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GE4T (Digital, Analog Circuits and Instrumentation)

Topic – Operational Amplifiers

Introduction:

Historically, an *operational amplifier* (or Op-Amp) was designed to perform a few mathematical operations such as addition, subtraction, integration and differentiation. Hence, the name operational amplifier has come into play. An operational amplifier is a multistage amplifier and consists of a differential amplifier stage, a high-gain CE amplifier stage and class *B* push-pull emitter follower. It is an integrated circuit and is widely used in computers, as video and audio amplifiers in communication electronics.

Because of their multi-purpose use, Op-Amps are used in all branches of electronics, both digital and linear circuits. In this e-report, we shall discuss the various aspects of operational amplifiers.

Features of an Op-Amp:

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

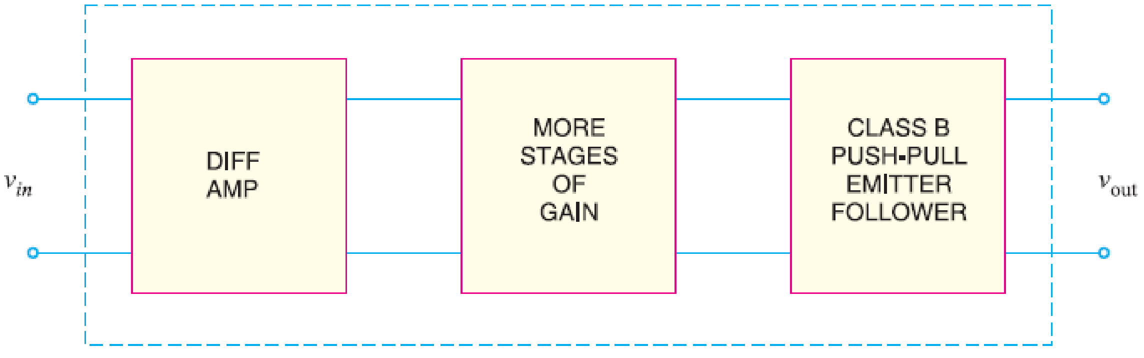
Fig. 1 shows the block diagram of an operational amplifier. It is important to note that Op-Amp is a multistage amplifier. The three stages are differential amplifier input stage followed by a high-gain CE amplifier and finally the output stage. The key electronic circuit in an Op-Amp is the differential amplifier. A differential amplifier (DA) can accept two input signals and amplifies the difference between these two input signals.

The following points may be noted about 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 an Op-Amp to amplify DC as well as AC signals.

(iii) An Op-Amp has very high input impedance Z_{in} (ideally infinite) and very low output impedance Z_{out} (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.

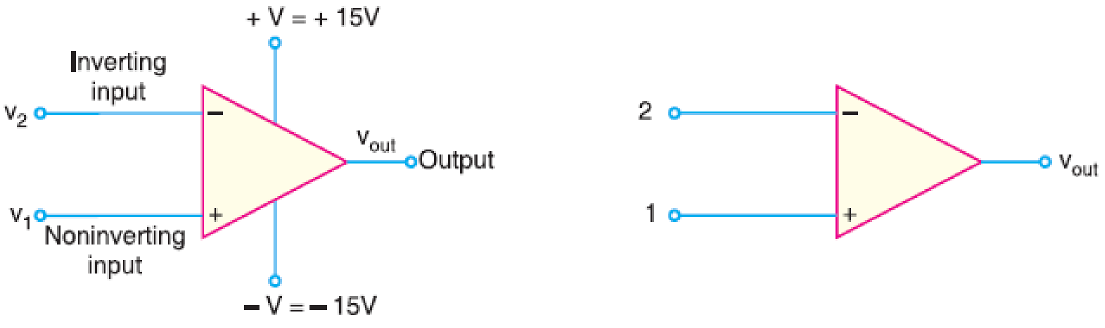


Block diagram of OP-Amp

Fig. 1

(iv) An Op-Amp has very high open-loop voltage gain (ideally infinite), typically $\sim 2 \times 10^5$.

(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 and gain stability.



(*i*) (*ii*)

Fig. 2

Schematic Symbol of an Op-Amp:

Fig. 2(*i*) shows the schematic symbol of an operational amplifier. The following points are worth noting,

(i) The basic operational amplifier has five terminals; two terminals for supply voltages $+V$ and $-V$, two input terminals (inverting input and non-inverting input) and one output terminal.

(ii) Note that the input terminals are marked + and –. These are not polarity signs. The – sign indicates the inverting input while the + sign indicates the non-inverting input. A signal applied to + terminal will appear in the same phase at the output as at the input. A signal applied to the – terminal will be shifted in phase 180^0 at the output.

(iii) The voltages v_1, v_2 and v_{out} are node voltages. This means that they are always measured from the ground. The differential input v_{in} is the difference of two node voltages v_1 and v_2. We normally do not show the ground in the symbol.

(iv) For the sake of simplicity, $+V$ and $-V$ terminals are often omitted from the symbol as shown in Fig. 2(*ii*). The two input leads are always shown on the symbol regardless of whether they are both used.

Voltage Gains of DA, Common Mode Rejection Ratio (CMRR):

The voltage gain of a DA operating in differential mode is called differential-mode voltage gain and is denoted by A_{DM}. The voltage gain of DA operating in common-mode is called common-mode voltage gain and is denoted by A_{CM}.

Ideally, a DA provides a very high voltage gain for differential-mode signals and zero gain for common-mode signals. However practically, differential amplifiers do exhibit a very small common-mode gain (usually much less than 1) while providing a high differential voltage gain (usually several thousands). The higher the differential gain in comparison to the common-mode gain, the better the performance of the DA in terms of rejection of common-mode signals.

A differential amplifier should have high differential mode voltage gain (A_{DM}) and very low common mode voltage gain (A_{CM}). The common mode rejection ratio (CMRR) is defined as,

$$CMRR = \frac{A_{DM}}{A_{CM}}$$

Clearly, it is a dimensionless quantity. But very often, the CMRR is expressed in decibels (dB). The decibel measure for CMRR is given by, $CMRR$ (in dB) $= 20\log_{10}\frac{A_{DM}}{A_{CM}} = 20\log_{10} CMRR$.

For example, a CMRR of 10^5 corresponds to 100 in dB unit of CMRR.

Types of Voltage Gains of Op-Amp:

The maximum possible voltage gain from a given Op-Amp is called *open-loop voltage gain* and is denoted by the symbol A_{OL}. The value of A_{OL} for an Op-Amp is generally greater than 10000.

The term open-loop indicates a circuit condition where there is no feedback path from the output to the input of Op-Amp. The Op-Amps are almost always operated with negative feedback i.e., a part of the output signal is fed back in phase opposition to the input. Consequently, the voltage gain of the Op-Amp is reduced. When a feedback path is present, the resulting circuit gain is referred to as *closed-loop voltage gain* (A_{CL}). Value of A_{CL} depends on the circuit parameters.

Comparison between Practical Op-Amp and Ideal Op-Amp:

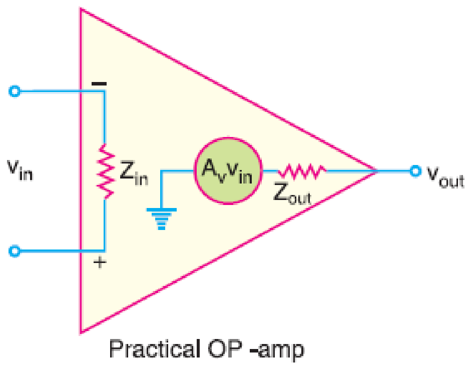


Fig. 3

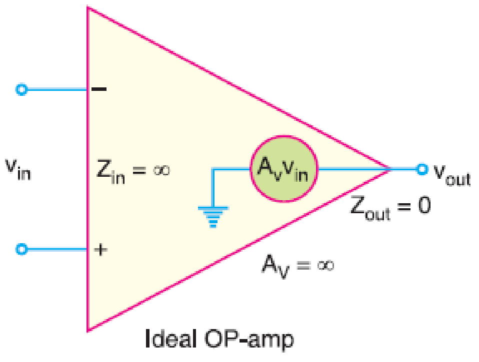


Fig. 4

The basic Op-Amp has two input terminals and one output terminal. The input terminals are labelled as + (non-inverting input) and – (inverting input). As discussed earlier, a signal applied to the non-inverting input will produce an output voltage that is in phase with the input voltage. However, a signal applied to the inverting input will produce an output voltage that is 180^0 out of phase with the input signal.

(i) Practical Op–Amp. Fig. 3 shows the AC equivalent circuit of a practical Op-Amp (IC 741). The characteristics of a practical Op-Amp are very high voltage gain, very high input impedance and very low output impedance. The input voltage v_{in} appears between the two input terminals and the output voltage is $A_{OL} v_{in}$ taken through the output impedance Z_{out}.

(ii) Ideal Op-Amp. Fig. 4 shows the AC equivalent circuit of an ideal Op-Amp. The characteristics of an ideal Op-Amp are infinite voltage gain, infinite input impedance Z_{in} and zero output impedance Z_{out}.

We can sum up the values of parameters of a practical Op-Amp and an ideal Op-Amp as under

	Practical Op-Amp	Ideal Op-Amp
Z_{in}	~ 2 MΩ	∞
A_{OL}	$\sim 10^5$	∞
Z_{out}	~ 100 Ω	0

Applications of OP-Amps:

We have already discussed that the name operational amplifier (or Op-Amp) has come into play, since it was designed to perform a few mathematical operations such as addition, subtraction, integration and differentiation. Because of its versatile nature, an Op-Amp has many practical applications. It can be connected in a large number of circuits to provide various operating characteristics. In this e-report, we shall discuss some important applications of Op-Amps.

1. Inverting Amplifier:

An operational amplifier can be operated as an *inverting amplifier* as shown in Fig. 5. An input signal v_{in} is applied through input resistor R_i to the inverting input. The output is fed back to the same inverting input through feedback resistor R_f. The non-inverting input is grounded. We should 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. 180^0 out of phase) as compared to the input. Hence the name inverting amplifier.

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 (at point A) because the other input (+) is grounded. The 0 V at the inverting input terminal (point A) is popularly referred to as *virtual ground*. This condition is illustrated in Fig. 5. The point A is said to be at virtual ground because it is at 0V (i.e. $V_A = 0$ V), but is not physically connected to the ground.

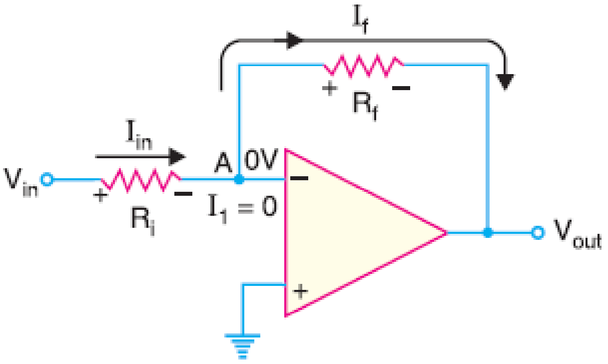


Fig. 5

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 $I_{in} = \frac{v_{in} - V_A}{R_i} = \frac{v_{in}}{R_i}$, since $V_A = 0$ V for virtual ground. Using the same argument, we also can write $I_f = \frac{V_A - v_{out}}{R_f} = -\frac{v_{out}}{R_f}$.

Therefore, $\frac{v_{in}}{R_i} = -\frac{v_{out}}{R_f}$. Finally we can write closed-loop voltage gain $A_{CL} = \frac{v_{out}}{v_{in}} = -\frac{R_f}{R_i}$. The negative sign indicates that output signal is inverted as compared to the input signal. The inverting amplifier can also be designed for *unity gain buffer*. Thus if $R_f = R_i$, then voltage gain, $A_{CL} = -1$. Therefore, the circuit provides a unity voltage gain with 180^0 phase inversion.

2. Non-Inverting 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 *non-inverting amplifier* as shown in Fig. 6. The input signal is applied to the non-inverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistor R_i. It is important to note that resistors R_f and R_i form a voltage divider at the inverting input (–). This produces negative feedback in the circuit. R_i is grounded. Since the input signal is applied to the non-inverting input (+), the output signal will be non-inverted i.e., the output signal will be in phase with the input signal. Hence, the name non-inverting amplifier.

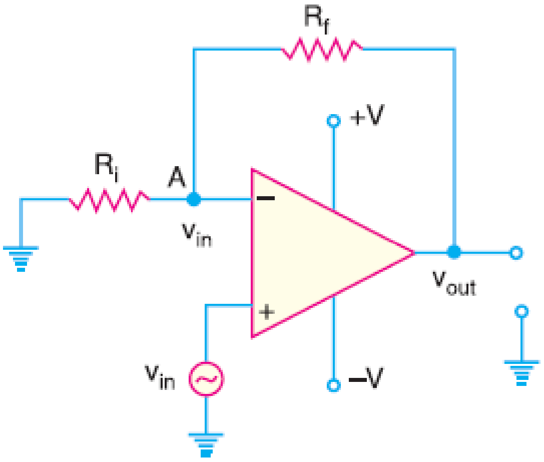


Fig. 6

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. Current through R_f is $\frac{v_{out}-V_A}{R_f} = \frac{v_{out}-v_{in}}{R_f}$. Current through R_i is $\frac{V_A}{R_i} = \frac{v_{in}}{R_i}$. Therefore, $\frac{v_{in}}{R_i} = \frac{v_{out}-v_{in}}{R_f}$. So, we can write closed-loop voltage gain $A_{CL} = \frac{v_{out}}{v_{in}} = 1 + \frac{R_f}{R_i}$.

The voltage gain is always positive. This is not surprising because output signal is in phase with the input signal. The voltage gain of a non-inverting amplifier can be made equal to or greater than 1.

3. Summing Amplifier (Adder):

A *summing amplifier* or *adder* is an inverted Op-Amp that can accept two or more inputs. The output voltage of a summing amplifier is proportional to the negative of the algebraic sum of its input voltages. Fig. 7 shows a three-input summing amplifier but any number of inputs can be used. Three voltages V_1, V_2 and V_3 are applied to the inputs and produce currents I_1, I_2 and I_3. Using the concepts of infinite impedance and virtual ground, we can see that inverting input of the Op-Amp is at virtual ground (0 V) and there is no current to the input. This means that the three input currents I_1, I_2 and I_3 combine at the summing point A and form the total current (I_f) which goes through R_f as shown in Fig. 7.

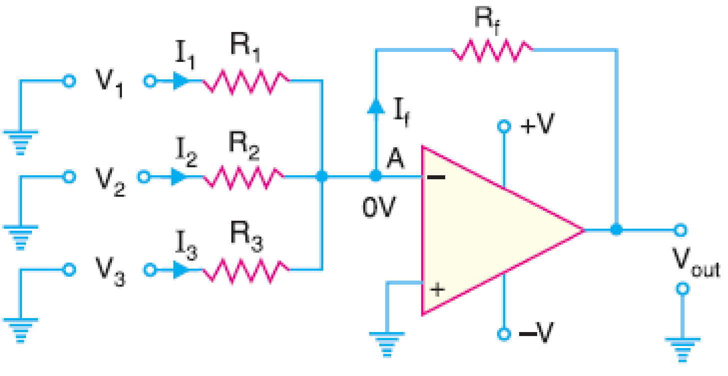


Fig. 7

When all the three inputs are applied, the output voltage is $v_{out} = -I_f R_f = -(I_1 + I_2 + I_3)R_f = -R_f(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3})$. We can see that the output voltage becomes a weighted sum of the input voltages.

If $R_1 = R_2 = R_3 = R$ we get $v_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3)$, the output becomes the algebraic sum of the input voltages.

This circuit can be used as a *subtractor* as well with two inputs, one of those being inverted by 180^0 phase.

4. Op-Amp Integrator:

An *integrator* is a circuit that performs integration of the input signal. The most popular application of an integrator is to produce a ramp output voltage (i.e. a linearly increasing or decreasing voltage). Fig. 8 shows the circuit of an Op-Amp integrator. It consists of an Op-Amp, input resistor R_i and feedback capacitor C_f. We note that the feedback component is a capacitor instead of a resistor. As we shall see, when a signal is applied to the input of this circuit, the output-signal waveform will be the integration of input-signal waveform.

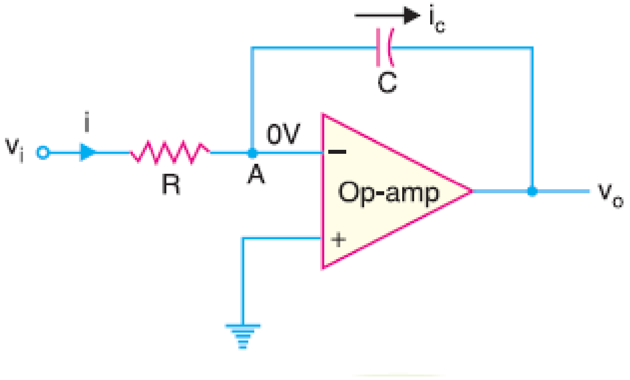


Fig. 8

Circuit Analysis. Since point A in Fig. 8 is at virtual ground and the Op-Amp has an infinite input impedance, all of the input current i flows through the capacitor i.e. $i = i_C = \frac{v_{in}-0}{R_i} = \frac{v_{in}}{R_i}$. Now voltage across the capacitor $v_C = 0 - v_{out} = -v_{out}$. So, $i_C = C_f\frac{dv_C}{dt}$ or $\frac{v_{in}}{R_i} = -C_f\frac{dv_{out}}{dt}$. So, we get $\frac{dv_{out}}{dt} = -\frac{1}{R_iC_f}v_{in}$.

Therefore, we finally get $v_{out} = -\frac{1}{R_iC_f}\int v_{in}dt$. This result shows that the output is the integral of the input with an inversion and scale multiplier of $-\frac{1}{R_iC_f}$.

5. 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. 9 shows the circuit of Op-Amp differentiator. It consists of an Op-Amp, an input capacitor C_i and feedback resistor R_f. We note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.

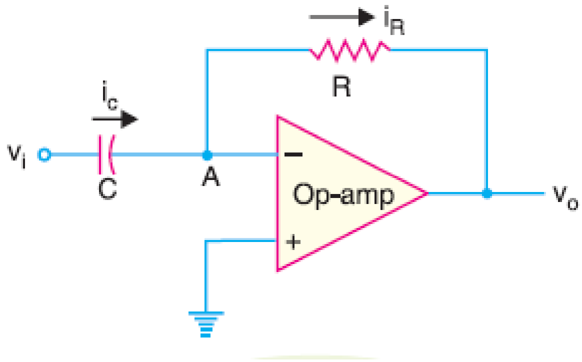


Fig. 9

Circuit Analysis. Because of virtual ground and infinite input impedance of Op-Amp, all the input current i_C flows through the feedback resistor R_f i.e. $i_C = i_R$. Now $i_R = \frac{0-v_{out}}{R_f} = -\frac{v_{out}}{R_f}$. We now can write $i_C = C_i\frac{dv_C}{dt} = C_i\frac{dv_{in}}{dt}$. Therefore $-\frac{v_{out}}{R_f} = C_i\frac{dv_{in}}{dt}$ or $v_{out} = -R_f C_i\frac{dv_{in}}{dt}$.

This equation shows that output is the differentiation of the input with an inversion and scale multiplier of $R_f C_i$.

6. Op-Amp Comparator:

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 (non-inverting 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 $A_{OL} = 10^5$. A voltage difference of only 0.25 mV between the inputs will produce an output voltage of (0.25 mV) (10^5) = 25 V. However, most of Op-Amps have output voltages of less than ±15 V because of their DC 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.

A comparator circuit has the following two characteristics:

(i) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of Op-Amp.

(ii) It is operated in a *non-linear mode*. These properties of a comparator permit it to perform many useful functions.

As a zero-crossing detector. When one input of a comparator is connected to ground, it is known as *zero-crossing detector* because the output changes when the input crosses 0 V. The zero-crossing circuit is shown in Fig. 10. The input and output waveforms are also shown. When the input signal is positive-going, the output is driven to positive maximum value (i.e. $+V_{sat} = +13$ V). When the input crosses the zero mark and begins to go negative, the output is driven to negative maximum value (i.e. $-V_{sat} = -13$ V).

From the input/output waveforms, you can see that every time the input crosses 0 V going positive, the output jumps to +13 V. Similarly, every time the input crosses 0 V going negative, the output jumps to –13 V. Since the change (+13 V or –13 V) occurs every time the input crosses 0 V, we can tell when the input signal has crossed 0 V. Hence the name zero-crossing detector.

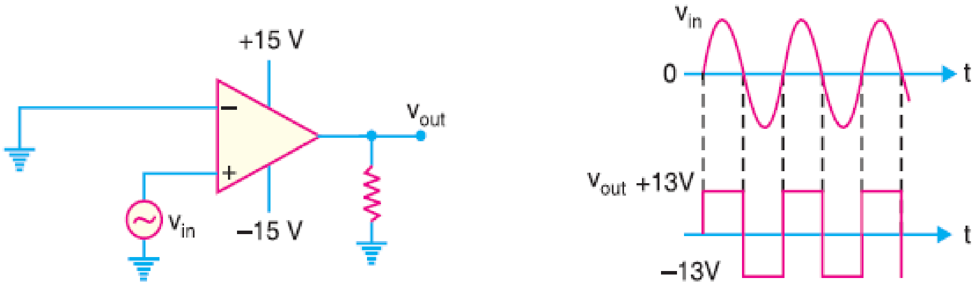


Fig. 10

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Reference:

Principles of Electronics, V.K. Mehta & Rohit Mehta, S. Chand & Company

(All the figures have been collected from the above mentioned reference)

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