Chapter 03

Operational Amplifier

The contents of the chapter are as follows:-

1. Ideal and practical op-amp characteristics
2. Saturable property of an op-amp, Virtual short
3. Op-amp applications: Comparator
4. Inverting amplifier
5. Non inverting amplifier
6. Voltage follower, Integrator, Differentiator
7. Adder, Subtractor

1. Introduction

In this chapter we will introduce a general purpose integrated circuit (IC), the Operational Amplifier (Op-Amp), which is a most versatile and widely used linear integrated circuit. The Op-Amp is a direct-coupled high-gain amplifier to which feedback is added to control its overall response characteristics.

The standard Op-Amp symbol is shown in left-hand figure below fig 1.1 It has two input terminals, the inverting (-) input and the non-inverting (+) input. The typical Op-Amp operates with two dc supply voltages, one positive and the other negative, as shown in the right-hand figure below. Usually these dc voltage terminals are left off the schematic symbol for simplicity but are always understood to be there. The pin diagram of IC741 is shown in fig 1.2

Schematic Symbol

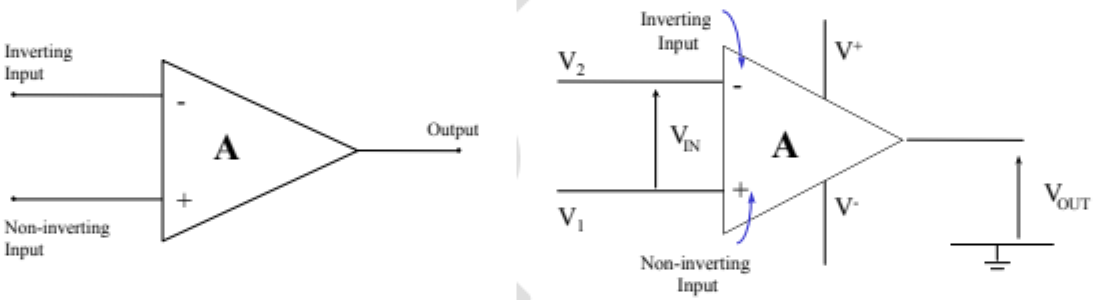

Fig 1.1 Schematic Symbol of an OP-Amp

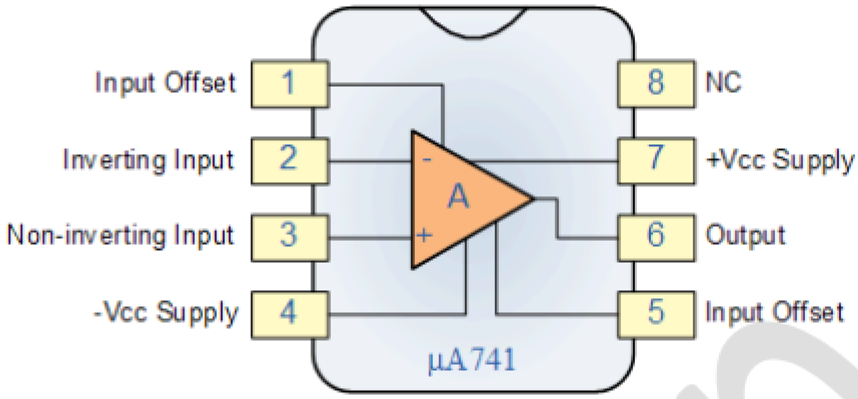

Fig 1.2 Pin diagram of IC741

2. Properties of an ideal Op-Amp:

1. Infinite Input Impedance: The ideal Op-amp does not draw any current from the voltage sources connected to its input terminals. This implies that the input impedance of an Op-amp is infinity.

2. Zero Output Impedance: The voltage at the output terminal is independent of the current drawn from it i.e. output impedance is zero. Hence the Op-amp can drive an infinite number of devices.

3. Infinite Bandwidth: This implies that the amplifier can amplify any frequency from zero to infinity without attenuation. In other words, the ideal Op-amp will amplify signals of any frequency with equal gain.

4. Infinite Voltage Gain: The open-loop voltage gain of an ideal Op-amp is very large, i.e., infinity.

5. Perfect Balance: The output voltage is zero when equal voltages are present at the two input terminals.

6. Infinite CMRR: This means that the output common-mode noise voltage is zero.

7. Infinite Slew Rate: Slew rate indicates the rapidity with which the output of an Op-amp changes in response to the changes in input frequency. (how fast the output of op-amp is going to respond for any change in input)

8. Temperature: The characteristics do not change with temperature.

3. Characteristics of a Practical Op-Amp

In practice the IC Op-Amp falls short of the ideal characteristics, however the following applies

- Very HIGH input resistance
- Very LOW output resistance
- Very large Open Loop Voltage Gain

For example, a popular 741 Op-Amp has the following characteristics:

- Open-Loop voltage gain ≈ 200,000
- Input impedance ≈ 2 MΩ
- Output impedance ≈ 75 Ω
- Bandwidth for unit gain ≈ 1 MHz
- CMRR ≈ 90dB
- Slew rate ≈ 0.5V/µs

4. Saturable Property of an Op-Amp:

'A' is a constant for a particular Operational Amplifier and is known as the open-loop gain since there is no feedback loop connecting the output terminal to the input terminal, which is the basic circuit of an op-amp.

This op-amp senses the difference between the input signals and amplifies the difference between the input signals. The output Vo is given by;

Vo = A*(V2 - V1) ---(i)
Hence, if V1= 0, Vo = A*V2 ---------- (ii)
And if V2= 0, Vo = - A*V1 --------(iii)

The open-loop voltage gain of an ideal op-amp is infinity; then, substituting A = ∞ in eq's (ii) & (iii) above, the output Vo of the op- amp should range from +∞ to -∞ However, in practice, Vo is limited by the magnitudes of the power supply voltages.
As the supply voltages are ± 15V, the opamp has the property to saturate the output at ±15 V. Output cannot be produced exceeding the saturation voltage levels. If the gain is 10^5 , then $V_d = V_0/A = \pm 150\mu V$. Thus only for the differential input of few µV the output saturates to ±Vsat depending on which input V1 or V2 is dominating.

When Vin > Vref the voltage at the non-inverting (+) terminal is greater than the voltage at the inverting (-) terminal and hence Vo = + Vsat it being approximately equal to +Vcc Therefore, when Vin crosses Vref the output voltage V0 changes instantaneously from one saturation level i.e. from +Vcc to -VEE or from -VEE to +Vcc.

A time-varying signal Vin is applied to the non-inverting terminal through a resistor R, and the reference voltage Vref of 1 V is applied to the inverting terminal through resistor R1. When Vin < Vref the voltage at the inverting (-) terminal is greater than the voltage at the non inverting (+) terminal and hence Vo = -Vsat it being approximately equal to -VEE. shown in the figure. 4.1

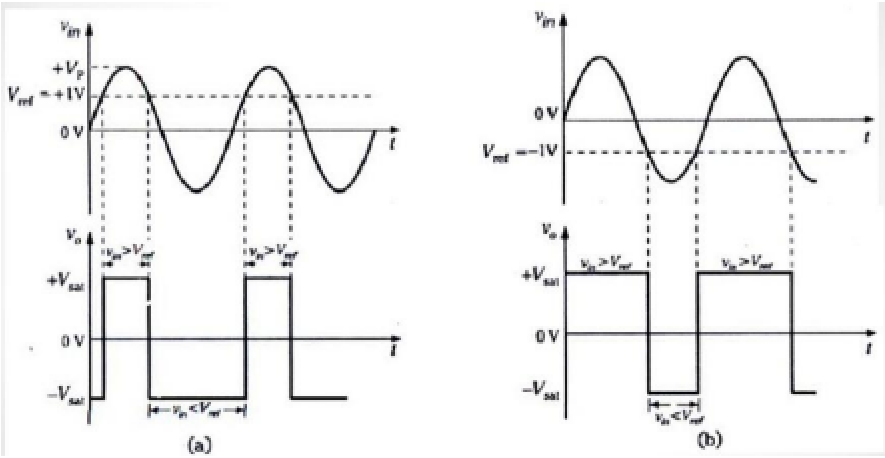

Fig 4.1 Saturable property of an Op-amp.

5. Op-Amp as Comparator:

A comparator circuit shown in fig 5.1 compares a signal voltage with a reference voltage. An Op-Amp comparator is an open loop Op-Amp. The reference voltage is applied to one of its input terminals, and the signal to be compared is applied to the other input terminal. Depending upon which of the two voltages is greater, the output voltage is held at the positive or negative saturation voltage.

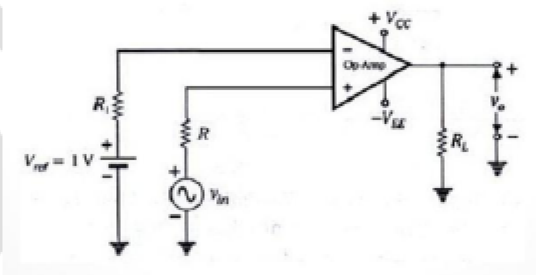

Fig 5.1 Op-amp as Comparator

6. Concept of Virtual Ground

An Op-Amp has a very high gain typically order of 10^5. If power supply voltage Vcc =15V Then maximum input voltage which can be applied V d = Vcc /A d = 15/ 10 5 = 150 µ V i.e. Op -Amp can work as a linear -VCC +VCC +Vout +Vin +Vi -Vi Slope: A d 5 i.e. Op -Amp can work as a linear amplifier from +Vi to –Vi as shown in fig 6.1 , if input voltage is less than 150 µV. Above that Op-Amp saturates. if V1 is grounded then V 2 cannot be more than 150 µV which is very very small and close to ground. Therefore V2 can also be considered at ground if V1 is at ground. Physically V 2 is not connected to the ground yet we considered V2 at ground that is called virtual ground.

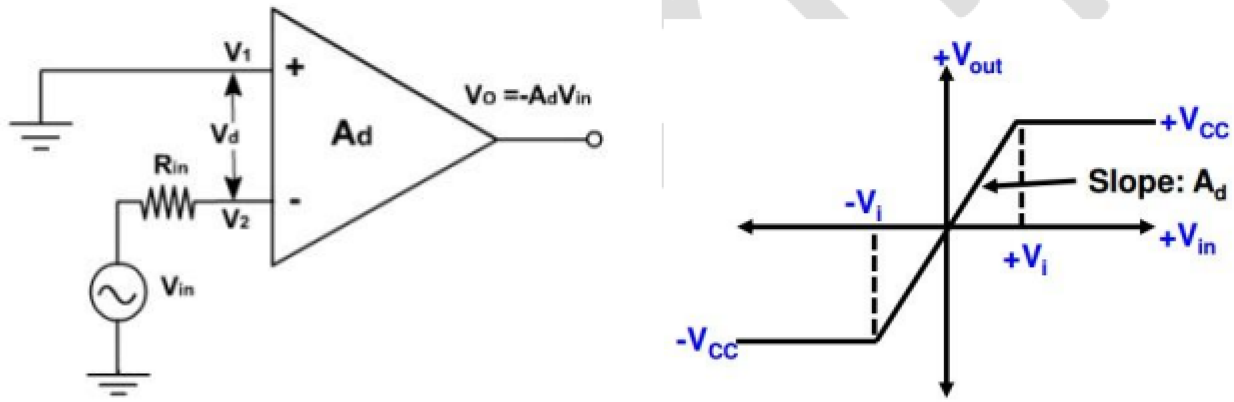

Fig 6.1 Virtual Ground

7. Need for Negative Feedback

As the Open-Loop Voltage Gain of the Op-Amp is very large, an extremely small difference in the two input voltages drives the Op-Amp into its saturated output states, i.e. it will cause the output voltage to go all the way to its extreme positive or negative voltage limit. As this is seldom desirable the full gain of the Op-Amp is not usually applied to an input, instead negative feedback (using external resistors) is applied to reduce the overall gain through signal feedback.

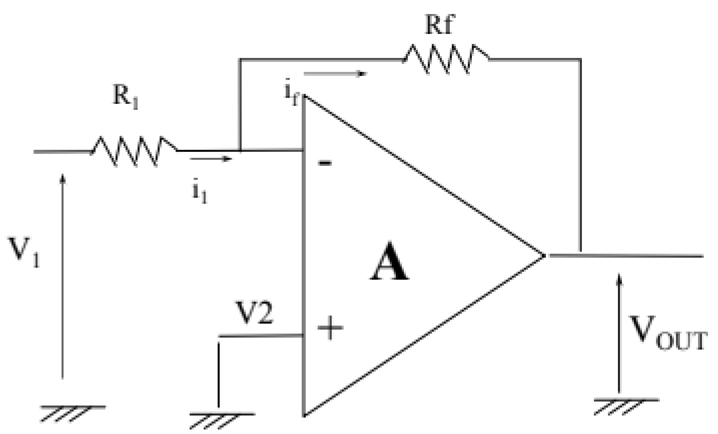

Fig 7.1 Op-amp With Negative Feedback

Where:
V_{IN} is the input signal
V_f is a portion of the output signal fed back to the inverting input
A_{cl} the closed loop gain is the voltage gain with negative feedback

The Op-Amp responds to the voltage V_{IN} at its non-inverting input, which moves the output towards saturation. However, a fraction of this output is returned to the inverting terminal through the feedback path. As the feedback signal approaches the value of V_{IN} $\Rightarrow$ there is nothing left for the Op-Amp to amplify as

$$V_f - V_{IN} \rightarrow 0$$

Thus the feedback signal tries (but never quite succeeds) in matching the input signal and thus the gain is controlled by the amount of feedback used.

8. Op-Amp Applications

8.1 The Basic Inverting Amplifier:

A signal V_{IN} is applied through a series resistor R_1 to the inverting input as shown below. The output is fed back through R_2 to the inverting input. The non-inverting input is grounded.

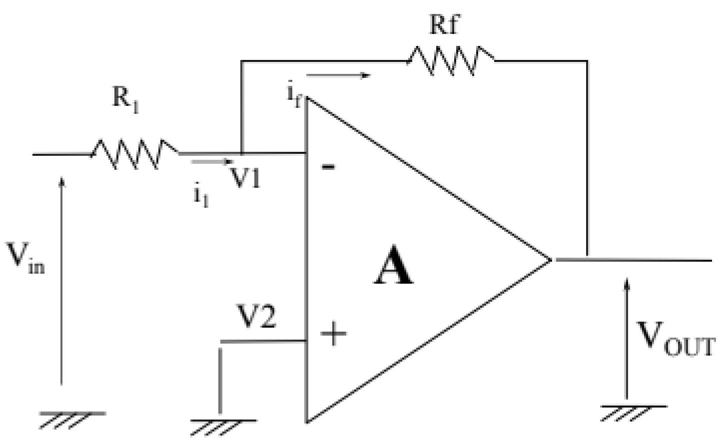

Fig 8.1 Inverting Amplifier

The Closed Loop Gain (A_{Cl}) is defined as the gain with feedback applied

Basic Inverting Amplifier

- **Closed Loop Gain (A_{Cl}) is:** $A_{Cl} = -\dfrac{R_f}{R_1}$
- **Input Resistance is ideally** $R_{IN} = R_1$

Derive the Closed Loop Gain the Basic Inverting Amplifier:

$$i_1 = \frac{V_{IN} - V1}{R_1} \quad \text{and:} \quad i_f = \frac{V1 - V_{OUT}}{R_f}$$

$i_1 = i_f$

$$\therefore \qquad \frac{V_{IN} - V1}{R_1} = \frac{V1 - V_{OUT}}{R_f}$$

$\therefore$

By Virtual Short V1 = V2,   from circuit diagram V2 = 0

$$\therefore \qquad \frac{V_{IN}}{R_1} = -\frac{V_{OUT}}{R_f}$$

$$\therefore \qquad V_{IN}R_f = -V_{OUT}R_1$$

$$\therefore \qquad \frac{R_f}{R_1} = -\frac{V_{OUT}}{V_{IN}}$$

$$\boxed{A_{Cl} = \frac{V_{OUT}}{V_{IN}} = -\frac{R_f}{R_1}}$$

Where A_{Cl} is the Closed Loop Gain and is defined as the gain with feedback applied

Note that A, the gain of the op-amp without feedback, is called the Open Loop Gain

We see that, as expected, the gain is negative and that ***the gain depends only on the ratio of the resistor values and not on the amplifier itself***.

$V = V^- - V^+$ and as shown above if A -> ∞ then V -> 0

$\therefore \quad V^- = V^+$

In the configuration above, we have V^+ grounded so therefore

$V^- = 0$

We cannot actually ground the inverting terminal but since its potential is $V^- = 0$, we say that a "**virtual ground**" exists at the inverting input terminal.

Since V^- is at virtual ground the ***input impedance seen by the signal source generating V_{IN} is (ideally) R_1 ohms***.

8.2 The Basic Non-Inverting Amplifier:

The input signal is applied to the non-inverting (+) input. A portion of the output signal is applied back to the inverting (-) input through the feedback network. This constitutes negative feedback.

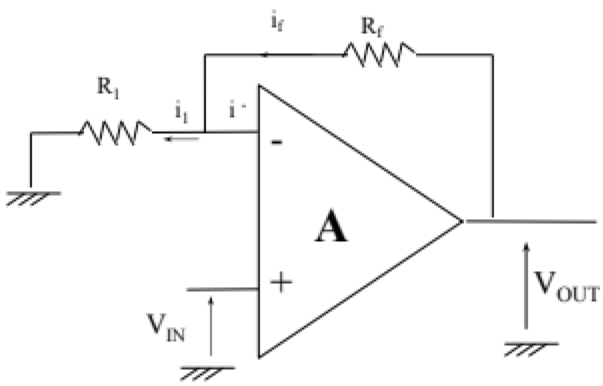

Fig 8.2 Non-Inverting Amplifier

Basic Non-inverting Amplifier

• **Closed Loop Gain (A_{Cl}) is:**	$A_{Cl} = 1 + \frac{R_f}{R_1}$
• **Input Resistance is ideally**	$R_{IN} = \infty$

Derive the Closed Loop Gain of the Basic Non-inverting Amplifier:

$$i_1 = \frac{V_{IN}}{R_1} \quad \text{and} \quad i_f = \frac{V_{OUT} - V_{IN}}{R_f}$$

$$\Rightarrow \quad \frac{V_{IN}}{R_1} = \frac{V_{OUT} - V_{IN}}{R_f}$$

$$\Rightarrow \quad V_{IN}R_f = V_{OUT}R_1 - V_{IN}R_1$$

$$\Rightarrow \quad V_{IN}(R_f + R_1) = V_{OUT}R_1$$

$$\Rightarrow \quad \frac{V_{OUT}}{V_{IN}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_f}{R_1}$$

The Closed Loop Gain (A_{Cl}) is:

$$\boxed{A_{Cl} = 1 + \frac{R_f}{R_1}}$$

8.3 The Voltage Follower: (Unity Gain Buffer Amplifier)

The Voltage Follower is a special case of the non-inverting Amplifier, where all of the output voltage is fed back to the inverting terminal by a straight connection as shown below.

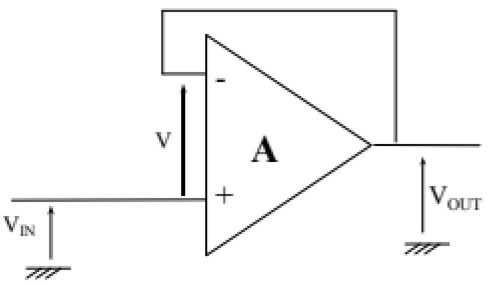

Fig 8.3 Voltage Follower

Voltage Follower Amplifier

• **Closed Loop Gain (A_{Cl}) is:**	$A_{Cl} = 1$
• **Input Resistance is ideally**	$R_{IN} = \infty$

$V_{OUT} = V$

By virtual short Vin = V

$\therefore\ V_{OUT} = V_{IN}$

It Unity Gain Buffer Amplifier is called a Voltage Follower since $V_{IN} = V_{OUT}$. The most important features of the voltage-follower configuration are its very high input impedance and its very low output impedance. Therefore, ***it may be used to allow a signal from a high impedance source to be coupled to a low impedance load.***

8.4 The Summing Amplifier or Op-amp as a Adder

The **Summing Amplifier** is another type of operational amplifier circuit configuration that is used to combine the voltages present on two or more inputs into a single output voltage. We saw previously in the inverting operational amplifier that the inverting amplifier has a single input voltage, (Vin) applied to the inverting input terminal. If we add more input resistors to the input, each equal in value to the original input resistor, Rin we end up with another operational amplifier circuit called a **Summing Amplifier**, "*summing inverter*" or even a "*voltage adder*" circuit as shown below.

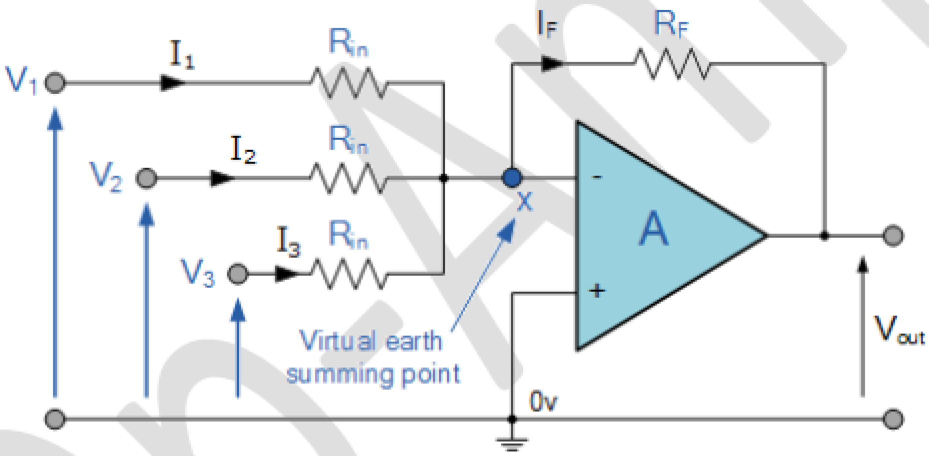

Fig 8.4 Summing Amplifier

$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin}\right]$$

$$\text{Inverting Equation: } Vout = -\frac{Rf}{Rin} \times Vin$$

$$\text{then, } -Vout = \left[\frac{R_F}{Rin}V1 + \frac{R_F}{Rin}V2 + \frac{R_F}{Rin}V3\right]$$

8.5 The Integrator Amplifier

The previous application showed that how an operational amplifier can be used as part of a positive or negative feedback amplifier or as an adder or Subtractor type circuit using just pure resistances in both the input and the feedback loop

By replacing this feedback resistance with a capacitor we now have an RC Network connected across the operational amplifiers feedback path producing another type of operational amplifier circuit commonly called an **Op-amp Integrator** circuit as shown below.

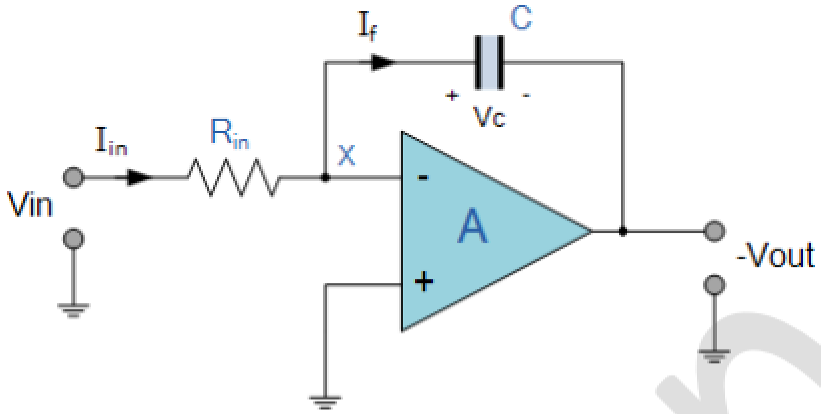

Fig 8.5 Op-amp as a integrator

As its name implies, the **Op-amp Integrator** is an operational amplifier circuit that performs the mathematical operation of Integration that is we can cause the output to respond to changes in the input voltage over time as the op-amp integrator produces an *output voltage which is proportional to the integral of the input voltage*.

If the capacitor is charging and discharging, the rate of charge of voltage across the capacitor is given as:

$$V_c = \frac{Q}{C}, \quad V_c = V_x - V_{out} = 0 - V_{out}$$

$$\therefore -\frac{dV_{out}}{dt} = \frac{dQ}{Cdt} = \frac{1}{C}\frac{dQ}{dt}$$

But dQ/dt is electric current and since the node voltage of the integrating op-amp at its inverting input terminal is zero, X = 0, the input current I(in) flowing through the input resistor, Rin is given as:

$$I_{in} = \frac{V_{in} - 0}{R_{in}} = \frac{V_{in}}{R_{in}}$$

The current flowing through the feedback capacitor C is given as:

$$I_f = C\frac{dV_{out}}{dt} = C\frac{dQ}{Cdt} = \frac{dQ}{dt} = \frac{dV_{out}.C}{dt}$$

Assuming that the input impedance of the op-amp is infinite (ideal op-amp), no current flows into the op-amp terminal. Therefore, the nodal equation at the inverting input terminal is given as:

$$I_{in} = I_f = \frac{V_{in}}{R_{in}} = \frac{dV_{out}.C}{dt}$$

$$\therefore \frac{V_{in}}{V_{out}} \times \frac{dt}{R_{in}C} = 1$$

From which we derive an ideal voltage output for the **Op-amp Integrator** as:

$$V_{out} = -\frac{1}{R_{in}C}\int_0^t V_{in}\,dt = -\int_0^t V_{in}\frac{dt}{R_{in}.C}$$

8.6 The Differentiator Amplifier

The basic **Op-amp Differentiator** circuit is the exact opposite to that of the Integrator Amplifier circuit.

This operational amplifier circuit performs the mathematical operation of **Differentiation** that is it "*produces a voltage output which is directly proportional to the input voltage's rate-of-change with respect to time*".

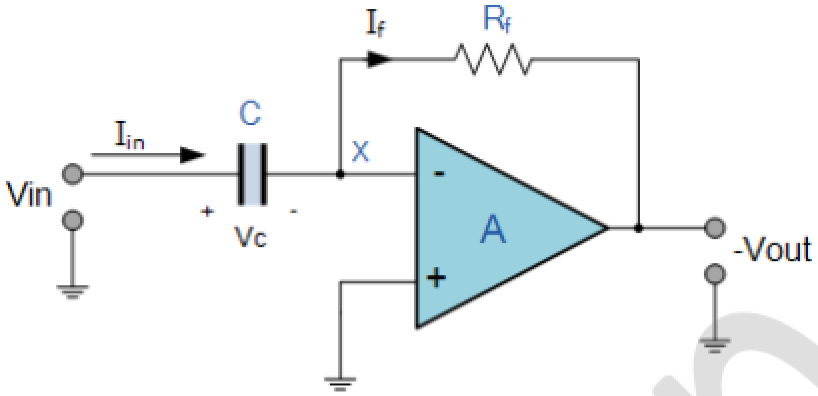

Fig 8.6 Differentiator Amplifier

The input signal to the differentiator is applied to the capacitor. The capacitor blocks any DC content so there is no current flow to the amplifier summing point, X resulting in zero output voltage. The capacitor only allows AC type input voltage changes to pass through and whose frequency is dependent on the rate of change of the input signal.

Since the node voltage of the operational amplifier at its inverting input terminal is zero, the current, i flowing through the capacitor will be given as:

$$I_{IN} = I_F \text{ and } I_F = -\frac{V_{OUT}}{R_F}$$

The charge on the capacitor equals Capacitance x Voltage across the capacitor

$$Q = C \times V_{IN}$$

The rate of change of this charge is

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

but dQ/dt is the capacitor current i

$$I_{IN} = C\frac{dV_{IN}}{dt} = I_F$$

$$\therefore\ -\frac{V_{OUT}}{R_F} = C\frac{dV_{IN}}{dt}$$

from which we have an ideal voltage output for the op-amp differentiator is given as:

$$V_{OUT} = -R_F C\frac{dV_{IN}}{dt}$$