25.37 OP-Amp Differentiator

A differentiator is a circuit that performs differentiation of the input signal. In other words, a differentiator produces an output voltage that is proportional to the rate of change of the input voltage. Its important application is to produce a rectangular output from a ramp input. Fig. 25.88 shows the circuit of OP-amp differentiator. It consists of an OP-amp, an input capacitor *C* and feedback resistor *R*. Note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.

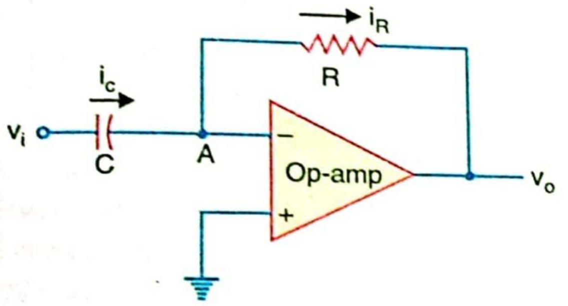


Fig. 25.88

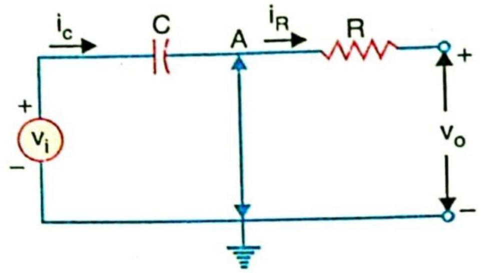


Fig. 25.89

Circuit analysis. Since point *A* in Fig. 25.88 is at virtual ground, the virtual-ground equivalent circuit of the operational differentiator will be as shown in Fig. 25.89. Because of virtual ground and infinite impedance of OP-amp, all the input current i_c flows through the feedback resistor *R* *i.e.* $i_c = i_R$.

$$\therefore \quad i_R = \frac{0 - v_o}{R} = -\frac{v_o}{R} \quad \text{and} \quad v_c = v_i - 0 = v_i$$

Also

$$i_c = C\frac{dv_c}{dt} = C\frac{dv_i}{dt}$$

$$\therefore \quad -\frac{v_o}{R} = C\frac{dv_i}{dt} \qquad (\because\ i_R = i_c)$$

or

$$v_o = -RC\frac{dv_i}{dt} \qquad \text{...(}i\text{)}$$

Eq. (*i*) shows that output is the differentiation of the input with an inversion and scale multiplier of *RC*. If we examine eq. (*i*), we see that if the input voltage is constant, dv_i/dt is zero and the output voltage is zero. The faster the input voltage changes, the larger the magnitude of the output voltage.

25.38. Comparators

Often we want to compare one voltage to another to see which is larger. In this situation, a *comparator* may be used. *A comparator is an OP-amp circuit without negative feedback* and takes advantage of very high open-loop voltage gain of OP-amp. A comparator has two input voltages (noninverting and inverting) and one output voltage. Because of the high open-loop voltage gain of an *OP*-amp, a very small difference voltage between the two inputs drives the amplifier to saturation. For example, consider an *OP*-amp having $A_{OL} = 100{,}000$. A voltage difference of only 0.25 mV between the inputs will produce an output voltage of (0.25 mV) (100,000) = 25V. However, most of OP-amps have output voltages of less than ± 15V because of their d.c. supply voltages. Therefore, a very small differential input voltage will drive the OP-amp to saturation. This is the key point in the working of comparator.

Fig. 25.93 illustrates the action of a comparator. The input voltages are v_1 (signal) and v_2 (*reference voltage). If the differential input is positive, the circuit is driven to saturation and output goes to maximum positive value (**$+V_{sat} = +13\text{V}$). Reverse happens when the differential input goes negative *i.e.* now output is maximum negative ($-V_{sat} = -13\text{V}$). This circuit is called comparator because it compares v_1 to v_2 to produce a saturated positive or negative output voltage. Note that output voltage rapidly changes from – 13V to + 13V and *vice-versa*.

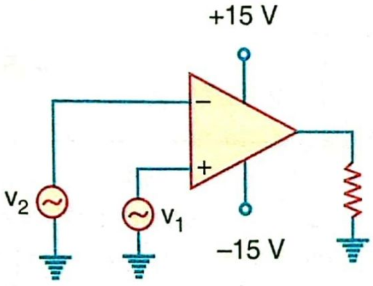


Fig. 25.93

25.26 Noninverting Amplifier

There are times when we wish to have an output signal of the same polarity as the input signal. In this case, the *OP*-amp is connected as noninverting amplifier as shown in Fig. 25.55. The input signal is applied to the noninverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistance R_i. Note that resistors R_f and R_i form a voltage divide at the inverting input (–). This produces **negative feedback* in the circuit. Note that R_i is grounded. Since the input signal is applied to the noninverting input (+), the output signal will be noninverted i.e., the output signal will be in phase with the input signal. Hence, the name non-inverting amplifier.

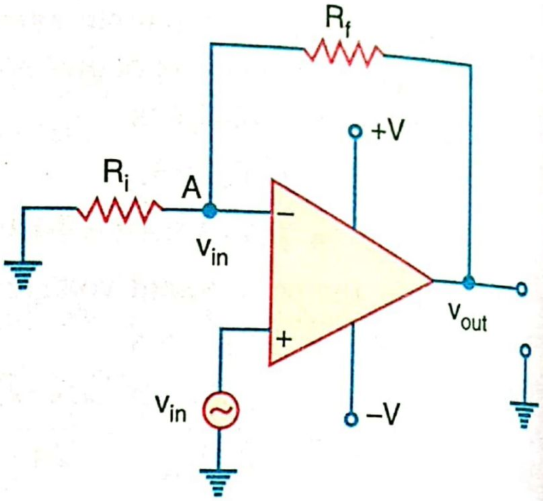


Fig. 25.55

Voltage gain. If we assume that we are not at saturation, the potential at point *A* is the same as V_{in}. Since the input impedance of *OP*-amp is very high, all of the current that flows through R_f also flows through R_i. Keeping these things in mind, we have,

$$\text{Voltage across } R_i = V_{in} - 0 \text{ ; Voltage across } R_f = V_{out} - V_{in}$$

Now $$\text{Current through } R_i = \text{Current through } R_f$$

or $$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

or $$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

or $$V_{in} (R_f + R_i) = V_{out} R_i$$

or $$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

$$\therefore \text{ Closed-loop voltage gain, } A_{CL} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_i}$$

25.24 Inverting Amplifier

An *OP* amplifier can be operated as an inverting amplifier as shown in Fig. 25.46. An input signal v_{in} is applied through input resistor R_i to the minus input (inverting input). The output is fed back to the same minus input through feedback resistor R_f. The plus input (noninverting input) is grounded. Note that the resistor R_f provides the **negative feedback*. Since the input signal is applied to the inverting input (–), the output will be inverted (*i.e.* 180° out of phase) as compared to the input. Hence the name inverting amplifier.

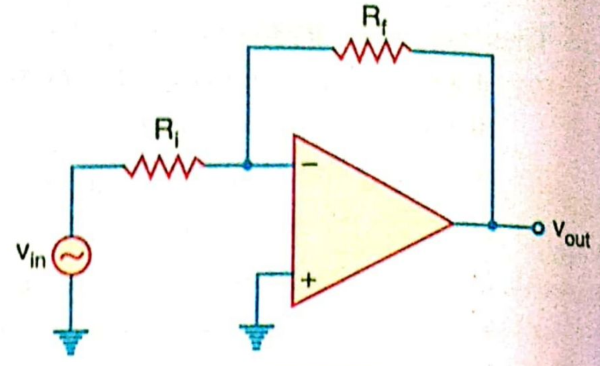
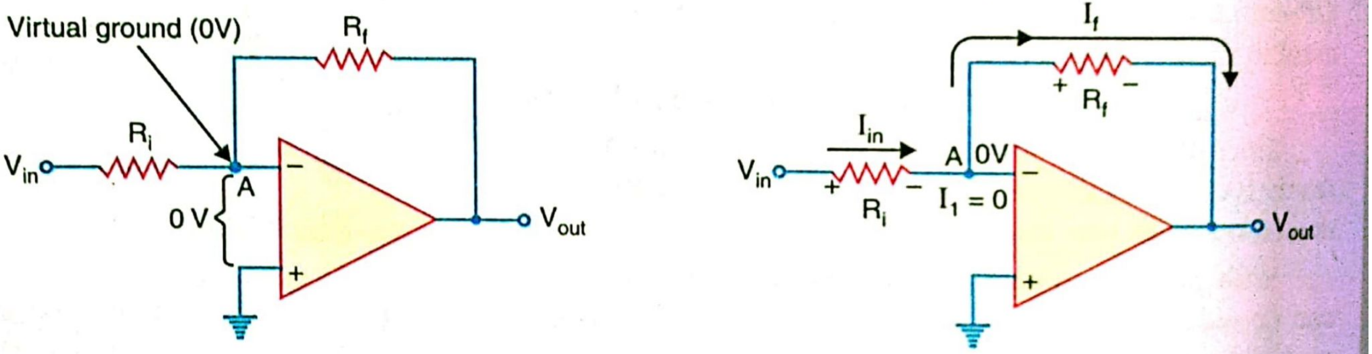


Fig. 25.46

Voltage gain. An OP-amp has an infinite input impedance. This means that there is zero current at the inverting input. If there is zero current through the input impedance, then there must be *no* voltage drop between the inverting and non-inverting inputs. This means that voltage at the inverting input (–) is zero (point *A*) because the other input (+) is grounded. The 0V at the inverting input terminal (point *A*) is referred to as **virtual ground.** This condition is illustrated in Fig. 25.47. The point *A* is said to be at virtual ground because it is at 0V but is not physically connected to the ground (*i.e.* $V_A = 0V$).



(*i*)

(*ii*)

Fig. 25.47

Referring to Fig. 25.47 (*ii*), the current I_1 to the inverting input is zero. Therefore, current I_{in} flowing through R_i entirely flows through feedback resistor R_f. In other words, $I_f = I_{in}$.

Now
$$I_{in} = \frac{\text{Voltage across } R_i}{R_i} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

and
$$I_f = \frac{\text{Voltage across } R_f}{R_f} = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

$$\text{Since } I_f = I_{in}, \quad -\frac{V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

$$\therefore \quad \text{Voltage gain, } A_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

25.15 Operational Amplifier (OP- Amp)

Fig. 25.38 shows the block diagram of an operational amplifier (*OP*-amp). The input stage of an *OP*- amp is a differential stage followed by more stages of gain and a class *B* push-pull emitter follower.

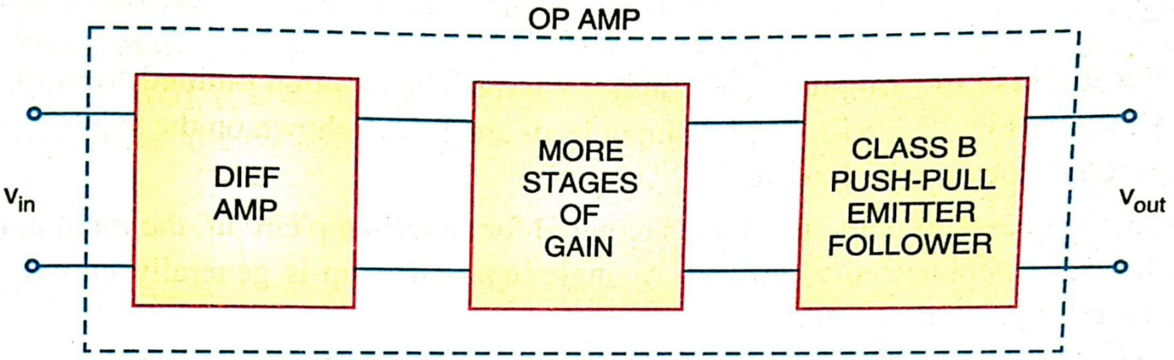


Fig. 25.38

The following are the important properties common to all operational amplifiers (*OP*-amps):

(*i*) An operational amplifier is a multistage amplifier. The input stage of an *OP*-amp is a differential amplifier stage.

(*ii*) An inverting input and a noninverting input.

(*iii*) A high input impedance (usually assumed infinite) at both inputs.

(*iv*) A low output impedance ($< 200\ \Omega$).

(*v*) A large open-loop voltage gain, typically 10^5.

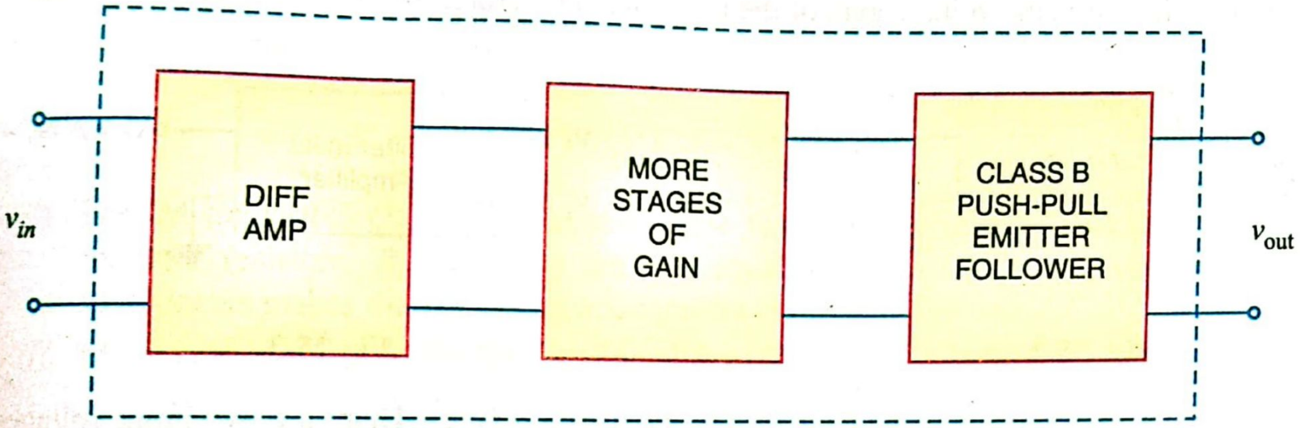
(*vi*) The voltage gain remains constant over a wide frequency range.

(*vii*) Very large *CMRR* (> 90 dB).

25.1 Operational Amplifier

An **operational amplifier** *(OP-Amp) is a circuit that can perform such mathematical operations as addition, subtraction, integration and differentiation.*

Fig. 25.1 shows the block diagram of an operational amplifier. Note that *OP*-Amp is a multistage amplifier. The three stages are : differential amplifier input stage followed by a high-gain *CE* amplifier and finally the output stage. *The key electronic circuit in an OP-Amp is the* **differential amplifier.** A differential amplifier (*DA*) can accept two input signals and amplifies the difference between these two input signals.



Block diagram of OP-Amp

Fig. 25.1

The following points may be noted about operational amplifiers (*OP*-Amps) :

(i) The input stage of an *OP*-Amp is a *differential amplifier* (*DA*) and the output stage is typically a class *B* push-pull emitter follower.

(ii) The internal stages of an *OP*-Amp are *direct-coupled i.e.*, no coupling capacitors are used. The direct coupling allows the *OP*-Amp to amplify d.c. as well as a.c. signals.

(iii) An OP-Amp has *very high input impedance* (ideally infinite) and *very low output impedance* (ideally zero). The effect of high input impedance is that the amplifier will draw a very small current (ideally zero) from the signal source. The effect of very low output impedance is that the amplifier will provide a constant output voltage independent of current drawn from the source.

(iv) An OP-Amp has *very high *open-loop voltage gain* (ideally infinite); typically more than 200,000.

(v) The OP-Amps are almost always operated with negative feedback. It is because the open-loop voltage gain of these amplifiers is very high and we can sacrifice the gain to achieve the advantages of negative feedback including large bandwidth (*BW*) and gain stability

AC Successive approximation

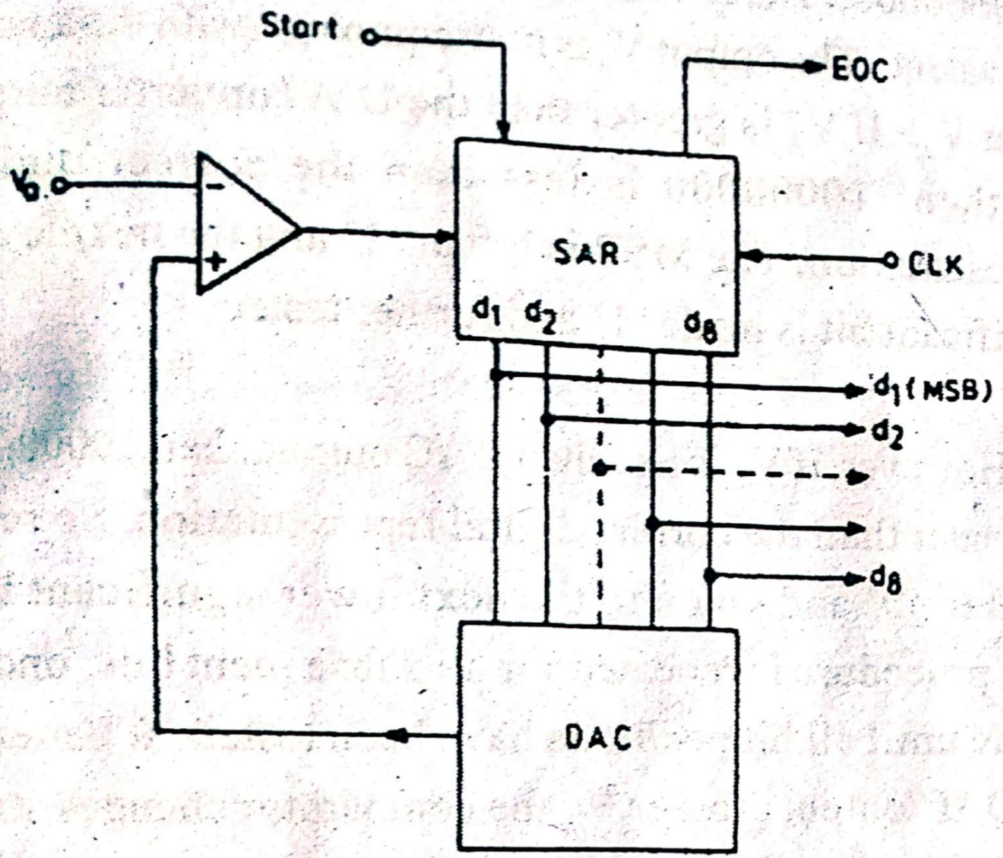


Figure shows a successive approximation type of A/D converter. It uses a very efficient strategy to complete n-bit conversion in just n-clock periods. The heart of the circuit is an 8-bit successive approximation register (SAR) its output is applied to an 8 bit D/A converter. The analog output of the D/A converter is then compared to an analog input signal by the comparator. The output of the comparator is a serial data input to the SAR. The SAR then adjusts its digital output until it is equivalent to analog input. The 8-bit latch at the end of conversion holds onto the resultant digital data output. The circuit words as follows.

With the arrival of the START command, the SAR sets the MSB $d_1 = 1$, with other bits to zero. So the trial code is 10000000. The D/A converter then generates an analog equivalent. The output V_d is now compared with the analog input V_A. If V_A is greater than the D/A converter output V_d, then 10000000 is less than the correct digital representation. The MSB is left at '1' and the next lower significant bit is made '1' and further tested.

However, if V_A is less than DAC output, then 10000000 is greater than the correct digital representation. So reset MSB to '0' and go on to the next lower significant bit. This procedure is repeated for all subsequent bits, one at a time until all bit positions have been tested. Whenever the DAC output crosses V_A the comparator changes state and this can be taken as the end of conversion (EOC) command. The advantage of the successive approximation A/D converter is its high speed and excellent resolution. For example, the 8-bit successive approximation A/D converter requires only eight clock pulse.