CHAPTER 16

Introduction to Operational Amplifiers

Learning Objectives

After completing this chapter, you will learn the following:

- Operational fundamentals of an opamp.
- Difference between an ideal opamp and a practical opamp.
- Internal architecture of a typical opamp.
- Major performance parameters of an opamp and their relevance to different application circuits configured around opamps.
- Selection criterion for choosing the right opamp for a given application.
- Types of opamps and their corresponding preferred application areas.

Amongst the general-purpose linear integrated circuits, the integrated circuit operational amplifier popularly known as opamp is undoubtedly the most widely used IC. Operational amplifier in essence is a high-gain differential amplifier capable of amplifying signals right down to DC due to use of direct coupling in the device's internal architecture. Owing to its high differential gain, high input impedance, low output impedance, large bandwidth and many other desirable features, operational amplifiers fit into almost every conceivable circuit application ranging from amplifiers to oscillators, computational building blocks to data conversion circuits, active filters to regulators and so on. This chapter gives an introduction to the fundamental topics relevant to operational amplifiers. The chapter begins with a brief description of the internal architecture of an operational amplifier. This is followed up by an introduction to different categories of operational amplifiers, selection criterion and definition and interpretation of major performance specifications. The text is amply illustrated by solved examples. Application circuits using operational amplifiers are discussed in the following chapter.

16.1 Operational Amplifier

An operational amplifier popularly known as an opamp is basically a high-gain differential amplifier capable of amplifying signals right down to DC. The capability of the opamp to amplify signals down to DC lies in the use of direct coupling mechanism in the internal architecture of the device. That is why it is also called a direct-coupled or a DC amplifier. The other main attributes of an opamp are very high input impedance, very low output impedance, very large bandwidth, extremely high value of open-loop gain and so on.

It is called an operational amplifier as it was originally conceived as an analog computation building block that could be used conveniently to perform mathematical functions like addition, subtraction, integration, differentiation and so on. Today opamps have unlimited applications. An opamp fits in any conceivable circuit application from analog computation to building amplifiers and oscillators, from active filters to phase shifters, from comparators to voltage regulators, from function generators to gyrators and so on and so forth. It is worthwhile mentioning here that an opamp becomes a true amplifier to perform all those above-listed circuit functions only when negative feedback is introduced around the opamp with the exception of oscillator, multivibrator and other similar building blocks which use positive feedback circuits. Figure 16.1 shows the circuit representation of an opamp. An opamp is usually a two input and one output device along with two power supply terminals one for positive supply and the other for negative supply with both having a common ground. The word "usually" is used here as there are opamps with differential outputs. There are also opamps with single power supply terminal.

The (+ve) input called non-inverting input gives a non-inverted amplified signal at the output. This means that with (–ve) input terminal grounded, the output signal is in phase with the input applied at the (+ve) input terminal. On the other hand, with (+ve) input terminal grounded, the output signal is inverted and amplified version of the signal applied at (–ve) input. That is why (–ve) input is also called inverting input.

The key parameters of an opamp like open-loop gain, input impedance, output impedance, common mode rejection ratio (CMRR), bandwidth and offsets should ideally be infinity, infinity, zero, infinity, infinity and zero, respectively. They do approach these values in the case of high performance opamps. These parameters, which often form the basis of selection criteria, are described in detail in Section 16.4. Not all key parameters are equally important while deciding the right type number for a given application. As an example, when the opamp is to be used as a comparator, the response time specification is perhaps the first priority and CMRR, a do not care one, whereas if we are building a differential amplifier with gain accuracy, CMRR and open-loop gain would be among the first few specifications to be paid more attention. Different categories of opamps are made with each category designed to suit a particular range of applications. Different types of opamps along with their salient features are described in detail in Section 16.5.

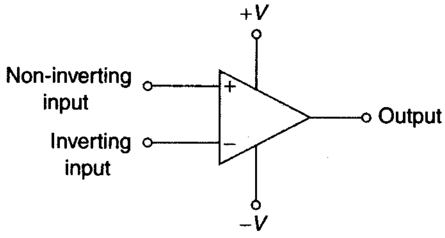


Figure 16.1 | Circuit representation of an opamp.

16.2 Inside of the Opamp

The inside circuit of a typical opamp consists of a differential amplifier input stage that is followed by one or more differential amplifier gain stages. Generally, the differential amplifier input stage provides a differential output and the gain stages provide a single-ended output. The number of gain stages may be different for different opamps. The output of the final gain stage feeds the input of a class-B push–pull output stage. The output stage acts like a level translator and output driver. Figure 16.2 shows the block schematic arrangement of the internal circuit of a typical opamp with a differential input and a single-ended output. Now,

$$V_{\text{out}} = A_{\text{OL}} \times V_{\text{in}}$$

where A_{OL} is the open-loop voltage gain of the opamp, that is, voltage gain in the absence of any negative feedback. In the following sections, we will look at the basic circuits used to implement each of the building blocks of the operational amplifier.

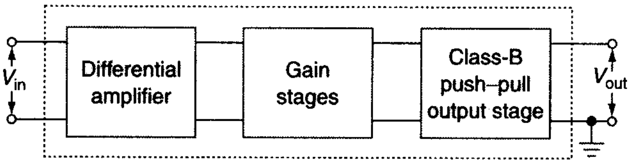


Figure 16.2 | Block schematic arrangement of a typical opamp.

Differential Amplifier Input Stage

Figure 16.3 shows the basic single-stage differential amplifier configuration. Note that the designers of IC amplifiers do not have the luxury of using coupling and bypass capacitors as it is not practical to fabricate large-value capacitors (larger than 50 pF) on the IC chip. This is one of the reasons that differential amplifier which requires no coupling and emitter bypass capacitors is the designers' preferred choice as the opamp input stage. Even large-value resistors are also not easy to fabricate in the IC form. Large-value resistances are simulated by using suitable transistor configurations.

The differential amplifier configuration is also sometimes called a long-tail pair as the two transistors share a common-emitter resistor. The current through this resistor is called the tail current. Figure 16.3 shows the configuration of a differential input–differential output differential amplifier. In the circuit of Figure 16.3, the base terminal of Q_1 is the non-inverting input and base terminal of transistor Q_2 is the inverting input. The output is in-phase with the signal applied at non-inverting input and out-of-phase with the signal applied at inverting input. This further implies that if two different input signals are applied to inverting and non-inverting inputs, the output is given by $A_d \times (V_1 - V_2)$.

For DC analysis, if we ignore the voltage drop across base–emitter junctions of the two transistors, the common emitter point for all practical purposes is at ground potential. That is, the tail current is given by V_{EE}/R_E, which is constant. The tail current is divided into two separate paths, one through Q_1 and the other through Q_2. As the two halves are symmetrical, total current sharing depends upon the voltages applied to the two inputs.

Figure 16.4 shows the circuit diagram and signal wave shapes at relevant points when the signal is applied to inverting and non-inverting inputs separately.

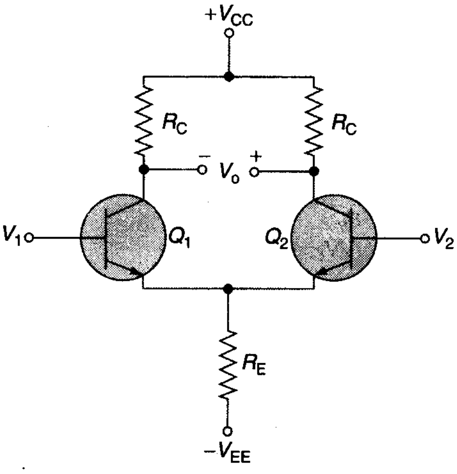


Figure 16.3 | Basic differential amplifier.

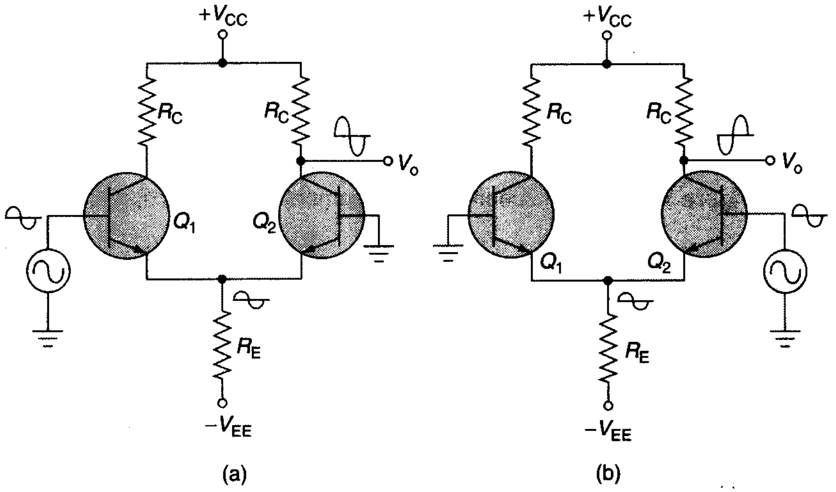


Figure 16.4 Differential amplifier with signal applied to (a) non-inverting input; (b) inverting input.

One of the key parameters of the differential amplifier is its ability to amplify differential input and its insensitivity to common mode input. This is expressed in terms of CMRR, which is nothing but ratio of differential gain to common mode gain. CMRR is described in detail Section 16.4 on opamp parameters. It can be verified that for the differential amplifier of Figure 16.3, differential gain is given by R_C/r_e' and the common mode gain is given by $R_C/2R_E$. CMRR therefore is given by $2R_E/r_e'$, where r_e' is the dynamic resistance of the base–emitter junctions of the two transistors.

It is evident from the expression for CMRR that the value of R_E should be as high as possible. That is why in practical opamp circuits, R_E is replaced by a constant current source. A current mirror configuration is also used to implement a constant current source. Figures 16.5 and 16.6, respectively, show differential

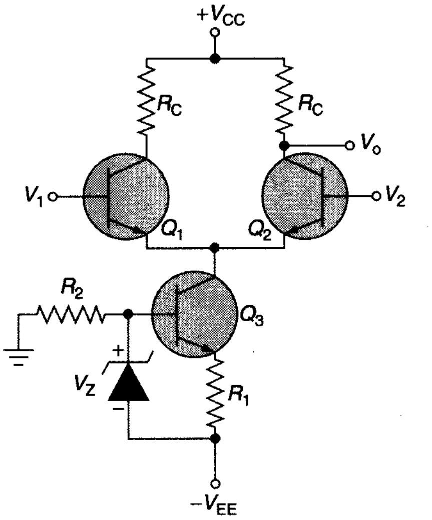


Figure 16.5 Differential amplifier with conventional constant current source in place of R_E.

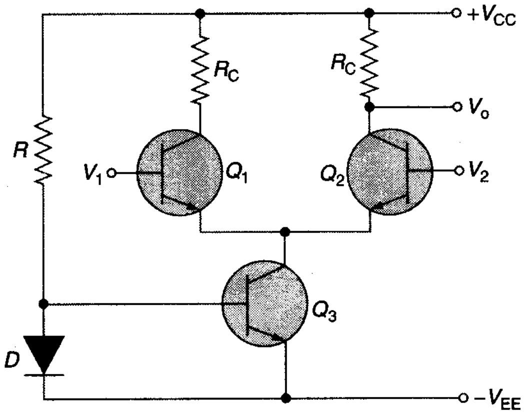


Figure 16.6 | Differential amplifier with current mirror based constant current source in place of R_E.

amplifier circuits with a conventional constant current source and a current mirror configuration. We are familiar with the functioning of conventional constant current sources. The current mirror works as follows. If the diode connected across the base–emitter junction and the base–emitter junction diode of the transistor had matched current-voltage characteristics, the collector current of the transistor equals the current through resistor *R*. In other words, the collector current is a mirror image of the resistor current. As it is very easy to match the current-voltage characteristics of a diode and base–emitter junction diode of a transistor in ICs because of both being on same chip, current mirror configuration is commonly used as current source and active load in IC opamps. Figure 16.7 shows a differential amplifier stage with current mirrors being used instead of emitter resistor R_E and collector resistor R_C.

As outlined earlier, common-emitter amplifier and class-B push–pull amplifier constitute the second and final stages of the opamp, respectively. These have been described in detail in earlier chapters. Common-emitter amplifier stage or a cascade arrangement of more than one such stage provides most of the gain of the opamp. These stages when used inside an opamp will have active loads.

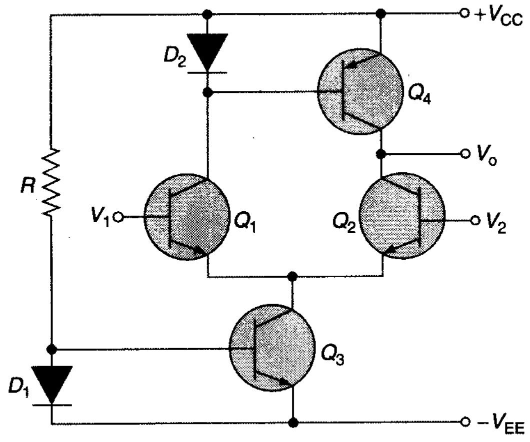


Figure 16.7 | Differential amplifier with current mirrors used in place of emitter and collector resistors.

Figure 16.8 shows the simplified internal circuit schematic of a typical opamp. The diagram shown is that of the industry standard opamp 741. Transistors Q_1 and Q_2 constitute the differential amplifier. Transistor Q_6 is configured as an emitter–follower buffer stage. Q_5 and associated components make the common-emitter stage that feeds the output class-B push–pull stage. The output stage is configured around transistors Q_8 and Q_9. One can notice the use of current mirror configuration as active loads and also as the tail resistor of differential amplifier.

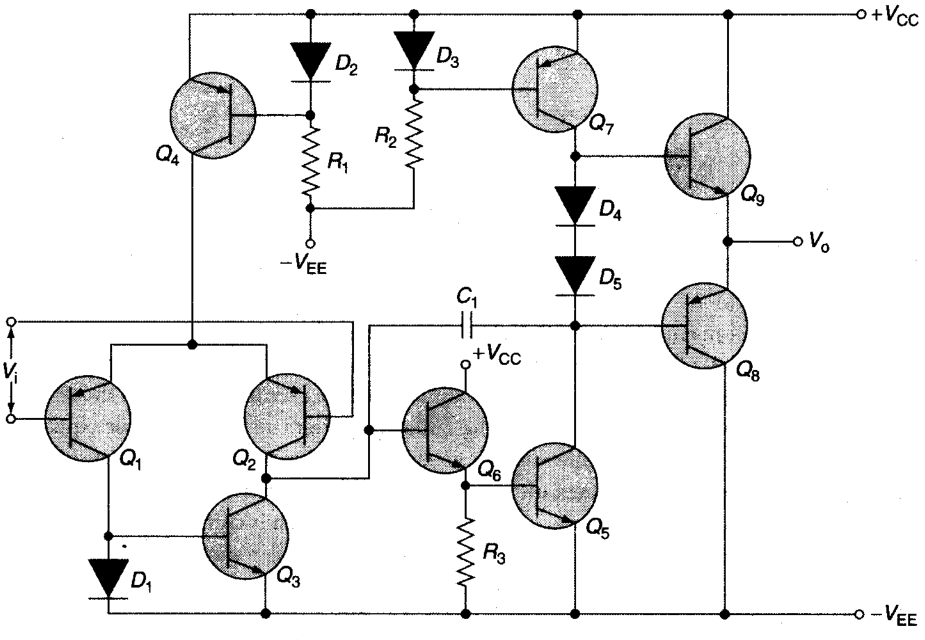


Figure 16.8 | Internal circuit diagram of a typical opamp.

EXAMPLE 16.1

Refer to the differential amplifier circuit of Figure 16.9. Determine the quiescent DC voltage at the collector terminal of each transistor assuming V_{BE} of the two transistors to be negligible. What will be the quiescent DC values if V_{BE} is taken as 0.7 V?

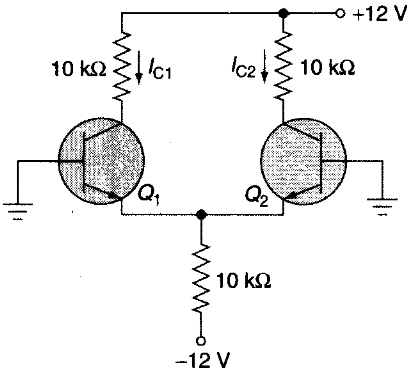


Figure 16.9 | Example 16.1.

Solution

1. Assuming V_{BE} to be negligible, the tail current $I_T = 12/10 \times 10^3 = 1.2$ mA.
2. Therefore emitter current of each transistor = $1.2 \times 10^{-3}/2 = 0.6$ mA.
3. Collector current of each transistor is approximately equal to its emitter current.
4. Therefore, collector current of each transistor = 0.6 mA.
5. Quiescent DC voltage at the collector of each transistor = $12 - 0.6 \times 10^{-3} \times 10 \times 10^3 = 6$ V.
6. If $V_{BE} = 0.7$ V, tail current = $(12 - 0.7)/(10 \times 10^3) = 1.13$ mA.
7. This gives emitter and hence collector current of each transistor as $(1.13 \times 10^{-3})/2 = 0.565$ mA.
8. Quiescent DC voltage at each collector in that case equals $12 - 0.565 \times 10^{-3} \times 10 \times 10^3 = 6.35$ V.

EXAMPLE 16.2

Refer to the differential amplifier circuit diagram of Figure 16.10. Determine the differential voltage gain, given that the transistors used in the circuit have $h_{ie} = 1$ *kΩ and* $h_{fe} = 40$.

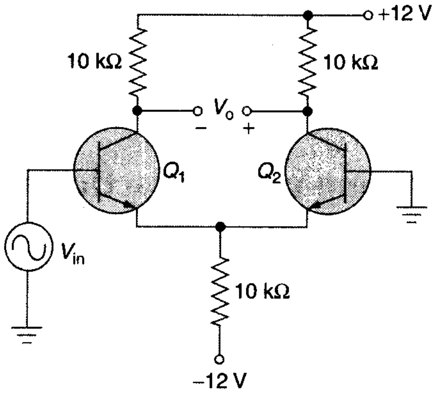


Figure 16.10 | Example 16.2.

Solution

1. Dynamic resistance r_e' of the base–emitter junction diode of the two transistors is given by h_{ie}/h_{fe}. Therefore, $r_e' = 1000/40 = 25\ \Omega$.
2. Differential voltage gain is given by $A_d = R_C/r_e'$.
3. Therefore, $A_d = 10{,}000/25 = 400$.

EXAMPLE 16.3

Refer to the differential amplifier circuit of Figure 16.11. Determine the tail current I_T *and also the quiescent DC voltage across the output. Assume diode voltage drop to be 0.7 V.*

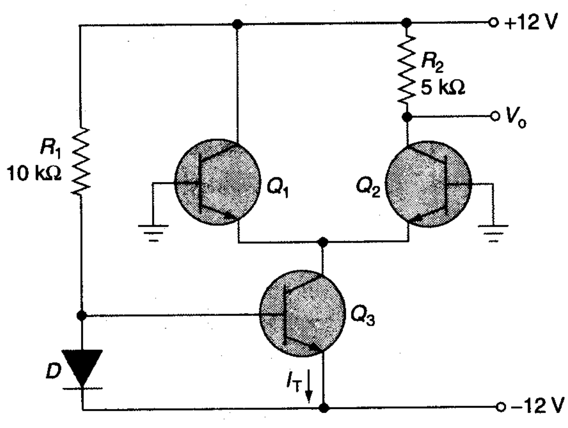


Figure 16.11 | Example 16.3.

Solution

1. Current I_R flowing through resistor R_1 is given by $I_R = (12 + 12 - 0.7)/(10 \times 10^3) = 23.3/(10 \times 10^3) = 2.33$ mA.
2. The tail current $I_T = I_R = 2.33$ mA.
3. Current flowing through each transistor is equal to half of the total tail current.
4. Therefore, current through each transistor $= 2.33 \times 10^{-3}/2 = 1.165$ mA.
5. Quiescent DC voltage across output $= 12 - 5 \times 10^3 \times 1.165 \times 10^{-3} = 6.175$ V.

16.3 Ideal Opamp versus Practical Opamp

As outlined in the earlier part of the chapter, an opamp is a direct-coupled high gain, high bandwidth differential amplifier with very high value of input impedance and very low value of output impedance. Figure 16.12 shows the Thevenin's equivalent model of a generalized amplifier fed at the input from a source having a source resistance R_s and the amplified output feeding a load resistance R_L. Owing to finite values of R_i and R_o, the effective value of the gain is less than what it would have been had R_i and R_o been infinite and zero, respectively.

Figure 16.13 shows the Thevenin's equivalent model of an opamp. V_I and V_{NI} are, respectively, inverting and non-inverting inputs and A_d is the open-loop differential voltage gain. This is the equivalent circuit model of a practical opamp. There are loading effects at the input and output ports due to finite values of

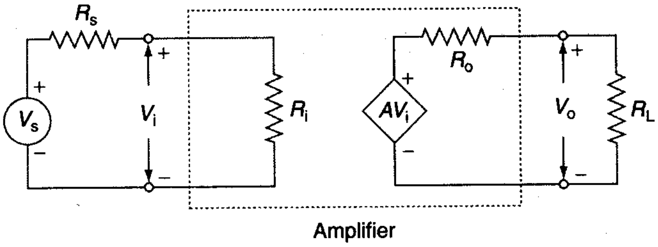


Figure 16.12 | Thevenin's equivalent model of generalized amplifier.

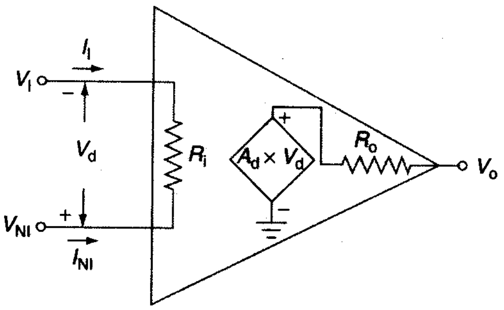


Figure 16.13 | Thevenin's equivalent model of an opamp.

input and output resistances. The ideal opamp model was derived to simplify circuit calculations. The ideal opamp model makes three assumptions. These are as follows:

1. Input resistance, $R_i = \infty$
2. Output resistance, $R_o = 0$
3. Open-loop gain, $A_d = \infty$

From the three above-mentioned primary assumptions, other assumptions can be derived. These include the following:

1. Since $R_i = \infty$, $I_I = I_{NI} = 0$.
2. Since $R_o = 0$, $V_o = A_d \times V_d$
3. For linear mode of operation of opamp and a finite output voltage and infinite differential gain, $V_d = 0$.
4. Since output voltage depends only on differential input voltage, it rejects any voltage common to both inputs. Therefore, common mode gain = 0.
5. Bandwidth and slew rate are also infinite as no frequency dependencies are assumed.
6. Drift is also zero as there are no changes in performance over time, temperature, power supply variations and so on.

Figure 16.14 shows the Thevenin's equivalent model of an ideal opamp. To sum up, an ideal opamp is characterized by following basic properties. Knowledge of these properties is sufficient to design and analyze most of the circuits configured around opamps.

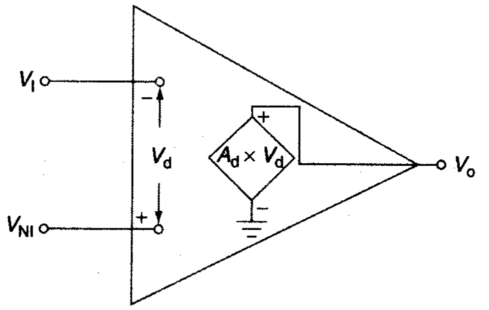


Figure 16.14 | Thevenin's equivalent model of an ideal opamp.

1. Infinite open-loop differential voltage gain.
2. Infinite input impedance.
3. Zero output impedance.
4. Infinite bandwidth.
5. Zero DC input and output offset voltages.
6. Zero input differential voltage.

Open-loop gain is the differential voltage gain in the absence of any positive or negative feedback. Practical opamps have open-loop gain in the range of 10,000 to 100,000. Input impedance of an ideal opamp is infinite. In the case of real devices, it could vary from hundreds of kilo-ohms for some low-grade opamps to tera-ohms for high-grade opamps. An ideal opamp acts like a perfect voltage source with zero internal output impedance. For real devices, output impedance may be in the range of 10 to 100 Ω. The ideal opamp amplifies all signals from DC to highest AC frequencies. In the case of real devices, bandwidth is rather limited and is specified by gain-bandwidth product. An ideal opamp produces a zero output when both the inputs are grounded. In the case of real devices, there may be some finite DC output, referred to as output offset voltage, even when both the inputs are grounded. Output offset may vary from few nano-volts for ultra-low offset opamps to few milli-volts for general-purpose opamps. In the case of ideal opamps, voltage appearing at one input also appears at the other input for linear mode of operation. That is, differential inputs stick together.

16.4 Performance Parameters

Like any other component, the key parameters of an opamp too decide its suitability for a particular application. For instance, an opamp with a CMRR of 120 dB is much better suited for building a differential amplifier than another opamp having CMRR of 80 dB. Also, on the basis of slew rate or response time specifications, we cannot evaluate the performance of a precision opamp. A brief description of the key parameters of an opamp along with their practical implications is given in the following paragraphs. Key opamp parameters include the following:

1. Bandwidth
2. Slew rate
3. Open-loop gain
4. Common mode rejection ratio (CMRR)
5. Power supply rejection ratio (PSRR)
6. Input impedance
7. Output impedance
8. Settling time
9. Offsets and offset drifts

Bandwidth

Bandwidth of an opamp tells us about the range of frequencies it can amplify for a given amplifier gain. The frequency response curve of a typical opamp looks like the graph of Figure 16.15(a). It is nothing but the frequency response of the general-purpose opamp 741 and the graph has been reproduced from the data sheet of the said opamp. The high-frequency roll-off is attributed to capacitive effects appearing in shunt. Beyond cut-off, the frequency falls at a rate of 6 dB per octave or 20 dB per decade. When the opamp is used in the closed-loop mode, the bandwidth increases at the cost of the gain. The bandwidth is usually expressed in terms of the *unity gain crossover frequency* (also called gain-bandwidth product). It is 1 MHz in the case of opamp 741 as is evident from the graph. It could be as high as 1500 MHz in the case of high bandwidth

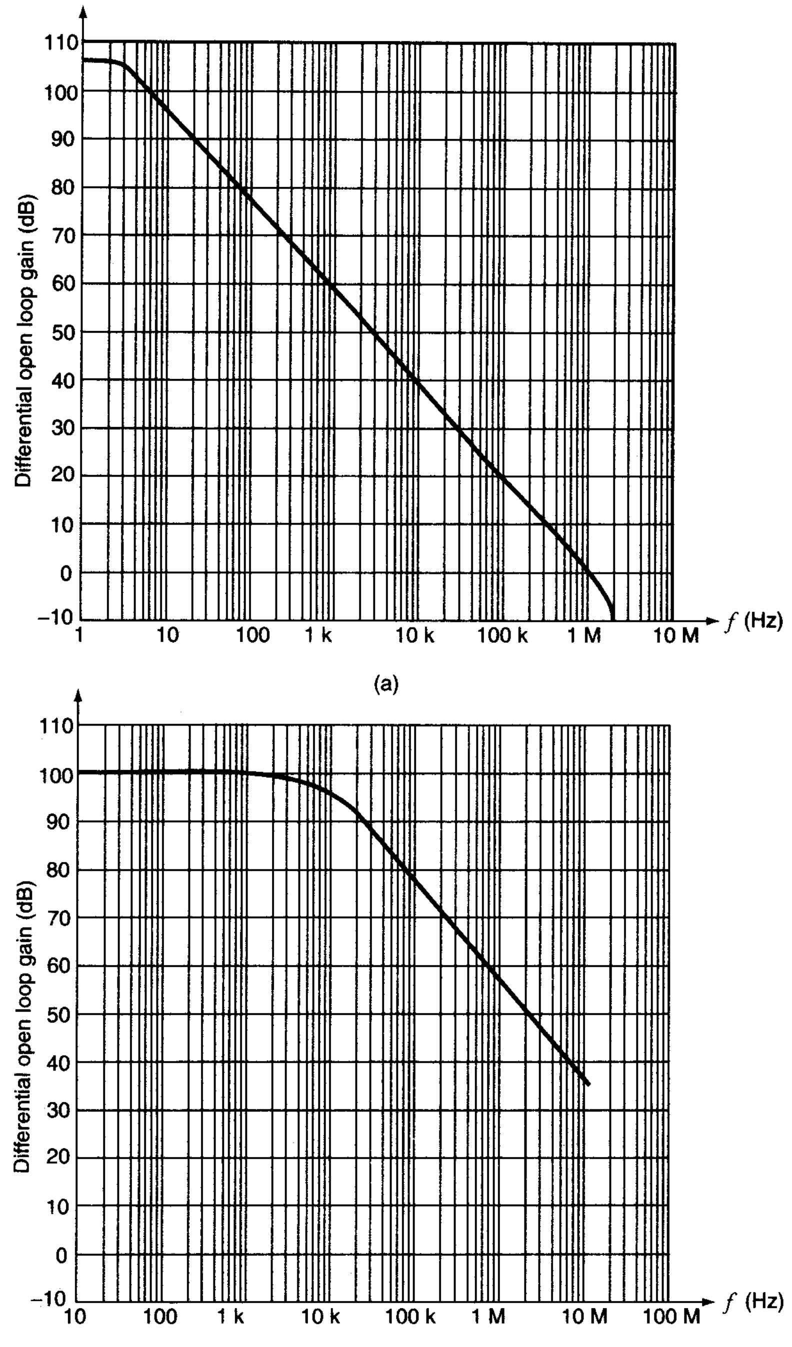


Figure 16.15 (a) Small signal bandwidth of general-purpose opamp 741; (b) small signal bandwidth of high-speed opamp AD829.

opamps. Figure 16.15(b) shows the frequency response of high-speed opamp AD829. It may be mentioned here that the plot shown in Figure 16.15 represents the small signal bandwidth of the opamp. That is, the output signal amplitude and the signal frequency are such that the rate of change of output is less than the slew rate of the opamp. If it is not so, the signal is termed as large signal and the large signal bandwidth is slew rate limited. Slew rate and the large signal bandwidth are discussed in the following paragraphs.

Slew Rate

Slew rate is one of the most important parameters of an opamp. It gives us an idea as to how well the opamp output follows a rapidly changing waveform at the input. It is defined as the rate of change of output voltage with time. It is determined by applying a step input and monitoring the output as shown in Figure 16.16. The step input simulates the large signal conditions. The incapability of the opamp to follow rapidly rising and falling input is, respectively, due to the minimum charge and discharge times required by an internally connected capacitor across the output. This capacitor has a value that guarantees stable operation of the opamp down to a gain of unity. This implies that the amplifier will give a stable operation and will not get into oscillations for any gain value as unity gain happens to be the worst condition. Now if it is so, then the amplifier is said to be fully internally compensated. Opamp 741 is an example.

In the case of an uncompensated opamp, this capacitor needs to be connected externally. In that case, we have a control on the slew rate specification. We can sacrifice stability to achieve a higher slew rate. For instance, if we know that we are never going to use our opamp for a gain less than 10, we could afford to connect a smaller capacitor and thus get a higher slew rate. But all this is possible only when we decide to use an uncompensated opamp. In an internally compensated opamp also, higher slew rate versions are available that provide a large charging current internally for the compensation capacitor. Opamp 741 has a slew rate of 0.5 V/μs. Slew rates of up to 10 V/μs are usually available in general-purpose opamps. In the case of some varieties of high-speed opamps, slew rate as high as hundreds of volts per microseconds is available. EL 2444 (high-speed quad opamp from Elantec) offers a slew rate of 325 V/μs.

Slew rate limits the large signal bandwidth. Peak-to-peak output voltage swing for a sinusoidal signal ($V_{\text{p-t-p}}$), slew rate and bandwidth are interrelated by the following equation:

$$\text{Bandwidth (highest frequency, } f_{\text{MAX}}) = \text{Slew rate}/(\pi \times V_{\text{p-t-p}}) \tag{16.1}$$

Open-Loop Gain

Open-loop gain is the ratio of single-ended output to the differential input. This parameter has a great bearing on the gain accuracy specification of the opamp wired as an amplifier. The ratio of the open-loop gain to the closed-loop gain (which depends upon the application circuit) is called the loop gain. Accuracy at any given frequency depends heavily on the magnitude of the loop gain at that frequency. The magnitude of loop gain at a given frequency depends directly on the value of the open-loop gain at that frequency as the value of closed-loop gain for a given application circuit is fixed. Figure 16.17 shows the open-loop gain versus frequency curve of an

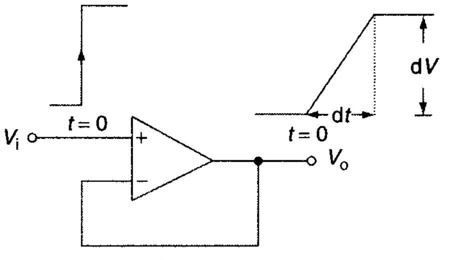


Figure 16.16 | Response to step input.

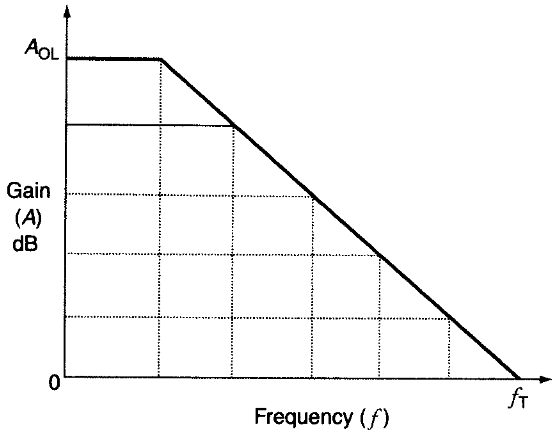


Figure 16.17 Open-loop gain versus frequency.

opamp. As a thumb rule, the gain error at any given frequency is given by the ratio of the closed-loop gain to the open-loop gain. Thus a higher open-loop gain gives a smaller error for a given closed-loop gain.

Common Mode Rejection Ratio

Common mode rejection ratio (*CMRR*) is a measure of the ability of the opamp to suppress common mode signals. It is the ratio of the desired differential gain (A_d) to the undesired common mode gain (A_c). The ratio CMRR is usually expressed as CMR given by 20 log (A_d/A_c) dB. A lower CMRR or CMR reflects in terms of larger variation in the output of a differential amplifier due to variation in the common mode input when the differential input stays put. The common mode input is the average value of the two inputs. The common mode input affects the bias point of the input differential amplifier stage. Owing to lack of perfect symmetry in the two halves of the input differential amplifier stage, change in bias point changes the offset voltage. This in turn changes the output voltage. CMRR is also defined as the ratio of the change in the common mode input to the corresponding change in the output offset voltage.

CMRR is always specified for a given input voltage range. Exceeding the input voltage range would degrade the CMRR specification. In some opamps, the input voltage range is specified separately which implies that the given value of CMRR is guaranteed over the listed input voltage range. CMRR as published in data sheet is a DC parameter. CMRR when graphed versus frequency falls with increase in frequency as shown in Figure 16.18. The graph shown in the figure is taken from data sheet of opamp 741.

Power Supply Rejection Ratio

Power supply rejection ratio (*PSRR*) is defined as the ratio of change in the power supply voltage to corresponding change in the output voltage. The mechanism that produces PSRR is the same as that is responsible for CMRR. The power supply affects the bias point of the input differential amplifier stage of the opamp. Owing to inherent mismatch in the input circuitry, changes in bias point changes the offset voltage, which in turn changes the output voltage. PSRR is also defined as the ratio of change in one of the power supply voltage to the change in the input offset voltage with the other power supply voltage held constant.

PSRR like CMRR too is a DC parameter and its value falls with increase in frequency. The parameter is particularly significant as switched mode power supplies can have noise in the frequency range of 20 kHz to 200 kHz and even higher. PSRR is almost zero at these frequencies with the result that power supply noise appears as noise at the output of the opamp. Figure 16.19 shows PSRR versus frequency graph of opamp type AD 829.

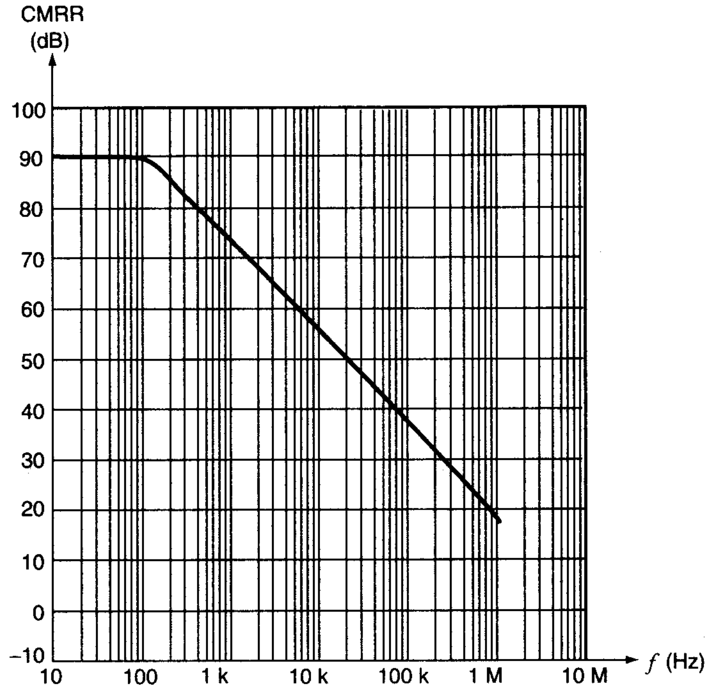


Figure 16.18 CMRR versus frequency.

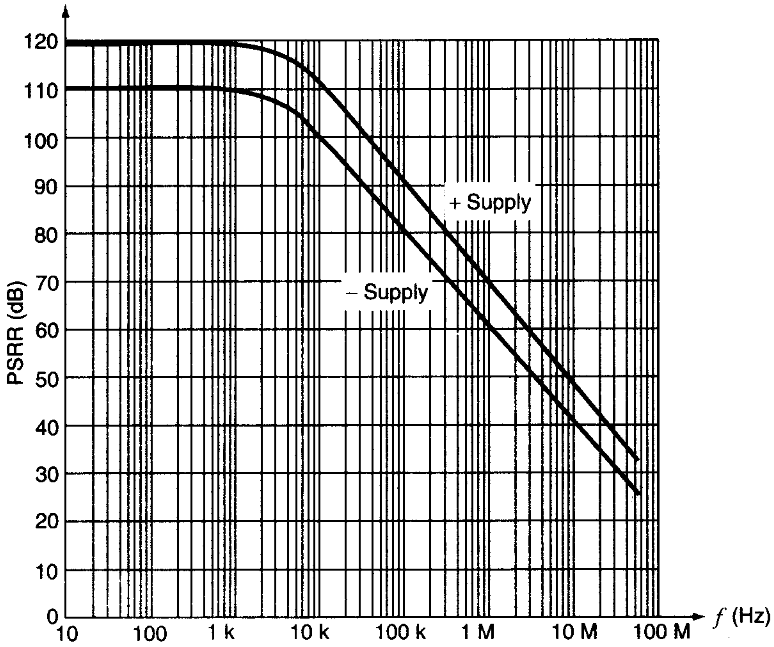


Figure 16.19 PSRR versus frequency.

Input Impedance

Input impedance is the impedance looking into the input terminals of the opamp and is mostly expressed in terms of resistance only. The effective input impedance is, however, different from what is specified in the data sheets when the opamp is used in the closed-loop mode. In the inverting amplifier configuration, the effective input impedance equals the input resistance connected externally from source of input signal to the inverting input terminal of the opamp. In the non-inverting amplifier configuration, it equals the product of loop gain and the specified opamp input impedance.

Output Impedance

Output impedance is defined as the impedance between the output terminal of the opamp and ground. Common-emitter (BJT) and common-source (FET) output stages used in rail-to-rail output opamps have higher output impedance than emitter–follower output stages. Output impedance becomes a critical parameter when using rail-to-rail output opamps to drive heavy loads. If the load were mainly resistive, it would decide how close the output can be to the rails. If the load were capacitive, the additional phase shift caused will erode the phase margin. Figure 16.20 shows the effect of output impedance on the output signal assuming that the output impedance is resistive in the case of a predominantly resistive load R_L [Figure 16.20(a)] and a capacitive load C_L [Figure 16.20(b)]. In the case of resistive load, Eq. (16.2) describes the output. Equation (16.3) gives the expression for the output in the case of capacitive load.

$$V_o = A_d \times V_d \times \left[\frac{R_L}{R_L + Z_o}\right] \tag{16.2}$$

$$V_o = A_d \times V_d \times \left[\frac{1}{j(f/f_o)+1}\right] \tag{16.3}$$

where $f_o = 1/2\pi Z_o C_L$ and Z_o is the output impedance of the opamp.

Settling Time

Settling time is a parameter specified in the case of high-speed opamps or the opamps with a high value of gain-bandwidth product. It gives the response of the opamp to large step inputs. It is expressed as the time taken by the opamp output to settle within a specified percentage of the final value (usually 0.1% or 0.01% of the final expected value) in response to a step at its input (Figure 16.21). The settling time is usually specified for opamp wired as a unity gain amplifier and it worsens for a closed-loop gain greater than 1.

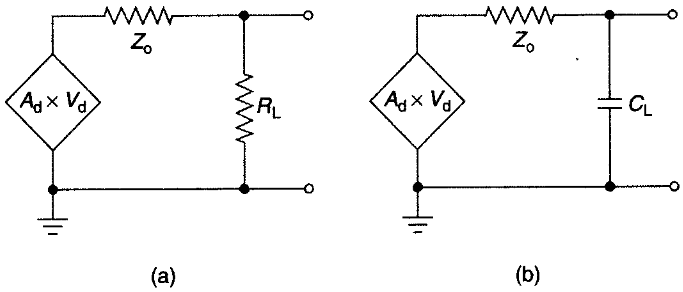


Figure 16.20 (a) Effect of resistive load R_L on output signal; (b) effect of capacitive load C_L on output signal.

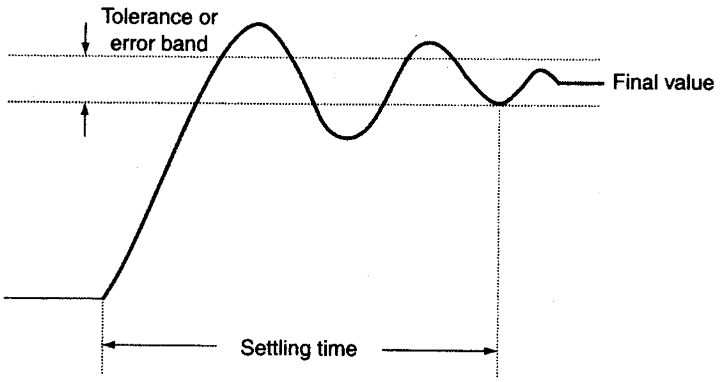


Figure 16.21 | Settling time.

Settling time is a design issue in data acquisition circuits when signals are changing rapidly. This parameter is very important when the opamp is being used as a sample-and-hold circuit at the input of an analog-to-digital converter or at the output of a high-speed digital-to-analog converter.

Offsets and Offset Drifts

Offset is a commonly used term with reference to opamps. An ideal opamp should produce a zero output for a zero differential input. But it is not so in the case of real opamps. It is observed that we need to apply a DC differential voltage externally to get a zero output. This externally applied input is referred to as the ***input offset voltage.*** This parameter may be as large as 5 mV in general-purpose opamps and as small as 200 μV in low offset opamps. The input offset voltage is often a function of power supply voltages. This variation is expressed in terms of PSRR. ***Output offset voltage*** is the voltage at the output with both the input terminals grounded. Another offset parameter is the ***input offset current.*** It is the difference between the two bias currents flowing towards the inputs of the opamp. Yet another important opamp parameter is the ***input bias current.*** It is defined as the average of the two bias currents flowing into the two input terminals of the opamp. The listed value of input and output offset voltages and input offset and bias currents tend to drift with temperature. This drift is also specified in the data sheets. Some general-purpose opamps (741 for instance) have a provision for externally nullifying the input offset voltage by usually connecting the fixed terminals of a potentiometer of a given resistance value across the designated terminals and connecting the center terminal to the negative supply voltage.

Having briefly described the key parameters in respect of different categories of opamps, the opamp selection should be no problem. Based on the circuit objectives, the first thing to be decided is the opamp category that would do the required job economically. Having made up our mind on the broad class of opamps, that is, we need a general-purpose opamp or a high-speed opamp or for that matter an instrumentation opamp, we can go through the specifications of the devices available in the chosen category to choose a device that suits our needs the best. We should give due attention to both AC as well as DC considerations. One of the major AC considerations for instance is the desired loop gain. As an example, if we wanted the opamp to yield an accuracy of 0.1% while amplifying an AC signal of 10 kHz by a gain of 10, then the opamp must have an open-loop gain of 10,000 at the operating frequency of 10 kHz. Opamp 741 will certainly not serve the purpose here. The open-loop gain for a given frequency can be verified from the gain versus frequency plot.

Similarly, slew rate must be high enough to follow the fastest changing input signal without causing distortion. It is always good as a thumb rule to choose an opamp that has a minimum slew rate of 25% larger than the fastest rate of change in the input signal.

Input offset voltage and the input bias current are the important DC considerations besides open-loop gain when it comes to choosing the right opamp in the precision category. Input bias current is particularly important when the source of input signal has relatively higher impedance. FET-input opamps or instrumentation amplifiers deserve an attention in such cases.

EXAMPLE 16.4

Opamp LM 741 is specified to have a slew rate of 0.5 V/μs. If the opamp were used as an amplifier and the expected peak output voltage were 10 V, determine the highest sinusoidal frequency that would get satisfactorily amplified.

Solution

1. Highest sinusoidal frequency f_{MAX} that would get satisfactorily amplified is given by f_{MAX} = Slew rate/$2\pi V_P$, where V_P is the expected peak output voltage.
2. In the present case, slew rate = 0.5 V/μs and $V_P = 10$ V.
3. Therefore, $f_{MAX} = (0.5 \times 10^6)/(2\pi \times 10) = 7.96$ kHz.

EXAMPLE 16.5

The differential voltage gain and CMRR of an opamp when expressed in decibels are 110 dB and 100 dB, respectively. Determine the common mode gain expressed as a ratio.

Solution

1. CMRR (in dB) = 20 log (A_d/A_{CM}) where A_d and A_{CM} are, respectively, the differential and common mode gain values.
2. CMRR (in dB) = 20 log A_d − 20 log A_{CM}.
3. That is, 20 log A_{CM} = 20 log A_d − CMRR = 110 − 100 = 10 dB.
4. This gives log A_{CM} = 10/20 = 0.5
5. Therefore, A_{CM} = Antilog 0.5 = 3.16

EXAMPLE 16.6

In the case of a certain opamp, 0.5 V change in common mode input causes a DC output offset change of 5 μV. Determine CMRR in dB.

Solution

1. CMRR = $\Delta V_{CM}/\Delta V_{OS} = 0.5/(5 \times 10^{-6}) = 10^5$.
2. CMRR in dB = 20 log 10^5 = 100 dB.

16.5 Types of Opamps

Opamps can be categorized on the basis of the performance specifications and consequently their application area and also on the basis of their internal structure as general-purpose opamps, high-speed and high-bandwidth opamps, precision opamps, power opamps, instrumentation opamps, Norton opamps (also known as current differencing opamps), opamp comparators and isolation opamps and so on and so forth.

General-Purpose Opamps

The term general-purpose opamp is generally used with reference to that category of opamps which has moderate or say reasonably good values for all the key parameters. In the case of general-purpose opamps, none of the major specifications as outlined earlier can be said to be exceptionally good or state-of-the-art and also none of the specifications is extremely poor. Within the broad category of general-purpose opamps, some type numbers may have slightly better overall performance specifications and thus called as high-performance general-purpose opamps. A general-purpose opamp of the type 741 may have an open-loop gain of typically 10^4–10^5, input impedance of 0.5–1 MΩ, output impedance of 50–100 Ω, CMRR of the order of 70–100 dB, output offset voltage of the order of a few milli-volts and an open-loop bandwidth in the range of 1 MHz. Those general-purpose opamps that have a JFET-based input differential amplifier stage have relatively much larger input impedance (typically 10^{12} Ω) and much better noise specifications. Hence, general-purpose opamps due to overall good performance specifications are used in a wide range of applications in low cost designs.

JEFT-input opamps are preferred in applications where high-input impedance and low noise are the main considerations.

High-Speed Opamps

High-speed opamps have high slew rate and bandwidth specifications. Today opamps with slew rate in hundreds of volts per microsecond and bandwidth in hundreds of MHz are commercially available. As an illustration, opamp type AD 829 from Analog Devices has slew rate and unity gain small-signal bandwidth specifications of 230 V/µs and 600 MHz, respectively. EL 2444 from Elantec is yet another high-speed opamp. It is a quad opamp with slew rate and unity gain small-signal bandwidth specifications of 325 V/µs and 60 MHz, respectively.

Precision Opamps

Precision opamps have extremely low offsets and a very high value of open-loop differential gain. The output offset voltage in such opamps may be of the order of several tens of microvolts. The open-loop gain approaches 120 dB.

Power Opamps

In power opamps, the power supply voltages and consequently the output voltage swing are no longer limited to ±18 V or so. These opamps have supply voltage rating of the order of several hundred volts and current delivering capability of the order of several amperes. However, these devices are very expensive and are manufactured by a few select manufacturers internationally.

Opamps Comparators

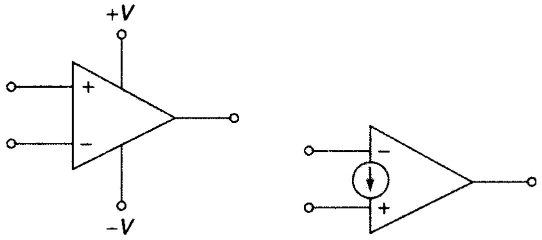
These are opamps specially designed for use in comparator applications. They have much faster response time (typically from a few nanoseconds to several tens of nanoseconds) than that of a conventional general purpose opamp (typically of the order of 1 µs). Comparator, in which one of the inputs is normally a reference voltage, switches between two states at the output depending upon whether the other input is higher or lower than the reference. In the case of general-purpose opamps being used as comparators, the output switches between two levels that are fixed and depends upon the supply voltages. These levels may not be compatible with the load requirement which in most of the applications is a logic circuit. In other words, the comparator output should be compatible to a certain logic family like TTL or CMOS. The response time and the output compatibility happen to be the two most important specifications in the case of opamp comparators. A comparator forms the basic building block in circuits like zero crossing detectors, level detectors, Schmitt triggers, square and triangle waveform generators.

Norton Opamps

A Norton opamp also known as the current differencing opamp differs from a conventional opamp in its internal circuit design. While in a conventional opamp, the input stage is a differential amplifier to achieve inverting and non-inverting input functions, in the case of a Norton opamp, the non-inverting input function is derived from the inverting input function by using a current mirror configuration. The non-inverting input current is derived from the one entering at the inverting input. While we talk about differential input voltage in the case of a conventional opamp, it is differential input current in the case of a Norton opamp. Single supply operation and the fact that most of the general-purpose opamp applications can be realized without significantly sacrificing performance characteristics coupled with low cost per opamp make Norton opamp a very attractive choice. A Norton opamp has a definite edge over a general-purpose opamp (of 741 types) in single supply operation. When a general-purpose opamp is used on a single supply, the minimum input voltage that can be applied while ensuring that the opamp responds to a differential input is limited by the minimum common mode input range (typically +2 V in general-purpose opamps). This is rather large. In addition, general-purpose opamps when used on single supply have poorer output voltage swing. Norton opamps have no such limitations. A Norton opamp is represented in a circuit by the circuit symbol of Figure 16.22(b). The conventional opamp is represented by the circuit symbol of Figure 16.22(a).

Instrumentation Opamps

An instrumentation opamp is a differential amplifier with a very high value of input impedance, very large CMRR and extremely low values of offsets and offset drifts. Like an opamp of the type described in the earlier paragraphs, it is differential input single-ended output gain block. Gain in an instrumentation opamp, if we so call it, is usually set with a single resistor whereas in a conventional opamp, the same in achieved with the help of two resistors. Instrumentation opamps are available in single IC packages. Figure 16.23 shows the circuit representation of an instrumentation opamp. Typical internal schematic of such a device is shown in Figure 16.24. As is clear from the schematic arrangement of Figure 16.24, it is a combination of three opamps. The output opamp has been wired as a differential amplifier with its non-inverting and inverting inputs fed from the outputs of the other two opamps wired as non-inverting amplifiers. The gain setting resistor (R_{gain}) is connected external to the device. Thus the two major problems in a conventional



(a) (b)

Figure 16.22 | Circuit representation: (a) Conventional opamp; (b) Norton opamp.

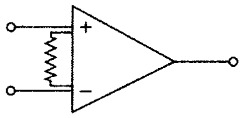


Figure 16.23 | Circuit representation of an instrumentation opamp.

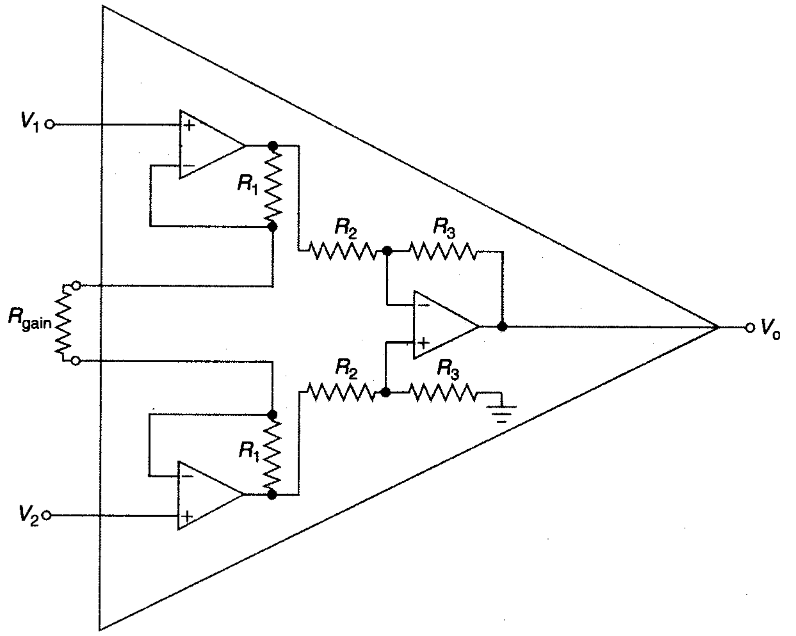


Figure 16.24 | Internal schematic of an instrumentation opamp.

opamp, namely, the low effective input impedance loading on to the signal source with comparatively high value of output impedance and the gain setting requiring simultaneous adjustment of two resistors leading to inaccuracies are overcome.

The essential characteristics of instrumentation opamps as outlined above make them very useful in amplifying low-level differential signals with high value of common mode content. Transducers such as thermocouples, biological probes, strain gauge bridges and current shunts produce small differential signals superimposed on common mode bias voltages. Instrumentation opamp is an excellent choice in such cases for meaningful acquisition and analysis of data in addition to its use in applications requiring a precision high quality differential amplifier. Some of these applications are discussed in chapter-17 on opamp application circuits.

Isolation Opamps

An isolation opamp is again a differential input, single-ended output amplifier with its output electrically isolated from the input. Isolation impedances as high as 10^{12} Ω and isolation voltages of about 1000 V are common. The differential amplifier in an isolation opamp may be an ordinary differential amplifier or an instrumentation amplifier. Figure 16.25 shows the circuit symbol of an isolation opamp. There are transformer-coupled isolation opamps [Figure 16.26(a)] mainly used in applications where linearity, gain accuracy, etc. are important and there optically coupled isolation opamps [Figure 16.26(b)] used in applications where speed and bandwidth are important.

Isolation opamps are used for those applications where electrical isolation between the source and the output is desirable. For instance, in medical instrumentation where the transducer or sensor is in physical contact with the patient, isolation opamp is an excellent interface between the transducer and the equipment (Figure 16.27). The isolation opamp provides a floating input for the signal source output and need for source ground connections is completely eliminated.

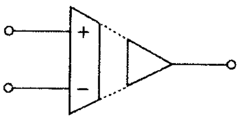
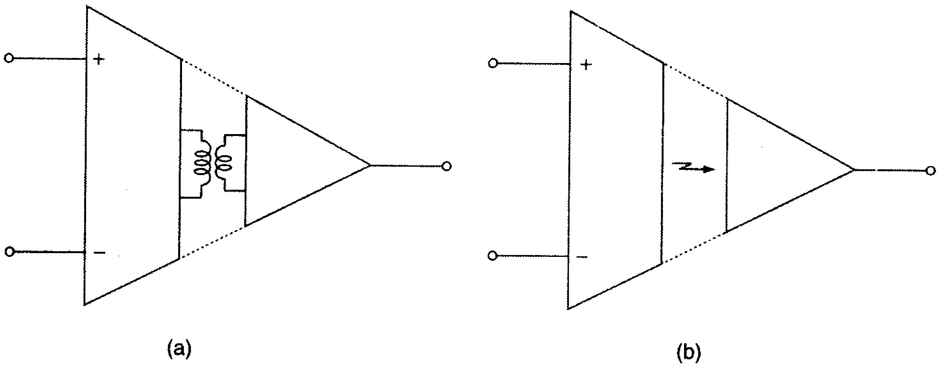


Figure 16.25 | Circuit symbol of an isolation opamp.



(a) (b)

Figure 16.26 | (a) Transformer coupled isolation opamp; (b) optically coupled isolation opamp.

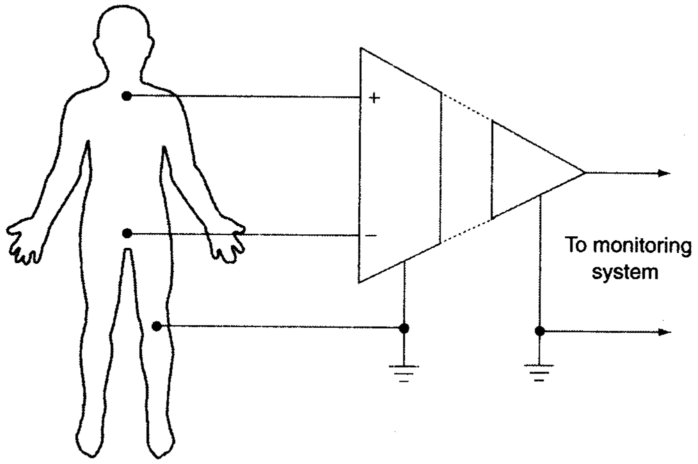


Figure 16.27 | Isolation opamp used in medical instrumentation.

KEY TERMS

Bandwidth
Common mode rejection ratio
Fully internally compensated opamp
General-purpose opamp
High-speed opamp
Ideal opamp
Input bias current
Input impedance
Input offset current
Input offset voltage
Instrumentation opamp
Isolation opamp
Loop gain
Norton opamp

Opamp
Opamp comparator
Open-loop gain
Output impedance
Output offset voltage
Power opamp
Precision opamp
Power supply rejection ratio
Settling time
Slew rate
Uncompensated opamp

OBJECTIVE-TYPE EXERCISES

Multiple-Choice Questions

1. An opamp can amplify
   - **a.** DC signals only
   - **b.** AC signals only
   - **c.** both AC as well as DC signals
   - **d.** neither DC nor AC signals
2. Which of the following statements describes an opamp the best?
   - **a.** It is a differential amplifier.
   - **b.** It is a large bandwidth amplifier.
   - **c.** It is direct-coupled amplifier.
   - **d.** It is a direct-coupled high-gain differential amplifier.
3. The input stage of an opamp in most of the cases is a
   - **a.** high-gain common-emitter amplifier
   - **b.** differential amplifier
   - **c.** emitter–follower buffer
   - **d.** none of these
4. The common mode rejection ratio is
   - **a.** same as the common mode gain
   - **b.** ratio of common mode gain to differential gain
   - **c.** ratio of differential gain to common mode gain
   - **d.** ratio of output DC offset voltage to change in common mode input
5. The input offset current is
   - **a.** zero
   - **b.** less than input bias current
   - **c.** more than input bias current
   - **d.** none of these
6. One of the following opamp parameters limits the large signal bandwidth.
   - **a.** Slew rate
   - **b.** CMRR
   - **c.** Settling time
   - **d.** Unity gain bandwidth
7. The frequency response of an opamp shows the cut-off frequency to be equal to 100 Hz. If the mid-band voltage gain is 100 dB, then the unity gain cross-over frequency will be
   - **a.** 1.0 MHz
   - **b.** 100 MHz
   - **c.** 10 MHz
   - **d.** indeterminate from given data
8. An opamp has open-loop gain and unity gain bandwidth specifications of 120 dB and 10 MHz, respectively. The open-loop cut-off frequency will be
   - **a.** 10 Hz
   - **b.** 100 Hz
   - **c.** 1000 Hz
   - **d.** 1 Hz
9. The compensating capacitor connected externally in the case of uncompensated opamps is to
   - **a.** increase large signal bandwidth
   - **b.** prevent oscillations
   - **c.** improve slew rate
   - **d.** increase CMRR
10. Identify the opamp type in which the output stage is designed to be compatible with some logic family.
    - **a.** Opamp comparator
    - **b.** High speed opamp
    - **c.** Isolation opamp
    - **d.** Instrumentation opamp
11. Which of the following opamp internally comprises three opamps out of which two are wired as buffers and the third is a difference amplifier?

a. Isolation opamp
b. Norton opamp
c. Instrumentation opamp
d. Opamp comparator

12. In which of the following opamp types, the input stage is not a conventional differential amplifier.
a. Norton opamp
b. Instrumentation opamp
c. Opamp comparator
d. Isolation opamp

13. Which of the following opamp types is ideally suited to single supply operation?
a. High bandwidth opamp
b. Instrumentation opamp
c. Norton opamp
d. General-purpose opamp

14. In the front-end differential amplifier inside an opamp, the tail resistor is usually replaced by
a. emitter–follower configuration
b. current mirror configuration
c. common-emitter amplifier configuration
d. a junction diode

15. In the internal circuit of an opamp, collector resistors are usually replaced by active loads to
a. increase differential gain
b. decrease common mode gain
c. increase bandwidth
d. increase efficiency

REVIEW QUESTIONS

1. What is an operational amplifier? How does it differ from common-emitter amplifier constructed using discrete components?

2. How would you characterize an ideal opamp? How does a practical opamp differ from an ideal opamp? Use Thevenin's equivalent circuit model to compare an ideal opamp with a practical opamp.

3. What is primarily responsible for giving an opamp the following characteristics?
a. High input impedance
b. Low output impedance
c. High open-loop gain
d. High common mode rejection ratio
e. Frequency response down to DC

4. Briefly describe the reasons for the following:
a. Why it is not possible to have an infinite CMRR?
b. Why internally compensated opamps have relatively lower slew rate?

5. Briefly describe the following opamp parameters with particular reference to their criticality for a given application circuit.
a. Slew rate
b. Open-loop gain
c. Settling time
d. Common mode rejection ratio

6. Briefly describe the following types of opamps with reference to major performance parameters.
a. High-speed opamps
b. Instrumentation opamps
c. Opamp comparators
d. General-purpose opamps

PROBLEMS

1. Refer to the differential amplifier circuit of Figure 16.28. Determine the quiescent DC voltage at the collector terminal of each transistor assuming V_{BE} of the two transistors to be equal to 0.7 V?

2. If the transistors used in the differential amplifier circuit of Figure 16.28 have $h_{ie} = 1\ k\Omega$ and $h_{fe} = 50$, determine the differential voltage gain.

3. Refer to the differential amplifier circuit of Figure 16.29. Determine the tail current I_T and also the quiescent DC voltage across the output. Assume V_{BE} of the transistors to be 0.7 V.

4. Opamp LF 356 is specified to have a slew rate of 5.0 V/μs. If the opamp were used as an amplifier and the expected peak output voltage were 12 V, determine the large signal bandwidth.

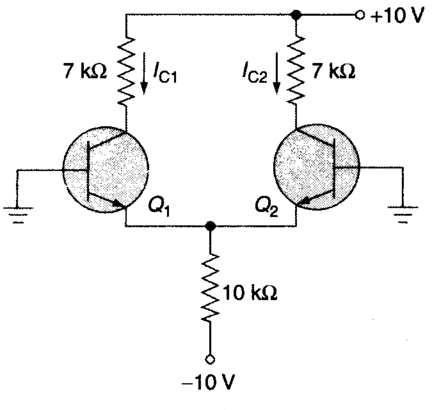


Figure 16.28 | Problem 1.

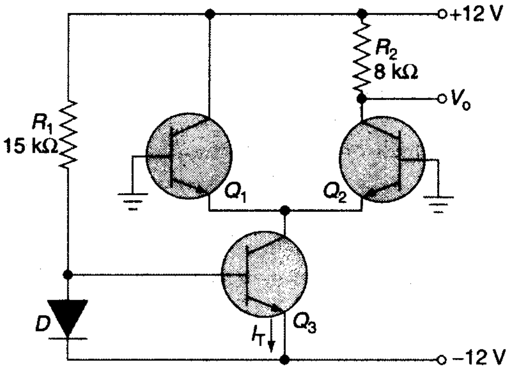


Figure 16.29 | Problem 3.

5. The differential voltage gain and CMRR of an opamp when expressed in decibels are 120 dB and 100 dB, respectively. Determine the common mode gain expressed as a ratio.

6. In the case of a certain opamp, 1.0 V change in common mode input causes a DC output offset change of 1.0 μV. Determine CMRR in dB.

7. The frequency response of an opamp shows the cut-off frequency to be equal to 10 Hz. If the mid-band voltage gain is 120 dB, determine the frequency at which the closed-loop gain will be unity.

ANSWERS

Multiple-Choice Questions

1. (c)
2. (d)
3. (b)
4. (c)
5. (b)
6. (a)
7. (c)
8. (a)
9. (b)
10. (a)
11. (c)
12. (a)
13. (c)
14. (b)
15. (a)

Problems

1. 6.745 V
2. 350
3. 1.55 mA, 5.8 V
4. 66.3 kHz
5. 10
6. 120 dB
7. 10 MHz

CHAPTER

17

Operational Amplifier Application Circuits

Learning Objectives

After completing this chapter, you will learn the following:

- Basic inverting and non-inverting amplifier configurations.
- Summing amplifier.
- Voltage follower circuit.
- Adder and subtractor circuits.
- Integrator and differentiator circuits.
- Rectifier circuits.
- Clipping and clamping circuits.
- Peak detector.
- Absolute value circuits.
- Comparator circuits.
- Active filters.
- Phase shifter circuits.
- Instrumentation amplifiers.
- Logarithmic amplifiers.
- Relaxation oscillators.
- Current-to-voltage and voltage-to-current converters.
- Sine wave oscillator circuits.

Fundamentals of operational amplifiers (opamps) in terms of internal architecture, characteristic parameters and types were discussed in detail in Chapter 16. The present chapter covers a large number of application circuits using opamps. As outlined in the previous chapter, an opamp fits into almost every conceivable circuit application due to its high differential gain, high input impedance, low output impedance, large bandwidth and many other desirable features. Application spectrum of opamps ranges from amplifiers to oscillators, computational building blocks (adder and subtractor circuits) to data conversion circuits (current-to-voltage, voltage-to-current, frequency-to-voltage, voltage-to-frequency, analog-to-digital and digital-to-analog converters), rectifiers to power supply regulators (linear and switching regulators), active filters, integrators and differentiators and so on. It is not possible to cover each and every conceivable circuit application in this chapter. However, almost all common applications of opamps are included in the chapter with particular emphasis on design equations governing different application circuits. Large number of solved examples are also included to illustrate the concepts discussed in the text.

17.1 Inverting Amplifier

An inverting amplifier is the one which in addition to changing the amplitude of the signal, changes the polarity of the input signal in the case of DC input and reverses the phase of the input signal in the case of AC input. Figure 17.1 shows the basic circuit diagram of an inverting amplifier configured around an opamp. It may be mentioned here that the power supply connections are not shown in the figures. It may be assumed that the opamps are given positive and negative supply connections as described in Chapter 16 unless otherwise stated. The circuit functions as follows. Assuming that the current flowing towards the negative opamp input terminal is zero, as would be the case for an ideal opamp, current flowing through input resistor R_1 is the same as the current flowing through the feedback resistor R_2. Owing to ground at (+ve) input, the R_1–R_2 junction is also at ground potential due to virtual earth phenomenon in opamps. Virtual earth with reference to opamps implies that there is a zero potential difference between the inverting and non-inverting input terminals. The concept of virtual earth has its origin in the infinite open-loop voltage gain of an ideal opamp, which further means that for a finite output, the differential input must be zero. Though virtual earth is valid for ideal opamps, the assumption yields very accurate results for opamps configured with heavy negative feedback. The expression for gain is derived as follows:

$$I = \frac{V_i}{R_1} = -\frac{V_o}{R_2} \tag{17.1}$$

So that

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \tag{17.2}$$

Hence, closed-loop voltage gain (A_{CL}) is given by

$$A_{CL} = -\left(\frac{R_2}{R_1}\right) \tag{17.3}$$

Minus sign indicates that output is the phase-inverted version of input. By selecting proper values of R_1 and R_2 desired magnitude of gain can be achieved.

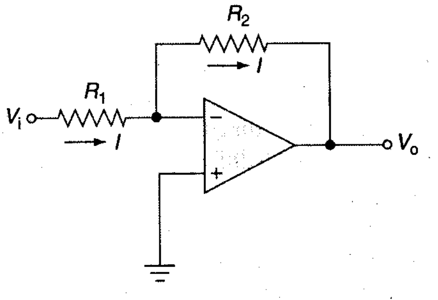


Figure 17.1 | Inverting amplifier.

Design Information

The inverting amplifier of Figure 17.1 has effective input impedance equal to R_1 as it comes in parallel with the high differential input impedance of the opamp. For a given value of closed-loop gain, higher the value of desired input impedance, higher is the value of resistor R_1, which in turn leads to a higher value of R_2. There is always an upper limit to the value of R_2 that can be connected for a given opamp. In fact, higher the input impedance of the opamp, larger is the maximum allowable value of R_2. In fact, the problem starts when the current flowing towards the negative input terminal of the opamp becomes comparable to the current (I). Things will be clearer if we look at the actual expression for gain that we would have arrived at if we had not made any assumptions.

The actual expression for the closed-loop gain A_{CL} for the amplifier circuit of Figure 17.1 is given by

$$A_{\mathrm{CL}} = -\frac{A_{\mathrm{OL}}R_2}{R_1 + R_2 + A_{\mathrm{OL}}R_1} \cong -\frac{R_2}{R_1 + (R_2/A_{\mathrm{OL}})} \tag{17.4}$$

where A_{OL} is the open-loop gain of the opamp. This implies that when ratio R_2/A_{OL} is much smaller than R_1, the gain expression reduces to the expression of Eq. (17.3).

The input impedance of this circuit is same as the input resistance value, R_1. The output impedance of this circuit is approximated as

$$R_{\mathrm{o}} = \left[\frac{R_1 + R_2}{R_1 A_{\mathrm{OL}}}\right] R_{\mathrm{OL}} \tag{17.5}$$

where R_{OL} is the open-loop output impedance of the opamp.

If the inverting amplifier of Figure 17.1 is needed to amplify AC signals only, the circuit may be modified to include coupling capacitors in series with input and output as shown in Figure 17.2. The frequency response of this amplifier does not extend down to zero. Coupling capacitors give a lower cut-off frequency depending upon the values of R_1 and C_1 on the input side and R_{L} and C_2 on the output side. R_{L} is the load resistance and is not shown in the figure. The lower cut-off frequency may be taken to be equal to higher of the two values. The two cut-off frequencies are given by Eqs. (17.6) and (17.7):

$$f_{\mathrm{CL1}} = \frac{1}{2\pi R_1 C_1} \tag{17.6}$$

$$f_{\mathrm{CL2}} = \frac{1}{2\pi R_{\mathrm{L}} C_2} \tag{17.7}$$

Closed-loop bandwidth or upper cut-off frequency (f_{CU}) is given by Eq. (17.8).

$$f_{\mathrm{CU}} = \text{Unity gain cross-over frequency of the opamp}/A_{\mathrm{CL}} \tag{17.8}$$

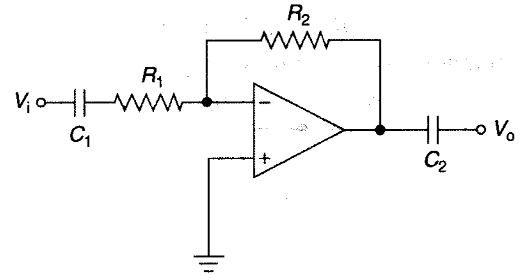


Figure 17.2 | Inverting amplifier for AC applications.

17.2 Non-Inverting Amplifier

Figure 17.3 shows an opamp-based non-inverting amplifier for DC applications. The expression for gain is derived as follows.

For the amplifier shown in Figure 17.3, due to virtual earth, the voltage of R_1–R_2 junction equals V_i. Also assuming that current flowing towards negative input terminal of the opamp is zero, we can write

$$I = \frac{V_i}{R_1} = \frac{V_o}{R_1 + R_2}$$

So that

$$\frac{V_o}{V_i} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

Hence, closed-loop voltage gain (A_{CL}) is

$$A_{CL} = 1 + \frac{R_2}{R_1} \tag{17.9}$$

Design Information

The actual gain expression in the case of an opamp-based non-inverting amplifier is given by

$$A_{CL} = \frac{A_{OL}(R_1 + R_2)}{R_1 + R_2 + A_{OL}R_1} \tag{17.10}$$

Equation (17.10) reduces to

$$\frac{R_1 + R_2}{R_1 + (R_2 / A_{OL})}$$

for $A_{OL} >> 1$. Again if $R_2/A_{OL} << R_1$, the expression reduces to the expression of Eq. (17.9).

The input impedance (R_i) of this configuration is given by

$$R_i = R_{IL} A_{OL}\left(\frac{R_1}{R_1 + R_2}\right) \tag{17.11}$$

$$= R_{IL} \times \text{Loop gain}$$

where R_{IL} is the open-loop input impedance of the opamp; loop gain is given by the ratio of open-loop gain to the closed-loop gain (i.e., A_{OL}/A_{CL}).

The output impedance (R_o) can be computed from the following equation:

$$R_o = R_{OL}/\text{Loop gain} \tag{17.12}$$

where R_{OL} is the open-loop output impedance of the opamp.

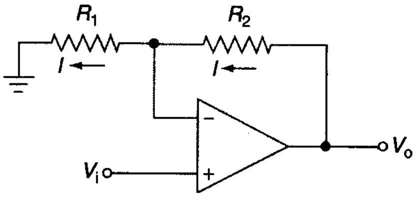


Figure 17.3 Non-inverting amplifier.

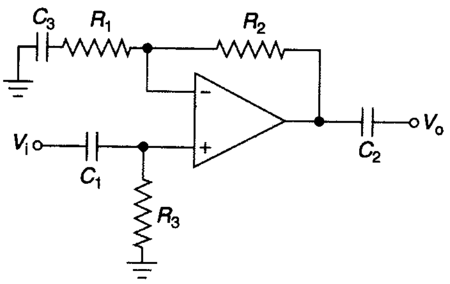


Figure 17.4 | Non-inverting amplifier for AC signals.

In case the non-inverting amplifier of Figure 17.3 is needed to amplify AC signals only, the circuit may be modified to include coupling capacitors C_1 and C_2 in series with input and output, respectively, and a bypass capacitor C_3 as shown in Figure 17.4. Coupling capacitors give a lower cut-off frequency depending upon the values of R_3 and C_1 on the input side and R_L and C_2 on the output side. R_L is the load resistance and is not shown in the figure. The two cut-off frequencies are given by the following equations:

$$f_{CL1} = \frac{1}{2\pi R_3 C_1} \tag{17.13}$$

$$f_{CL2} = \frac{1}{2\pi R_L C_2} \tag{17.14}$$

The bypass capacitor produces a lower cut-off frequency given by

$$f_{CL3} = \frac{1}{2\pi R_1 C_3} \tag{17.15}$$

The lower cut-off frequency may be taken as the highest of the three values. The upper cut-off frequency or the closed-loop bandwidth is given by the ratio of unity gain cross-over frequency of the opamp to the closed-loop gain.

17.3 Voltage Follower

Voltage follower is nothing but a non-inverting amplifier circuit with unity gain. Figure 17.5 shows the basic voltage-follower circuit. If we compare the voltage-follower circuit with the basic circuit arrangement of a non-inverting amplifier as shown in Figure 17.3, we find that $R_1 = \infty$ and $R_2 = 0$. Substituting these values in the expression for gain, we get $A_{CL} = 1$. In the circuit shown, there is 100% negative feedback from output to input. The negative feedback is of voltage-series type. This leads to increase in input impedance and decrease in output impedance by a large factor, approximately equal to open-loop gain A_{OL}.

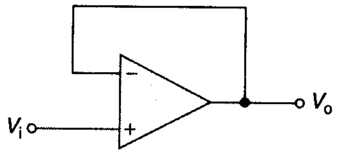


Figure 17.5 | DC voltage-follower circuit.

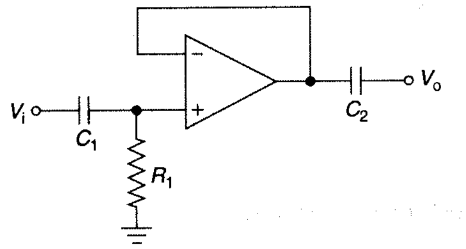


Figure 17.6 | Voltage follower for AC applications.

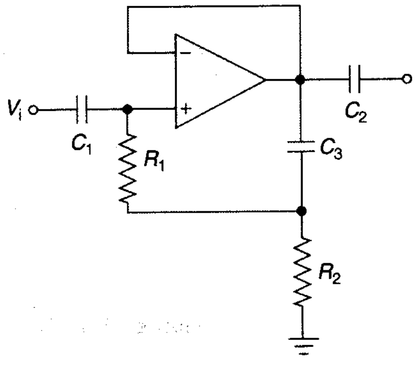


Figure 17.7 | Modified voltage follower for AC applications.

For AC applications, the input is applied through a capacitor C_1 and another capacitor C_2 is put in series with the output lead. These capacitors are meant for blocking the DC. The circuit is shown in Figure 17.6. Resistor R_1 provides a discharge path for capacitor C_1 and hence offers DC stability. The disadvantage of using resistor R_1 is that the input impedance of the voltage-follower configuration reduces practically to R_1, thus losing one of the key advantages of the voltage-follower configuration of high input impedance.

This is overcome in the circuit arrangement of Figure 17.7. For AC signals, capacitor C_3 is almost a short circuit. This means that signal amplitude on both ends of resistor R_1 is the same, resulting in practically zero current through it. This in turn implies very large input impedance due to near infinite effective value of R_1.

Voltage-follower circuit has many advantages. Owing to its extremely high input impedance, extremely low output impedance and unity gain; it acts as an ideal interface between a high impedance source and a low impedance load. Also, unity closed-loop gain leads to a very high closed-loop bandwidth equal to the unity gain cross-over frequency of the opamp. The output offset error is also very low because due to unity closed-loop gain, input errors are not amplified.

EXAMPLE 17.1

Design an inverting amplifier using an opamp. The amplifier should have a voltage gain of 10 and an input impedance not less than 10 kΩ. If the input signal, which is a sinusoidal one, has a peak amplitude varying from 100 to 300 mV, determine the maximum possible input signal frequency that would be faithfully amplified. The chosen opamp has slew rate of 0.5 V/μs.

Solution

1. Figure 17.8 shows the circuit diagram. The gain of this amplifier is $-(R_2/R_1)$ and its input impedance is approximately R_1.

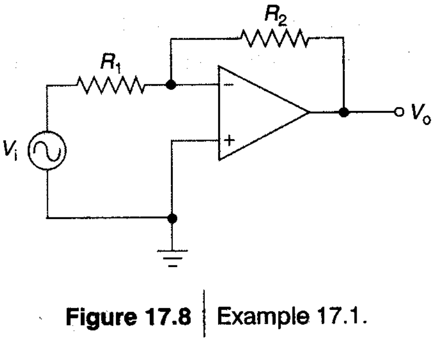


Figure 17.8 | Example 17.1.

2. Since the input impedance of the amplifier is not to be less than 10 kΩ, we can safely choose $R_1 = 10$ kΩ.
3. Therefore, $R_2 = 10 \times 10 \times 10^3 = 100$ kΩ.
4. The largest input signal amplitude = 300 mV.
5. Corresponding output signal = $300 \times 10^{-3} \times 10 = 3000$ mV = 3 V.
6. Highest sine wave frequency that would be faithfully amplified is given by f_{MAX} = Slew rate/$2\pi V_{o(max)}$.
7. Solving this equation, we get $f_{MAX} = 26.5$ kHz.

EXAMPLE 17.2

Design an opamp based non-inverting amplifier having a voltage gain of 11. Determine the input impedance of this amplifier if the chosen opamp has an open-loop gain of 100,000 and open-loop input impedance of 1 MΩ.

Solution

1. Figure 17.9 shows the basic non-inverting amplifier circuit.
2. Voltage gain of this amplifier is given by $[1 + (R_2/R_1)]$.
3. Therefore, $1 + R_2/R_1 = 11$. This gives $R_2/R_1 = 10$.
4. Let us choose $R_1 = 10$ kΩ. This gives $R_2 = 100$ kΩ.
5. Input impedance of this amplifier = Open-loop input impedance × Loop gain.
6. Loop gain = Open-loop gain/Closed-loop gain = 100,000/11 = 9090.91.
7. Therefore, input impedance = $1 \times 10^6 \times 9090.91 = 9090.91$ MΩ.

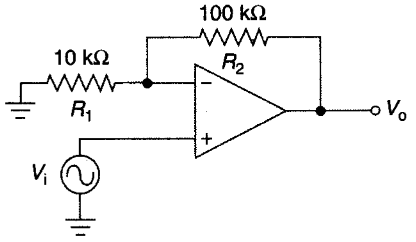


Figure 17.9 | Example 17.2.

EXAMPLE 17.3

Refer to the inverting amplifier circuit of Figure 17.10. Determine the voltage gain of the circuit when the voltage applied to the gate of junction FET is (a) 0 V and (b) −5 V given that JFET has $r_d = 500$ Ω and $V_{GS(OFF)} = -5$ V.

Solution

1. When $V_{GS} = 0$, JFET is conducting and its $r_d = 500$ Ω. Since the externally connected drain resistance is much larger than r_d, the non-inverting terminal is grounded for all practical purposes. Therefore, voltage gain = $(-100 \times 10^3)/(100 \times 10^3) = -1$.

2. When $V_{GS} = -5$ V, JFET is in cut-off state. The circuit in this case acts both like a non-inverting amplifier and an inverting amplifier simultaneously. Non-inverting voltage gain is $1 + (100 \times 10^3)/(100 \times 10^3) = 2$ and inverting voltage gain is $(-100 \times 10^3)/(100 \times 10^3) = -1$. This gives an overall voltage gain of 1.

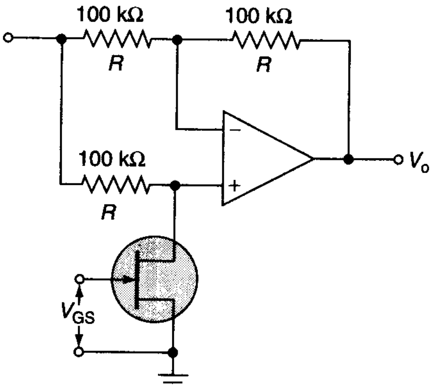


Figure 17.10 | Example 17.3.

EXAMPLE 17.4

Refer to the amplifier circuit of Figure 17.11. Determine the voltage gain of the amplifier when the variable terminal of the potentiometer is at (a) point A and (b) point B.

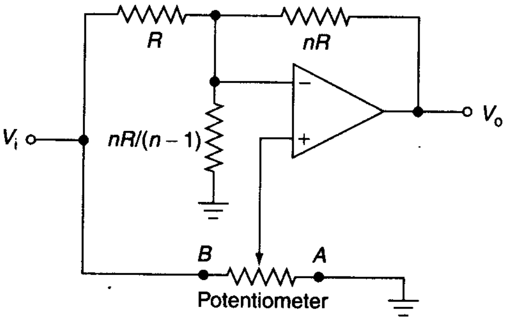


Figure 17.11 | Example 17.4.

Solution

1. When the variable terminal of the potentiometer is at A, the non-inverting terminal is grounded. The amplifier is a simple inverting amplifier with a voltage gain of $-(nR/R) = -n$.
2. When the variable terminal of the potentiometer is at B, the opamp acts both like a non-inverting and an inverting amplifier. Voltage gain in this condition is equal to a non-inverting voltage gain of

$$1+\frac{nR(2n-1)}{nR}=2n$$

and an inverting voltage gain of $-nR/R = -n$. Net voltage gain in this condition is therefore equal to $2n - n = n$.

EXAMPLE 17.5

Refer to the voltage-follower circuit of Figure 17.12. Determine (a) no load output voltage, (b) bandwidth and (c) closed-loop output impedance if the voltage observed across the load of 10 Ω were 99.5 mV. The opamp used has a unity gain cross-over frequency of 1 MHz.