voltage  $v_o$  is directly proportional to the algebraic difference between the two input voltages. In other words the OPAMP amplifies the difference between the two input voltages. It does not amplify the input voltages themselves. The polarity of the output voltage depends on the polarity of the difference voltage  $v_d$ .

**Ideal Voltage Transfer Curve:**

The graphic representation of the output equation is shown in [fig. 6](#) in which the output voltage  $v_o$  is plotted against differential input voltage  $v_d$ , keeping gain  $A_d$  constant.

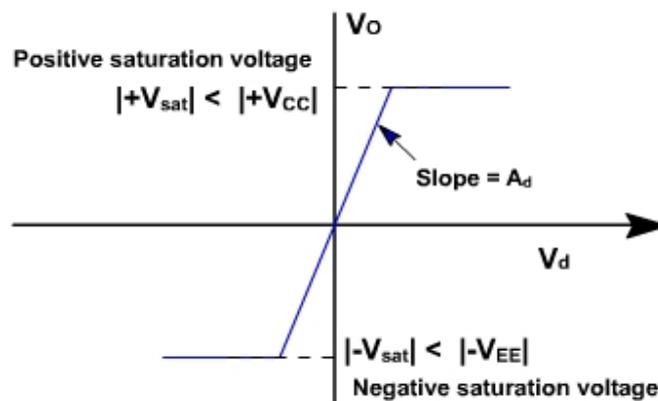


Fig. 6

The output voltage cannot exceed the positive and negative saturation voltages. These saturation voltages are specified 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 and thereafter the output voltage remains constant.

Thus curve is called an ideal voltage transfer curve, ideal because output offset voltage is assumed to be zero. If the curve is drawn to scale, the curve would be almost vertical because of very large values of  $A_d$ .

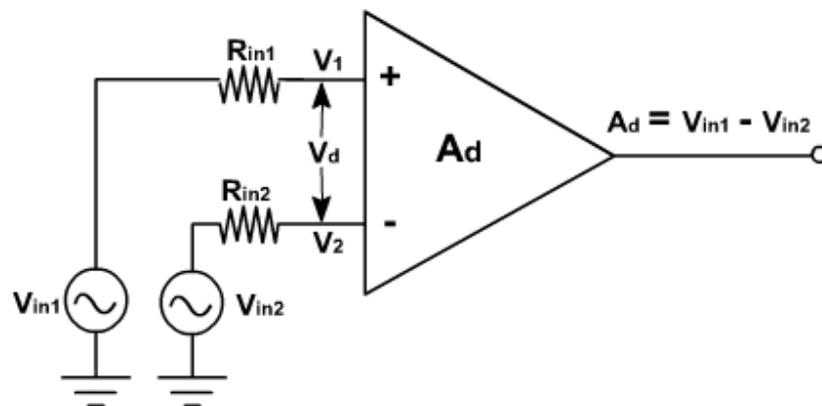
**Open loop OPAMP Configuration:**

In the case of amplifiers the term open loop indicates that no connection, exists between input and output terminals of any type. That is, the output signal is not fed back in any form as part of the input signal.

In open loop configuration, The OPAMP functions as a high gain amplifier. There are three open loop OPAMP configurations.

**The Differential Amplifier:**

[Fig. 1](#), shows the open loop differential amplifier in which input signals  $v_{in1}$  and  $v_{in2}$  are applied to the positive and negative input terminals.



**Fig. 1**

Since the OPAMP amplifies the difference between the two input signals, this configuration is called the differential amplifier. The OPAMP amplifies both ac and dc input signals. The source resistance  $R_{in1}$  and  $R_{in2}$  are normally negligible compared to the input resistance  $R_i$ . Therefore voltage drop across these resistances can be assumed to be zero.

Therefore

$$v_1 = v_{in1} \text{ and } v_2 = v_{in2}.$$

$$v_o = A_d (v_{in1} - v_{in2})$$

where,  $A_d$  is the open loop gain.

**The Inverting Amplifier:**

If the input is applied to only inverting terminal and non-inverting terminal is grounded then it is called inverting amplifier. This configuration is shown in [fig. 2](#).

$$v_1 = 0, v_2 = v_{in}$$

$$v_o = -A_d v_{in}$$

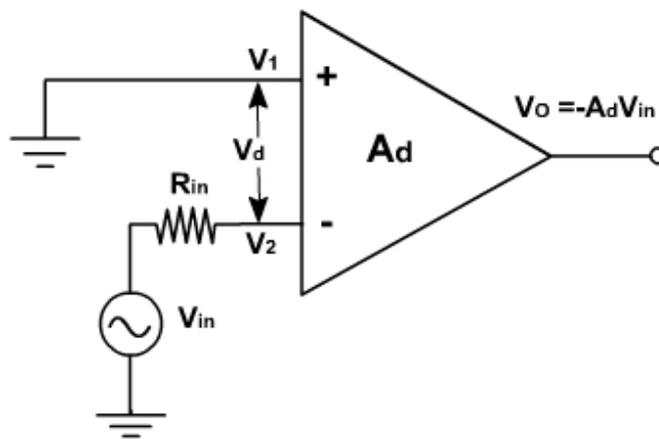


Fig. 2

The negative sign indicates that the output voltage is out of phase with respect to input  $180^\circ$  or is of opposite polarity. Thus the input signal is amplified and inverted also.

**The non-inverting amplifier:**

In this configuration, the input voltage is applied to non-inverting terminals and inverting terminal is ground as shown in [fig. 3](#).

$$v_1 = +v_{in} \quad v_2 = 0$$

$$v_o = +A_d v_{in}$$

This means that the input voltage is amplified by  $A_d$  and there is no phase reversal at the output.

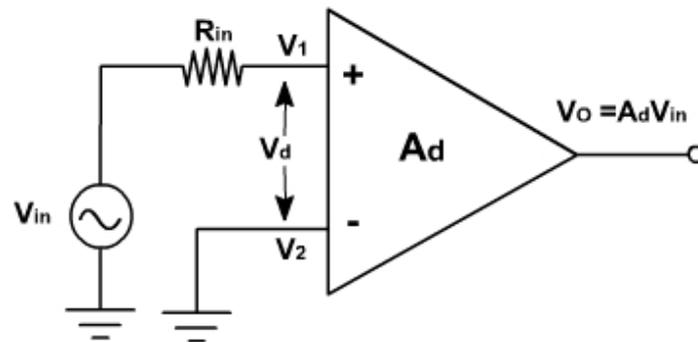


Fig. 3

In all these configurations any input signal slightly greater than zero drive the output to saturation level. This is because of very high gain. Thus when operated in open-loop, the output of the OPAMP is either negative or positive saturation or switches between positive and negative saturation levels. Therefore open loop op-amp is not used in linear applications.

#### Closed Loop Amplifier:

The gain of the OPAMP can be controlled if feedback is introduced in the circuit. That is, an output signal is fed back to the input either directly or via another network. If the signal feedback is of opposite or out phase by  $180^\circ$  with respect to the input signal, the feedback is called negative feedback.

An amplifier with negative feedback has a self-correcting ability of change in output voltage caused by changes in environmental conditions. It is also known as degenerative feedback because it reduces the output voltage and, in turn, reduces the voltage gain.

If the signal is fed back in phase with the input signal, the feedback is called positive feedback. In positive feedback the feedback signal aids the input signal. It is also known as regenerative feedback. Positive feedback is necessary in oscillator circuits.

The negative feedback stabilizes the gain, increases the bandwidth and changes, the input and output resistances. Other benefits are reduced distortion and reduced offset output voltage. It also reduces the effect of temperature and supply voltage variation on the output of an op-amp.

A closed loop amplifier can be represented by two blocks one for an OPAMP and other for a feedback circuit. There are four following ways to connect these blocks. These connections are shown in [fig. 4](#).

These connections are classified according to whether the voltage or current is fed back to the input in series or in parallel:

- Voltage – series feedback
- Voltage – shunt feedback
- Current – series feedback

- Current – shunt feedback

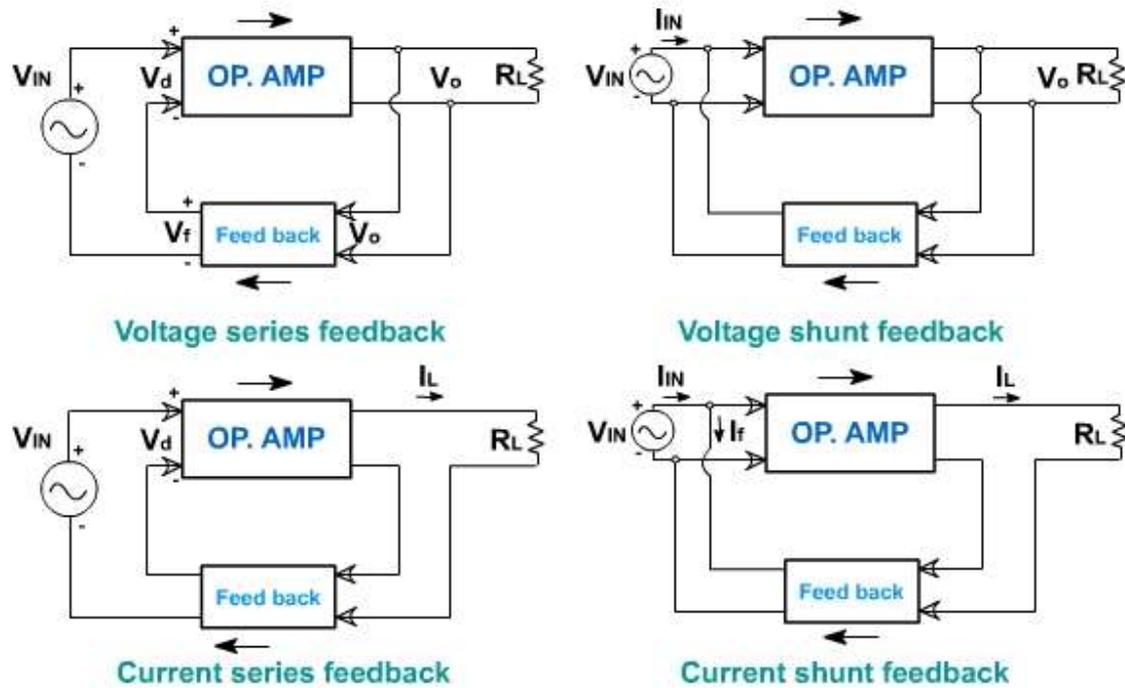


Fig. 4

In all these circuits of [fig. 4](#), the signal direction is from input to output for OPAMP and output to input for feedback circuit. Only first two, feedback in circuits are important.

**Voltage series feedback:**

It is also called non-inverting voltage feedback circuit. With this type of feedback, the input signal drives the non-inverting input of an amplifier; a fraction of the output voltage is then fed back to the inverting input. The op-amp is represented by its symbol including its large signal voltage gain  $A_d$  or  $A$ , and the feedback circuit is composed of two resistors  $R_1$  and  $R_f$ , as shown in [fig. 5](#)

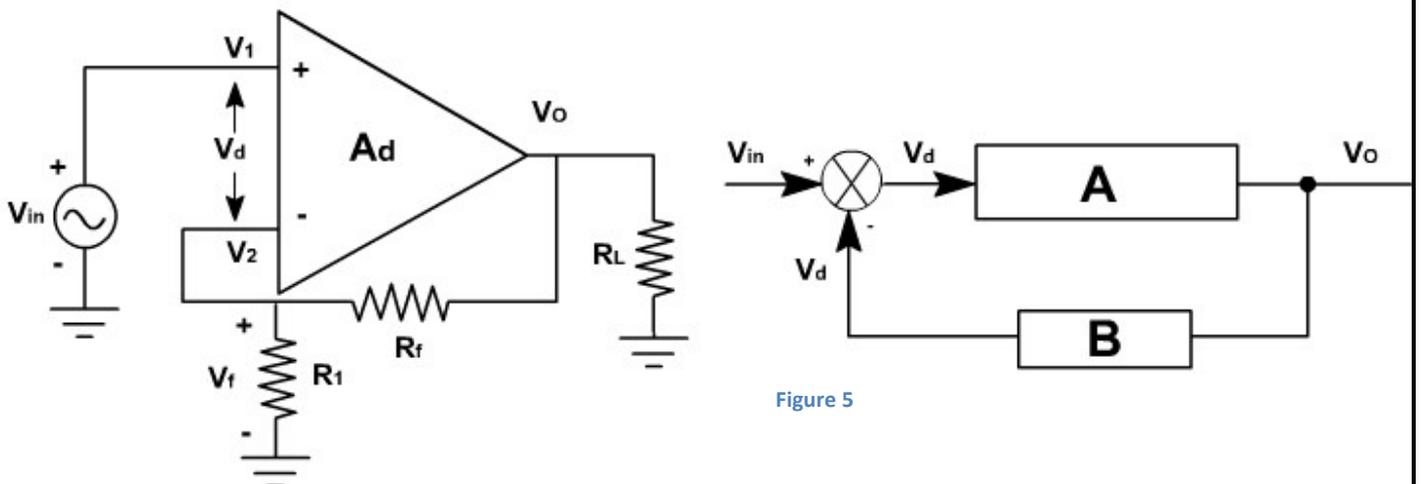


Figure 5

Open loop voltage gain  $A_d = \frac{v_o}{v_d}$

Closed loop voltage gain  $A_{CL} = \frac{v_o}{v_{in}}$

Feedback circuit gain  $B = \frac{v_f}{v_o}$

The differential voltage input  $v_d = v_{in} - v_f$

The feedback voltage always opposes the input voltage, (or is out of phase by  $180^\circ$  with respect to input voltage), hence the feedback is said to be negative.

The closed loop voltage gain is given by

$$\begin{aligned} A_{CL} &= \frac{v_o}{v_{in}} \\ v_o &= A (v_1 - v_2) = A (v_{in} - v_f) \\ &= A (v_{in} - Bv_o) \\ v_o (1 + AB) &= A v_{in} \\ \frac{v_o}{v_{in}} &= \frac{A}{1 + AB} \end{aligned}$$

The product A and B is called loop gain. The gain loop gain is very large such that  $AB \gg 1$

$$\begin{aligned} \therefore \frac{v_o}{v_{in}} &= \frac{A}{AB} = \frac{1}{B} \\ &= \frac{R_1 + R_f}{R_1} \\ &= 1 + \frac{R_f}{R_1} \end{aligned}$$

This shows that overall voltage gain of the circuit equals the reciprocal of B, the feedback gain. It means that closed loop gain is no longer dependent on the gain of the op-amp, but depends on the feedback of the voltage divider. The feedback gain B can be precisely controlled and it is independent of the amplifier.

*Physically, what is happening in the circuit?* The gain is approximately constant, even though differential voltage gain may change. Suppose A increases for some reasons (temperature change). Then the output voltage will try to increase. This means that more voltage is feedback to the inverting input, causing  $v_d$  voltage to decrease. This almost completely offset the attempted increases in output voltage.

Similarly, if A decreases, The output voltage decreases. It reduces the feedback voltage  $v_f$  and hence,  $v_d$  voltage increases. Thus the output voltage increases almost to same level.

**Different Input voltage is ideally zero.**

Again considering the voltage equation,

$$v_o = A_d v_d$$

$$\text{or } v_d = v_o / A_d$$

Since  $A_d$  is very large (ideally infinite)

Therefore:  $v_d \gg 0$ .

and  $v_1 = v_2$  (ideal).

This says, that the voltage at non-inverting input terminal of an op-amp is approximately equal to that at the inverting input terminal provided that  $A_d$  is very large. This concept is useful in the analysis of closed loop OPAMP circuits. For example, ideal closed loop voltage gain can be obtained using the results

$$\begin{aligned} v_1 &= v_{in} \\ v_2 &= v_f = \frac{R_1}{R_1 + R_f} v_o \\ \therefore v_1 &= v_2 \\ \therefore v_{in} &= \frac{R_1}{R_1 + R_f} v_o \\ v_o &= \left( 1 + \frac{R_1}{R_f} \right) v_{in} \end{aligned}$$

### Analog Inverter and Scale Changer:

The circuit of analog inverter is shown in [fig. 1](#). It is same as inverting voltage amplifier.

Assuming OPAMP to be an ideal one, the differential input voltage is zero.

i.e.  $v_d = 0$   
Therefore,  $v_1 = v_2 = 0$

Since input impedance is very high, therefore, input current is zero. OPAMP do not sink any current.

$$\begin{aligned} \therefore i_{in} &= i_f \\ v_{in} / R &= -v_o / R_f \\ v_o &= - (R_f / R) v_{in} \end{aligned}$$

If  $R = R_f$  then  $v_o = -v_{in}$ , the circuit behaves like an inverter.

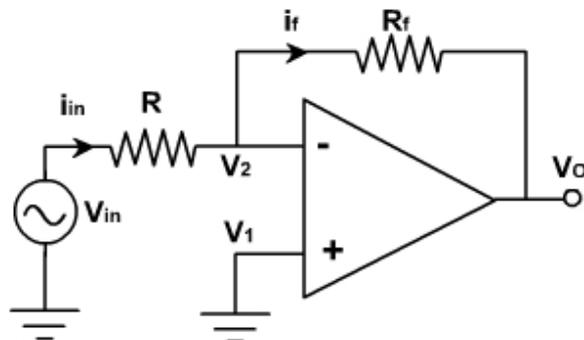


Fig. 1

If  $R_f / R = K$  (a constant) then the circuit is called inverting amplifier or scale changer voltages.

**Inverting summer:**

The configuration is shown in **fig. 2**. With three input voltages  $v_a, v_b$  &  $v_c$ . Depending upon the value of  $R_f$  and the input resistors  $R_a, R_b, R_c$  the circuit can be used as a summing amplifier, scaling amplifier, or averaging amplifier.

Again, for an ideal OPAMP,  $v_1 = v_2$ . The current drawn by OPAMP is zero. Thus, applying KCL at  $v_2$  node

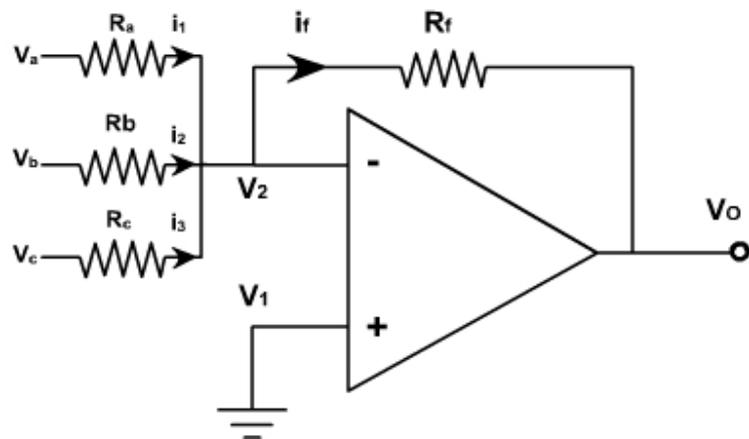
$$i_1 + i_2 + i_3 = i_f$$

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

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

If in the circuit shown,  $R_a = R_b = R_c = R$

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



**Fig. 2**

This means that the output voltage is equal to the negative sum of all the inputs times the gain of the circuit  $R_f / R$ ; hence the circuit is called a summing amplifier. When  $R_f = R$  then the output voltage is equal to the negative sum of all inputs.

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

If each input voltage is amplified by a different factor in other words weighted differently at the output, the circuit is called then scaling amplifier.

$$\frac{R_f}{R_a} \neq \frac{R_f}{R_b} \neq \frac{R_f}{R_c}$$

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

The circuit can be used as an averaging circuit, in which the output voltage is equal to the average of all the input voltages.

In this case,  $R_a = R_b = R_c = R$  and  $R_f / R = 1 / n$  where  $n$  is the number of inputs. Here  $R_f / R = 1 / 3$ .

$$V_o = -(V_a + V_b + V_c) / 3$$

In all these applications input could be either ac or dc.

**Noninverting configuration:**

If the input voltages are connected to noninverting input through resistors, then the circuit can be used as a summing or averaging amplifier through proper selection of  $R_1, R_2, R_3$  and  $R_f$ , as shown in [fig. 3](#).

To find the output voltage expression,  $v_1$  is required. Applying superposition theorem, the voltage  $v_1$  at the noninverting terminal is given by

$$v_1 = \frac{R/2}{R+R/2}v_a + \frac{R/2}{R+R/2}v_b + \frac{R/2}{R+R/2}v_c$$

$$V_1 = \frac{V_a + V_b + V_c}{3}$$

Hence the output voltage is

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 = \left(1 + \frac{R_f}{R_1}\right) \left(\frac{V_a + V_b + V_c}{3}\right)$$

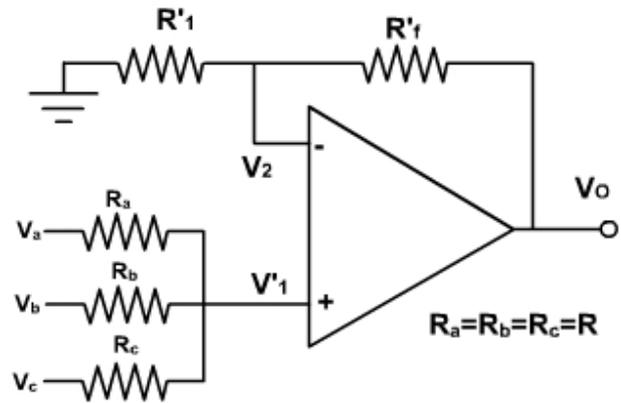


Fig. 3

This shows that the output is equal to the average of all input voltages times the gain of the circuit  $(1 + R_f / R_1)$ , hence the name averaging amplifier.

If  $(1 + R_f / R_1)$  is made equal to 3 then the output voltage becomes sum of all three input voltages.

$$V_o = V_a + V_b + V_c$$

Hence, the circuit is called summing amplifier.

**Differential Amplifier:**

The basic differential amplifier is shown in [fig. 1](#).

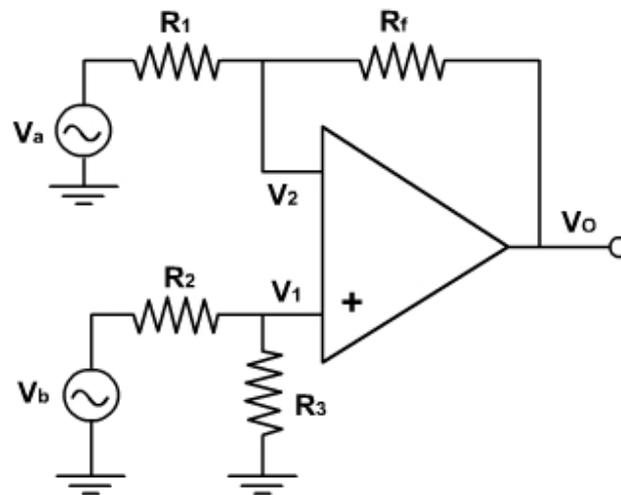


Fig. 1

Since there are two inputs superposition theorem can be used to find the output voltage. When  $V_b = 0$ , then the circuit becomes inverting amplifier, hence the output due to  $V_a$  only is

$$V_{o(a)} = -(R_f / R_1) V_a$$

Similarly when,  $V_a = 0$ , the configuration is a inverting amplifier having a voltage divided network at the noninverting input

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

The output due to  $v_b$  only is

$$\begin{aligned} V_{o(b)} &= \left(1 + \frac{R_f}{R_1}\right) \left(\frac{R_3}{R_2 + R_3}\right) V_b \\ &= \left(\frac{R_1 + R_f}{R_1}\right) \left(\frac{R_3}{R_2 + R_3}\right) V_b \end{aligned}$$

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

$$V_{o(b)} = \frac{R_f}{R_1} V_b$$

Therefore the total output voltage  $v_o$  is given by

$$\begin{aligned} V_o &= V_{o(a)} + V_{o(b)} \\ V_o &= \frac{R_f}{R_1} (-V_a + V_b) \end{aligned}$$

### Integrator:

A circuit in which the output voltage waveform is the integral of the input voltage waveform is called integrator. [Fig. 4](#), shows an integrator circuit using OPAMP.

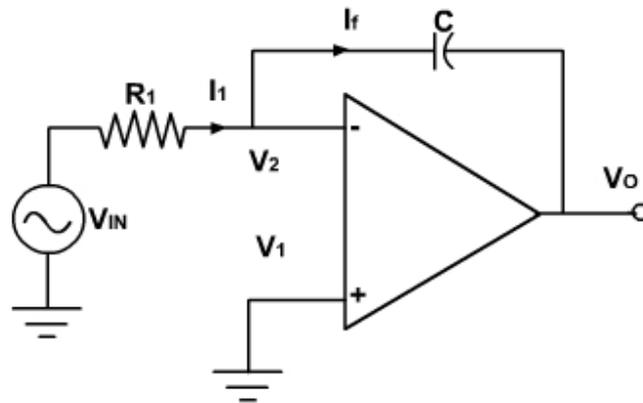


Fig. 4

Here, the feedback element is a capacitor. The current drawn by OPAMP is zero and also the  $V_2$  is virtually grounded.

Therefore,  $i_1 = i_f$  and  $v_2 = v_1 = 0$

$$\frac{v_{in} - 0}{R} = C \frac{d(0 - v_o)}{dt}$$

Integrating both sides with respect to time from 0 to t, we get

$$\int_0^t \frac{v_{in}}{R} dt = \int_0^t C \frac{d(-v_o)}{dt} dt$$

$$= C(-v_o) + v_o \Big|_{t=0}$$

if  $v_o \Big|_{t=0} = 0$  V, then

$$v_o = -\frac{1}{R} \int_0^t v_{in} dt$$

The output voltage is directly proportional to the negative integral of the input voltage and inversely proportional to the time constant RC.

If the input is a sine wave the output will be cosine wave. If the input is a square wave, the output will be a triangular wave. For accurate integration, the time period of the input signal T must be longer than or equal to RC.

[Fig. 5](#), shows the output of integrator for square and sinusoidal inputs.

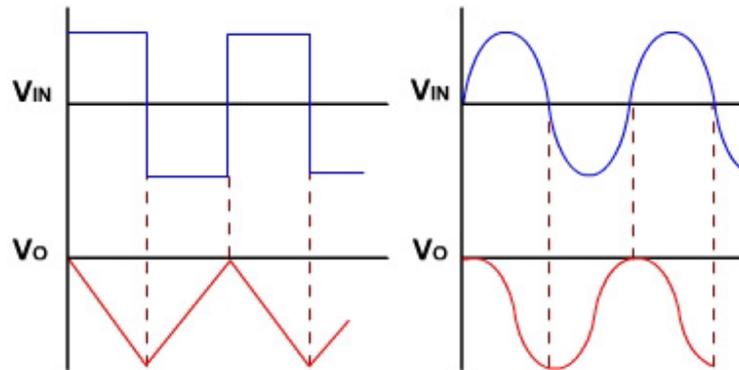


Fig. 5

**Example - 3**

Prove that the network shown in [fig. 6](#) is a non-inverting integrator with  $v_o = \frac{2}{RC} \int v_s(t) dt$ .

**Solution:**

The voltage at point A is  $v_o / 2$  and it is also the voltage at point B because different input voltage is negligible.

$$v_B = v_o / 2$$

Therefore, applying Node current equation at point B,

$$\frac{v_B - v_A}{R} + \frac{v_B - v_o}{R} + C \frac{dv_B}{dt} = 0$$

or

$$\frac{2v_B}{R} - \frac{v_s}{R} - \frac{v_o}{R} + C \frac{dv_B}{dt} = 0$$

or

$$\frac{v_o}{R} - \frac{v_s}{R} - \frac{v_o}{R} + \frac{C}{2} \left( \frac{dv_o}{dt} \right) = 0$$

$$\therefore \frac{dv_o}{dt} = \frac{2v_s}{RC}$$

and

$$v_o = \int \frac{2}{RC} v_s$$

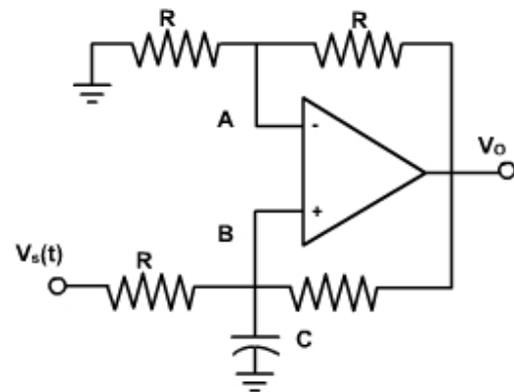


Fig. 6

**Differentiator:**

A circuit in which the output voltage waveform is the differentiation of input voltage is called differentiator. as shown in [fig. 1](#).

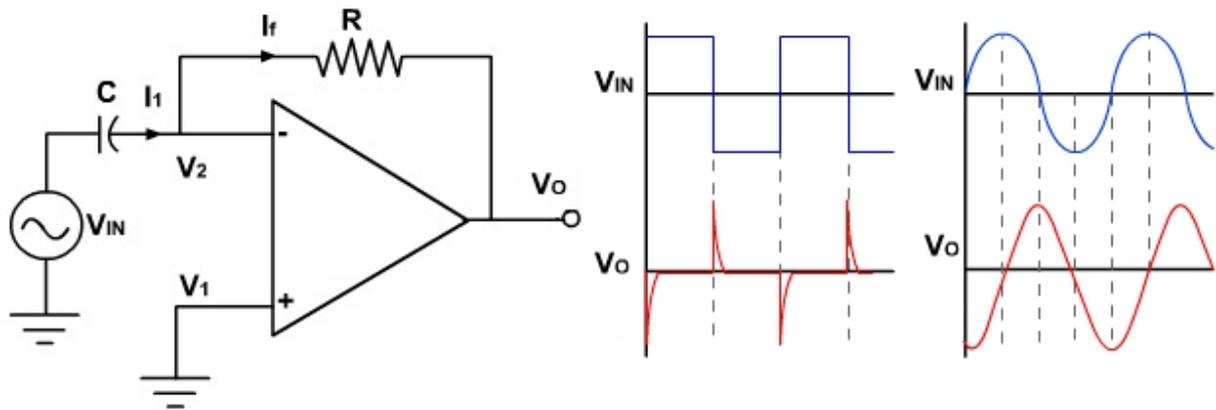


Fig. 1

The expression for the output voltage can be obtained from the Kirchoff's current equation written at node  $v_2$ .

Since,  $i_{in} = i_f$

$$\text{Therefore, } C \frac{d}{dt}(V_{in} - 0) = \frac{0 - V_o}{R}$$

$$V_o = -RC \frac{dV_{in}}{dt}$$

Thus the output  $v_o$  is equal to the RC times the negative instantaneous rate of change of the input voltage  $v_{in}$  with time. A cosine wave input produces sine output. [fig. 1](#) also shows the output waveform for different input voltages.

The input signal will be differentiated properly if the time period T of the input signal is larger than or equal to  $R_f C$ .

$$T \geq R_f C$$

As the frequency changes, the gain changes. Also at higher frequencies the circuit is highly susceptible at high frequency noise and noise gets amplified. Both the high frequency noise and problem can be corrected by adding, few components. as shown in [fig. 2](#).

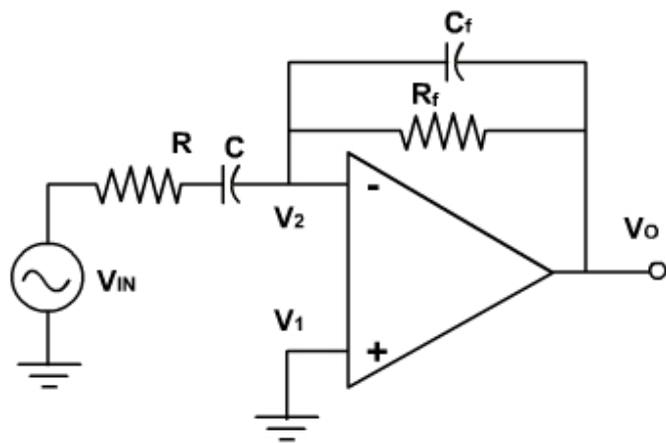


Fig. 2