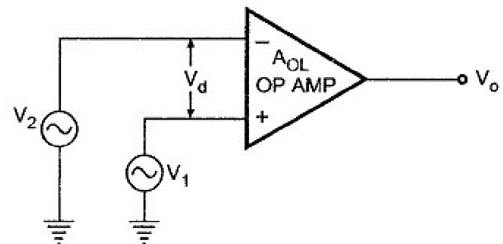
UNIT - II

OP-AMP CIRCUITS AND APPLICATIONS

Open Loop Operation

In the open loop operation there is no feedback provided in the amplifier circuit. Therefore, two signals one at inverting terminal and the other at the non-inverting terminal applied then, the Op-Amp amplifies the difference of the two applied signals. This difference of the two input signals is called as differential input voltage.



The output of Op-Amp is given by

$$V_{out}=A\ \text{open loop}(V_1-V_2)$$

Where,

V_{out} =output voltage

A open loop=Open Loop gain of Op−Amp

V_1=Voltage at the noninverting terminal

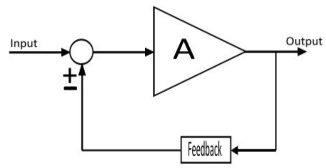
V_2=Voltage at the inverting terminal

(V_1-V_2) =Differential input voltage

The output of the Op-Amp is non-zero only when the differential input voltage is nonzero i.e. V_1 and V_2 are not equal. The open loop gain (A) of Op-Amp is very high. Thus an open loop Op-Amp can amplify a small differential input signal to a high value. The Op-Amp can amplify the input signal to a very high value but cannot exceed the supply voltage of operational amplifier.

Close Loop Operation

When the Op-Amp provided with a feedback signal is known as closed loop operational amplifier. The feedback path feeds the output signal to the input.



The output equation for the closed loop operation is given by

$$V_{out} = A \text{ close loop}(V_1 - V_2)$$

When the feedback is connected to non-inverting terminal then feedback is called as the positive feedback. The positive feedback is used in oscillator applications.

When the feedback is connected to inverting terminal then it is called as negative feedback. The negative feedback is used the amplification applications.

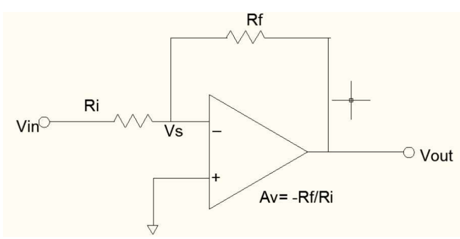
OP-AMP AS INVERTING AMPLIFIER:

DEFINITION:

If a signal (ac or dc) is applied to the inverting input terminal and –ve feedback is given, then the circuit amplifies by inverting the input. Such a circuit is called inverting amplifier.

WORKING:

The given figure shows an inverting amplifier using op-amp.



From the circuit, when a voltage Vi is applied to its input, the current i1 is flowing through Ri (input resistor), and also the current if is flowing through Rf (feedback resistor). Since its input impedance is high, no current enters into an operational amplifier.

i_1 – Current flows through

R_i i_f – Current flows through Rf

V_s – Ground potential

Applying Kirchhoff's current law at the inverting node,

$$i_1 = i_f$$

$$\frac{V_i - V_s}{R_i} = \frac{V_s - V_o}{R_f}$$

Vs = 0, because it is virtual ground.

Hence $\frac{V_i}{R_i} = -\frac{V_0}{R_f}$

$$V_0 = -\frac{R_f}{R_i} \times V_i$$

$$= \frac{R_f}{R_i} \times (-V_i)$$

$$\text{Voltage gain, } A_v = \frac{V_0}{V_i} = -\frac{R_f}{R_i}$$

The input voltage is amplified in accordance with the values (ratio) of Rf and Ri, and also inverted.

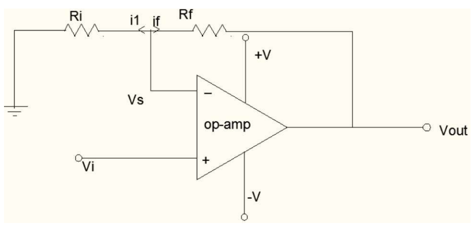
OP-AMP AS NON-INVERTING AMPLIFIER:

DEFINITION:

If a signal (ac or dc) is applied to the non-inverting input terminal and feedback is given, then ***the circuit amplifies without inverting the input***. Such a circuit is called non-inverting amplifier.

WORKING:

The circuit diagram of non-inverting amplifier using op-amp is shown in given figure.



The input voltage V_i is directly applied to the non-inverting terminal. According the characteristics of an op-amp, the applied input voltage V_i is also developed at the inverting input terminal (Vs).

$$V_s = V_i$$

Applying Kirchhoff's current law

$$i_1 = i_f$$

$$\frac{V_s}{R_i} = \frac{V_O - V_s}{R_f}$$

$$\frac{V_i}{R_i} = \frac{V_O - V_i}{R_f}$$

$$\frac{V_O}{R_f} = \frac{V_i}{R_i} + \frac{V_i}{R_f}$$

$$\frac{V_0}{R_f} = V_i\left(\frac{1}{R_i} + \frac{1}{R_f}\right) = \left(\frac{R_i + R_f}{R_f R_i}\right) V_i$$

$$V_0 = R_f \left(\frac{R_i + R_f}{R_f R_i}\right) V_i$$

$$V_0 = \left(\frac{R_i}{R_i} + \frac{R_f}{R_i}\right) V_i$$

$$V_0 = \left(1 + \frac{R_f}{R_i}\right) V_i$$

$$\text{Voltage gain, } A_v = \frac{V_0}{V_i} = 1 + \frac{R_f}{R_i}$$

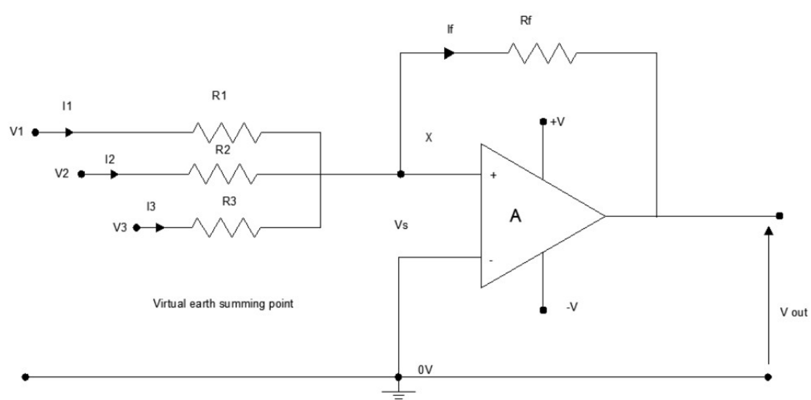
The output voltage is always in phase with the input. The gain of this amplifier also depends upon the external connected components of R_f and R_i.

Difference between Inverting Amplifier and Non-inverting Amplifier:

Inverting Amplifier	Non-inverting Amplifier:
The input is given to the inverting input terminal of the op-amp.	The input is given to the noninverting input terminal of the op-amp.
It gives an inverted output.	It gives an output which is in phase with the input signal.
The gain of the inverting amplifier, when used with a negative feedback, is directly proportional to the ratio of the feedback resistor/ input resistor.	The gain of the non-inverting amplifier is also proportional to the ratio of the feedback resistor/ input resistor but with an intercept value.

SUMMING AMPLIFIER:

A typical three input summing amplifier is shown in given figure. It is also identical with the circuit of an added.



According to the Kirchhoff's current law at the inverting terminal,

$$i_1 + i_2 + i_3 = i_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f} \ (\text{since } V_s = 0)$$

Choose: $R_1 = R_2 = R_3 = R$, the above equation becomes

$$\frac{V_1}{R} + \frac{V_2}{R} + \frac{V_3}{R} = -\frac{V_0}{R_f}$$

Now, commonly take $\frac{1}{R}$ outside.

$$\frac{1}{R}(V_1 + V_2 + V_3) = -\frac{V_0}{R_f}$$

$$V_0 = -\frac{R_f}{R}(V_1 + V_2 + V_3)$$

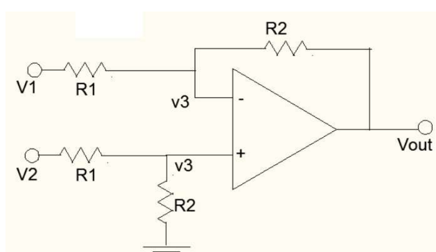
Assume, $A_v = -\frac{R_f}{R}$

$$V_0 = A_v(V_1 + V_2 + V_3),$$

The output signal is the amplification of sum of input signal voltages.

OP-AMP AS DIFFERENTIAL AMPLIFIER:

Differential amplifier will amplify the difference between the two input signals.



The circuit diagram of differential amplifier is shown in above figure. Since the differential voltage at the input terminals of the op-amp is zero, nodes ‘a’ and ‘b’ are at same potential, assumed as V_3.

The nodal equation at ‘a’ is

$$i_1 = i_2$$

$$\frac{V_1 - V_3}{R_1} = \frac{V_3 - V_o}{R_2}$$

$$\frac{V_1}{R_1} - \frac{V_3}{R_1} - \frac{V_3}{R_2} = -\frac{V_0}{R_2}$$

$$\frac{V_1}{R_1} - V_3\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = -\frac{V_0}{R_2} \ldots\ldots\ldots\ldots(1)$$

The nodal equation at ‘b’ is

$$i_3 = i_4$$

$$\frac{V_2 - V_3}{R_1} = \frac{V_3}{R_2}$$

$$\frac{V_2}{R_1} - \frac{V_3}{R_1} - \frac{V_3}{R_2} = 0$$

$$\frac{V_2}{R_1} - V_3\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = 0 \ldots\ldots\ldots\ldots..(2)$$

Subtracting equ (1) from equ (2)

$$\frac{V_2}{R_1} - V_3\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = 0 \ldots\ldots\ldots\ldots..(2)$$

(-)

$$\frac{V_1}{R_1} - V_3\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = -\frac{V_0}{R_2} \ldots\ldots\ldots\ldots.(1)$$

(-) (+) (+)

$$\frac{V_2}{R_1} - \frac{V_1}{R_1} = 0 + \frac{V_0}{R_2}$$

$$\frac{V_2}{R_1} - \frac{V_1}{R_1} = \frac{V_0}{R_2}$$

$$\frac{V_2 - V_1}{R_1} = \frac{V_o}{R_2}$$

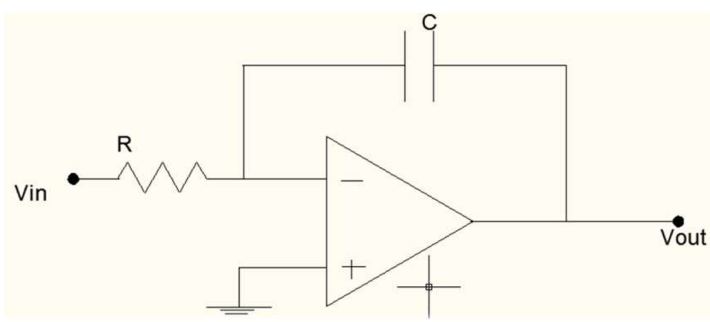
$$V_0 = \frac{R_2}{R_1}(V_2 - V_1)$$

$$V_0 = A_v(V_2 - V_1)\left(\therefore A_v = \frac{R_2}{R_1}\right)$$

If can be considered as instrumentation amplifier. But it is not used as an instrumentation amplifier because imbalance may be produced by circuit components.

INTEGRATOR:

An integrator circuit integrates the input signal with respect to time (frequency).



The circuit diagram of integrator is shown in the above figure. The feedback element is capacitor and the input element is resistor.

The charge on a capacitor C, when a supply voltage of V applied is Q = CV. In general, the current through the capacitor,

$$I_c = \frac{dQ}{dt} = \frac{dCV}{dt} = \frac{CdV}{dt}, \text{since C is constant}$$

By using Kirchhoff's current law in the circuit. $i_1 = i_f$

The current flows through the resistor R i_1 $\longrightarrow$

The current flows through the capacitor C $\longrightarrow i_f$

$$\frac{V_i - V_s}{R} = C\ \frac{dV}{dt}$$

$$\frac{V_i - V_s}{R} = C\ \frac{d(V_s - V_0)}{dt}$$

Since V_s=0 (it is virtual ground)

$$\frac{V_i}{R} = -C\ \frac{dV_0}{dt}$$

$$\frac{\mathrm{dV_0}}{\mathrm{dt}} = -\frac{\mathrm{V_i}}{\mathrm{RC}}$$

Integrating on both sides with respect to time

$$\mathrm{V_0} = -\frac{1}{\mathrm{RC}}\int \mathrm{V_i} + \mathrm{Vk}(0)$$

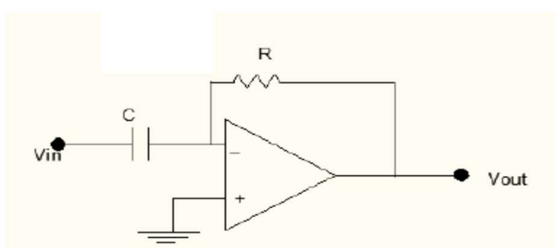
Where $V_k(0)$ is the initial voltage produced at the output.

- For a square wave input, it produces triangular output waveform.
- For a sine wave input, it produces cosine output waveform.

The integrator is most commonly used in analog computers and A/D converters.

DIFFERENTATOR:

It produces the output signal, which is the derivative of input signal V_i.



If the resistor and capacitor of an integrator are interchanged, it will act as differentiator. The circuit diagram of differentiator is shown in above figure.

The charge on a capacitor C, when a supply voltage of V applied is Q=CV.

The current flow through the capacitor $\rightarrow I_c$

The feedback current $\rightarrow I_f$

By using Kirchhoff's current law

$$\mathrm{i_c} = \mathrm{i_f}$$

$$\frac{C\ d(V_i - V_s)}{dt} = \frac{V_s - V_0}{dt}$$

Vs = 0, because it is a virtual ground;

$$\frac{CdV_i}{dt} = -\frac{V_0}{R}$$

$$\frac{V_0}{R} = -\frac{CdV_i}{dt}$$

$$V_0 = -RC\frac{dV_i}{dt}$$

The output signal is the differentiation of input signal with respect to time.

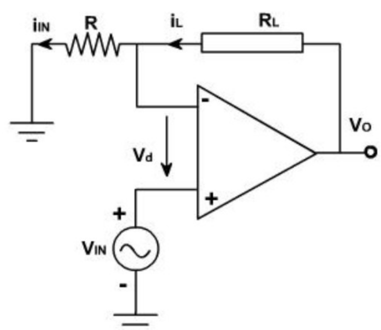
- For a square wave input, it produces spike output.
- For a cosine wave input, it produces sine wave output.
- For a triangular wave input, it produces square wave output.

VOLTAGE TO CURRENT CONVERTER (Transconductance amplifier)

In voltage to current converter, ***the output current is proportional to input voltage.*** The voltage to current converter is also called as Transconductance amplifier**.** There are two types of circuits are possible in voltage to current converter. They are

i) V to I converter with floating load

ii) V to I converter with grounded load



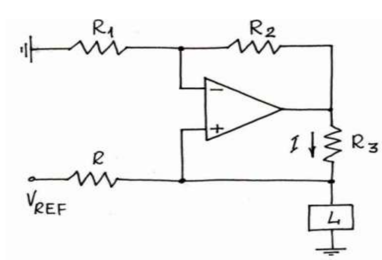
The circuit diagram of voltage to current converter with floating load is shown in above figure. The voltage at node 'a' is equal to V_i.

Therefore, $V_i = i_L.R_i$

$$\therefore i_L = \frac{V_i}{R_i} = KV_i \left(\therefore \frac{1}{R_i} = K \right)$$

$$i_L \propto V_i$$

Hence, the output (load) current is directly proportional to the input voltage.



A voltage to current converter with grounded load is shown in above figure.

Writing KCL, we get, $i_1 + i_2 = i_L$

$$\frac{V_i - V_1}{R} + \frac{V_0 - V_1}{R} = i_L$$

$$\frac{V_i - V_1 + V_0 - V_1}{R} = i_L$$

$$\frac{V_i - 2V_1 + V_0}{R} = i_L$$

$$V_i + V_0 - 2V_1 = i_L R$$

$$2V_1 = V_i + V_0 - i_L R$$

$$V_1 = \frac{V_i + V_0 - i_L R}{2}$$

Since the op-amp is used in non-inverting mode, the gain of the amplifier

$$A_v = \frac{V_0}{V_i} = 1 + \frac{R_f}{R_i}$$

Assume, $R_f = R_i = R$

$$\frac{V_0}{V_i} = 1 + \frac{R}{R}$$

$$\frac{V_0}{V_i} = 1 + 1 = 2$$

$$V_0 = 2\,V_i$$

Assume $V_i = V_1$

The output voltage is $V_0 = 2V_1$

Now substitute the value of V_1

$$V_0 = 2\left(\frac{V_i + V_0 - i_L R}{2}\right)$$

$$V_0 = V_i + V_0 - i_L R$$

$$V_0 - V_0 = V_i - i_L R$$

$$0 = V_i - i_L R$$

$$V_i = i_L R$$

$$\text{so, } i_L = \frac{V_i}{R}$$

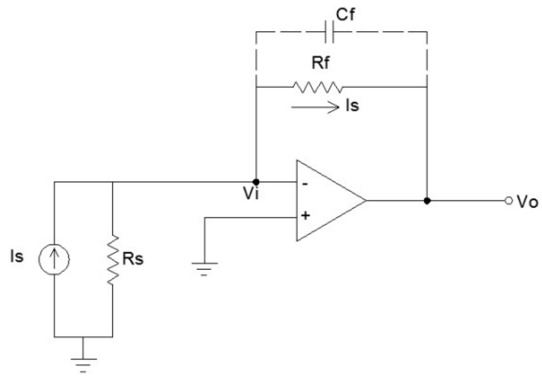
$$i_L = KV_i \left(\therefore K = \frac{1}{R}\right)$$

$$i_L \propto V_i$$

Hence the output load current is directly proportional to the input voltage.

CURRENT TO VOLTAGE CONVERTER: (Transimpedance amplifier)

It produces **output voltage is proportional to the input current** The circuit diagram of current to voltage converter is shown in given figure. Since the (-) negative input terminal is at virtual ground, no current flows through Rs and current are flows through the feedback resistor R_f.



In this circuit $I_s = \frac{V_i - V_0}{R_f}$

$$V_i = 0$$

$$I_s = \frac{-V_0}{R_f}$$

$$V_0 = -I_s R_f$$

$$(\therefore K = -R_f)$$

$$V_0 = -I_s K$$

$$V_0 \alpha I_S$$

It is also called Transresistance amplifier. The capacitor (Cf) is used to reduce high frequency noise and the possibility of oscillations.