EEE 1231

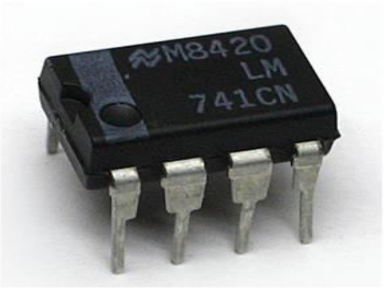
Electronic Devices and Circuits

Lecture-8

Operational Amplifier
(Op-Amp)

Operational Amplifier

- An operational amplifier (or an op-amp) is an integrated circuit (IC) that operates as a voltage amplifier. It is a differential amplifier that amplifies the difference of voltages applied to its two input terminals (differential input), and provides a single ended output.
- These amplifiers are called "operation" amplifiers because they were initially designed as an effective device for performing arithmetic operations in an analog circuit. The op-amp has many other applications in signal processing, measurement, and instrumentation.



Symbol & Terminals

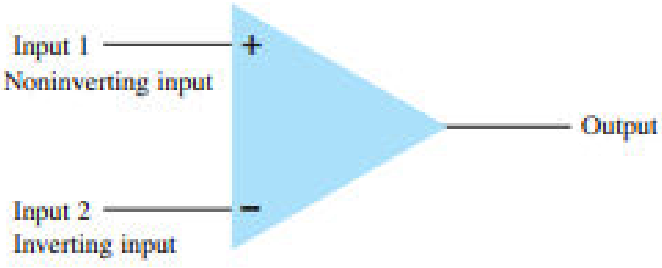


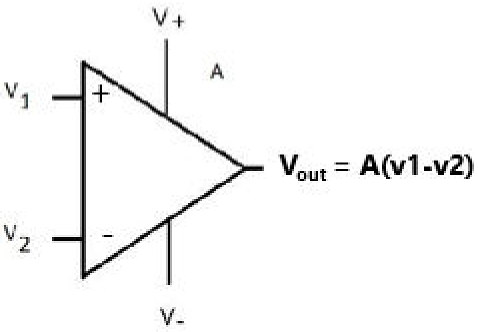
FIG. 10.1
Basic op-amp.

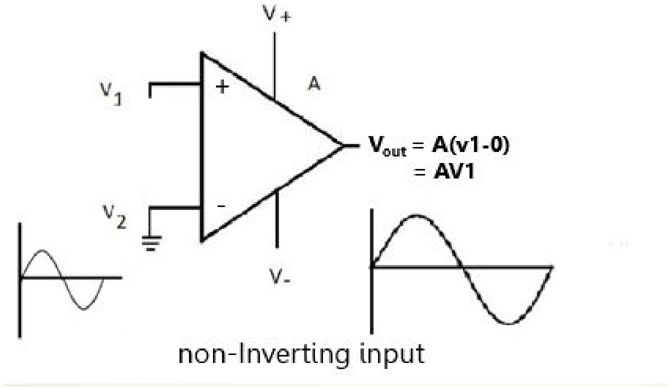
Op-Amp terminals

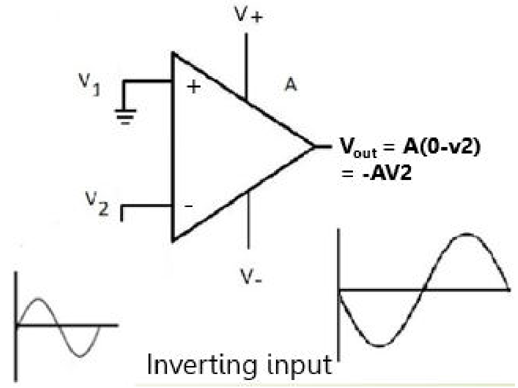
An OP-AMP has a two input terminal, one **output terminal** and two **supply voltage** terminals.

- The input terminal marked with negative (-) sign is called as an **inverting terminal** .If we connect the input signal to this terminal then the amplified output signal is 180° out of phase with respect to input.
- The input terminal marked with positive (+) sign is called as **Non-Inverting terminal**. If the input is applied to this pin then the amplified output is in phase with the input.
- $+V_s$ (positive supply) & $-V_s$ (Negative supply) are power supply or biasing voltage.
- Offset null is used to nullify the offset voltage and pin no 8 is dummy pin.

Inverting & Non-Inverting input







Op-Amp Application

1. Several operation
    - Addition
    - Subtraction
    - Integration
    - differentiation etc.
2. Active filter
3. Oscillator
4. Waveform convertor
5. ADC & DAC convertors
6. Voltage follower
7. Voltage comparator

Op-Amp voltage transfer characteristics

- The graph that relates the output voltage to the input voltage is called the voltage transfer curve and is fundamental in designing and understanding amplifier circuits.
- The voltage transfer curve of the op-amp is shown below

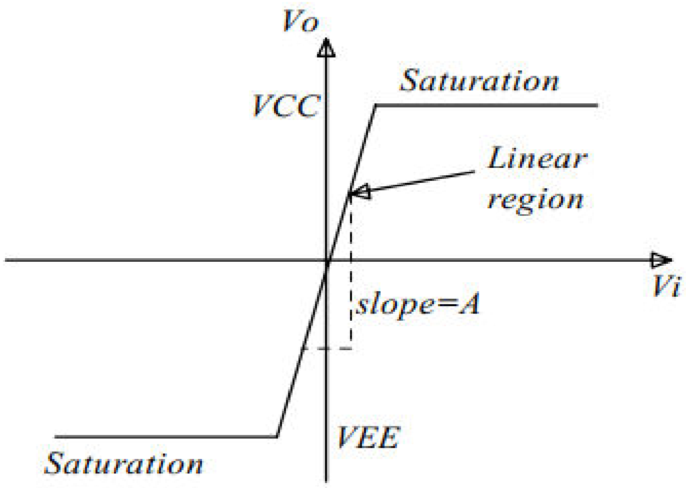


Figure 3. Op-amp voltage transfer characteristics.

OP-AMP input modes

1. Single ended mode : If the input signal is applied to only one of the inputs and the other input terminal is connected to ground it is said to be operating in single ended mode.

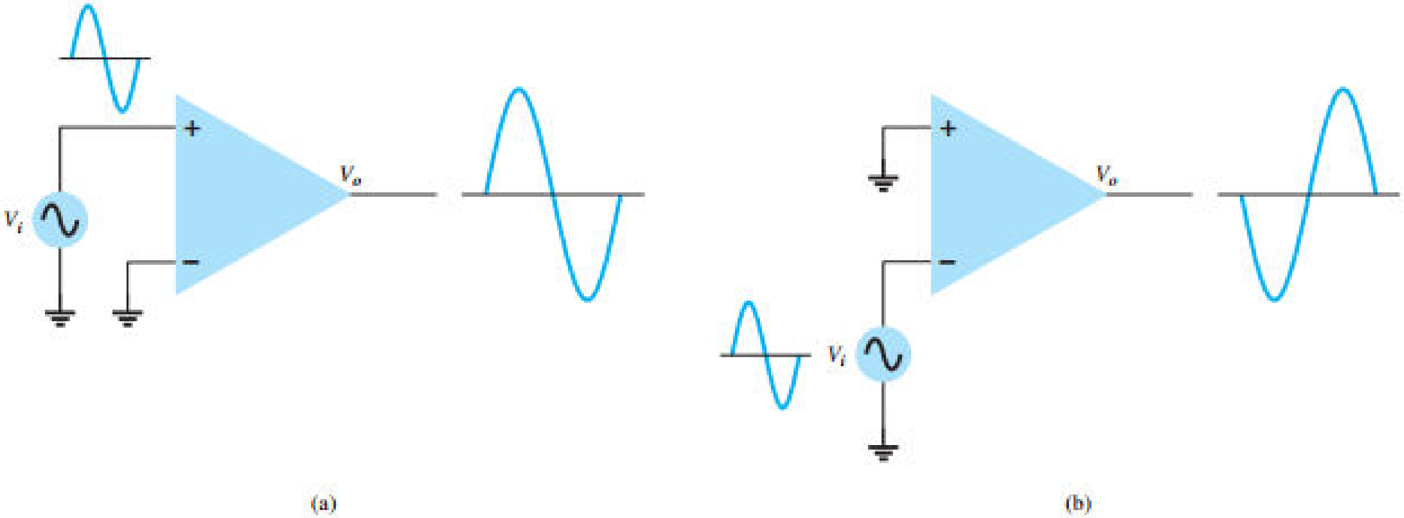


FIG. 10.2
Single-ended operation.

OP-AMP input modes

2. Differential mode/double ended: In differential mode ,two opposite polarity signal are applied to the two inputs of op amp. The difference between the input signal is amplified appears at the output

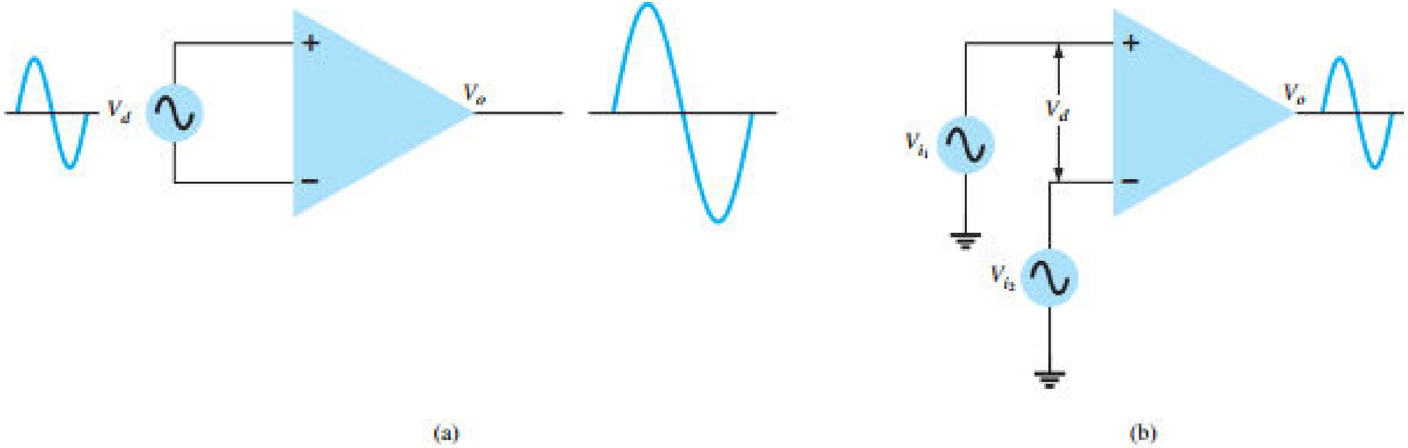


FIG. 10.3
Double-ended (differential) operation.

OP-AMP input modes

3. Common mode: In the common mode of operation, the same input signal is applied to both the input terminals. Ideally a zero voltage should be produced by the op amp.

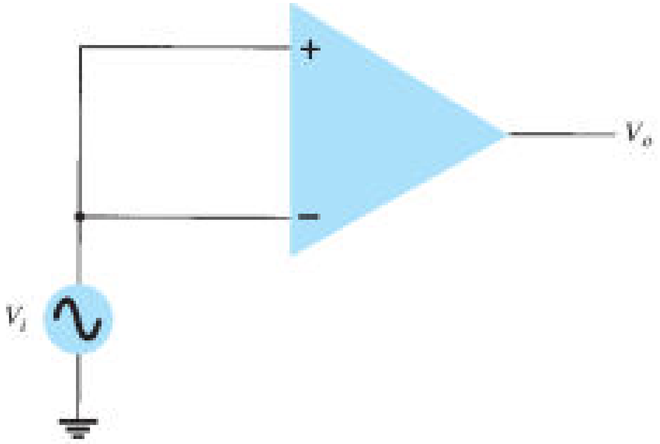


FIG. 10.8
Common-mode operation.

Common-mode and Differential-mode Signals:

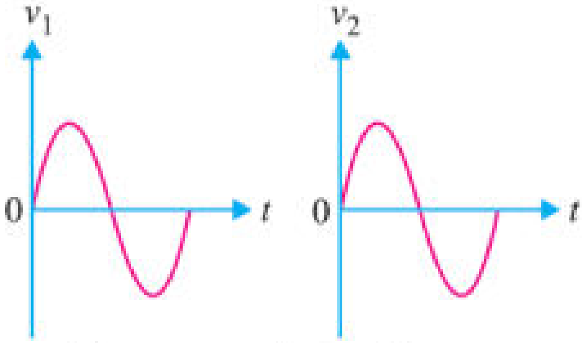
- The importance of a differential amplifier lies in the fact that the outputs are proportional to the difference between the two input signals. Thus the circuit can be used to amplify the difference between the two input signals or amplify only one input signal simply by grounding the other input. The input signals to a Differential Amplifier (DA) are defined as:

  (i) Common-mode signals
  (ii) Differential-mode signals

Common-mode and Differential-mode Signals:

- **(i) Common-mode signals :** When the input signals to a DA are in phase and exactly equal in amplitude, they are called common-mode signals. The common-mode signals are rejected (not amplified) by the differential amplifier. It is because a differential amplifier amplifies the difference between the two signals (v1 – v2) and for common-mode signals, this difference is zero. In common-mode operations, v1 = v2.

- The voltage gain of DA operating in **common-mode** is called common mode voltage gain and is denoted by A_{CM}

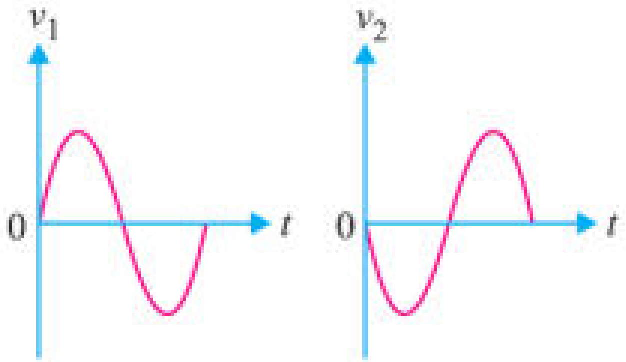


Common-mode signals

Common-mode and Differential-mode Signals:

- **(ii) Differential-mode signals.** When the input signals to a DA are 180° out of phase and exactly equal in amplitude, they are called differential-mode signals. The differential-mode signals are amplified by the differential amplifier. It is because the difference in the signals is twice the value of each signal. For differential-mode signals, v1 = –v2.

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



Differential-mode signals

Differential Amplifier (DA)

A **differential amplifier** *is a circuit that can accept two input signals and amplify the difference between these two input signals.*

Fig. 25.2 shows the block diagram of an ordinary amplifier. The input voltage v is amplified to Av where A is the voltage gain of the amplifier. Therefore, the ouput voltage is $v_0 = Av$.

Fig. 25.2

Fig.25.3

Fig. 25.3 shows the block diagram of a differential amplifier. There are two input voltages v_1 and v_2. This amplifier amplifies the difference between the two input voltages. Therefore, the output voltage is $v_0 = A(v_1 - v_2)$ where A is the voltage gain of the amplifier.

Math Problem

Example 25.1. *A differential amplifier has an open-circuit voltage gain of 100. The input signals are 3.25 V and 3.15V. Determine the output voltage.*

Solution.

$$\text{Output voltage, } v_0 = A(v_1 - v_2)$$

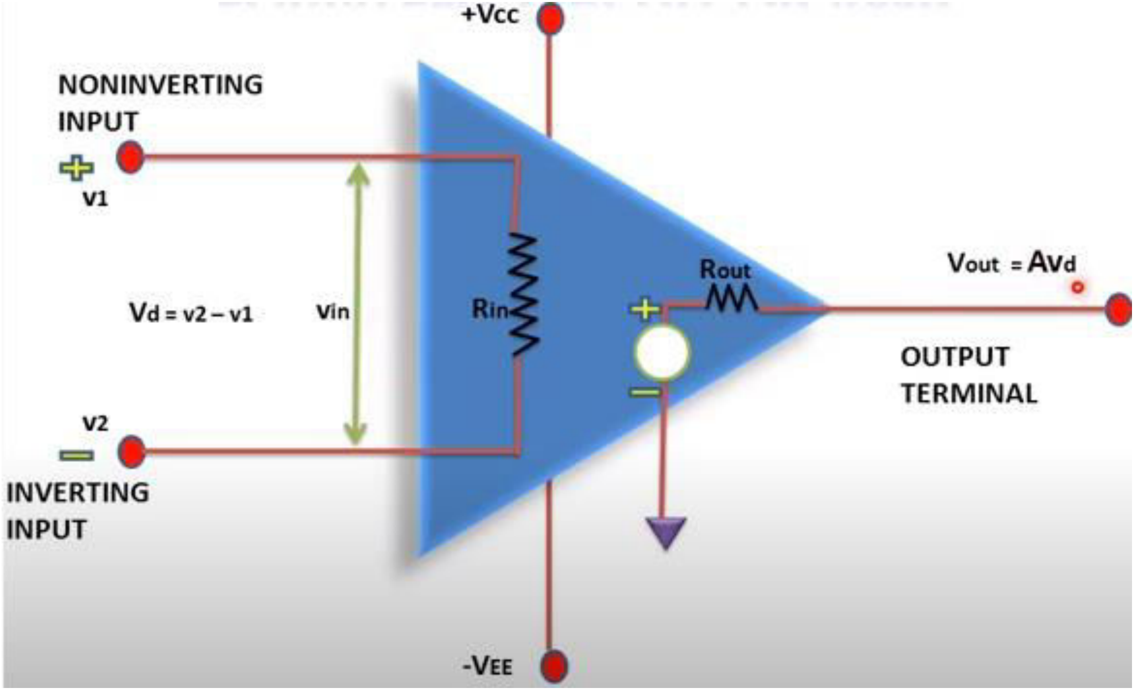
Here, $A = 100 ; v_1 = 3.25 \text{ V} ; v_2 = 3.15\text{V}$

$$\therefore \quad v_0 = 100(3.25 - 3.15) = \mathbf{10V}$$

Voltage Gains of DA:

- 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 with result. the common-mode gain, the better the performance of the DA in terms of rejection of common-mode signals.

Op-Amp Equivalent Circuit



Characteristics of Ideal op-amp

1. Infinite (∞) voltage gain
2. Input impedance, $R_i = \infty$
3. Zero output impedance, $R_0 = 0$
4. Slew rate = ∞
5. CMRR = ∞
6. Bandwidth = ∞

Common-mode Rejection Ratio (CMRR):

- A differential amplifier should have high differential voltage gain (A_{DM}) and very low common mode voltage gain (A_{CM}). The ratio A_{DM}/A_{CM} is called common-mode rejection ratio (CMRR). That is,
- $CMRR = A_{DM}/A_{CM}$
- Very often, the CMRR is expressed in decibels (dB). The decibel measure for CMRR is given by,

$$CMRR_{dB} = 20\ log_{10} \frac{A_{DM}}{A_{CM}} = 20\ log_{10} CMRR$$

Importance of CMRR:

- The CMRR is the ability of a DA to reject the common-mode signals. The larger the CMRR, the better the DA is at eliminating common-mode signals.

Math Problem

EXAMPLE 10.21 Calculate the CMRR for the circuit measurements shown in Fig. 10.52.

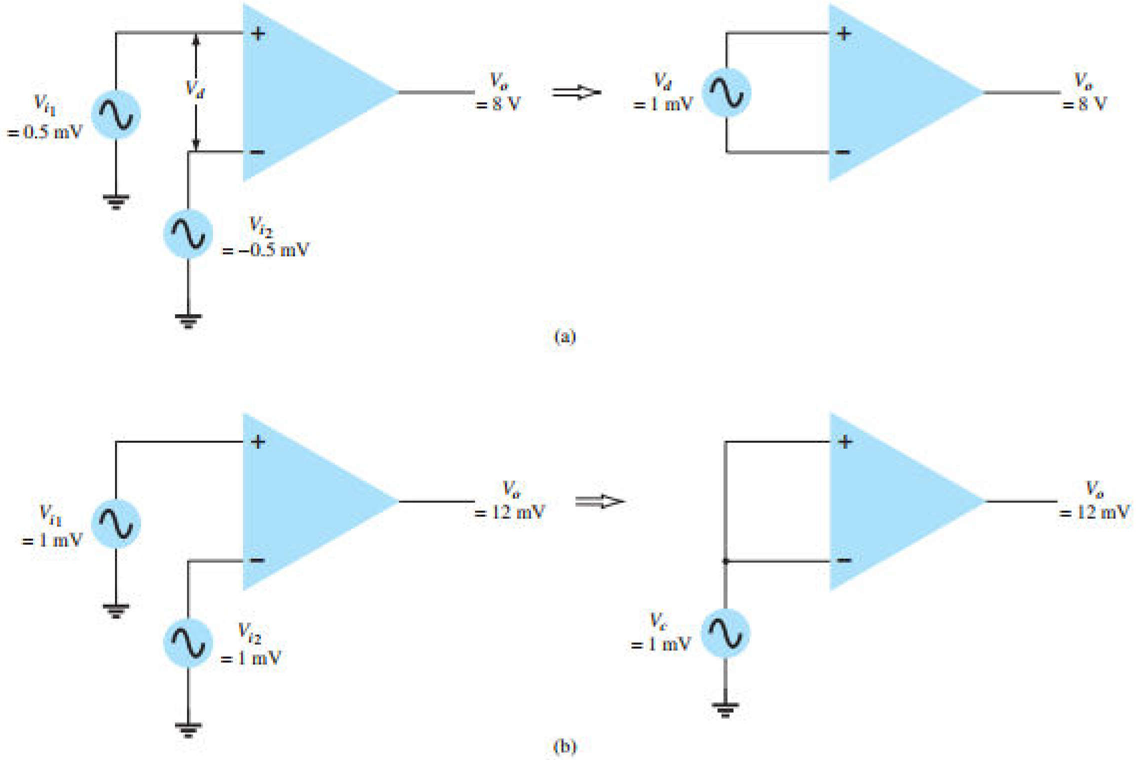


FIG. 10.52

Math Problem

Solution: From the measurement shown in Fig. 10.52a, using the procedure in step 1 above, we obtain

$$A_d = \frac{V_o}{V_d} = \frac{8\ \text{V}}{1\ \text{mV}} = 8000$$

The measurement shown in Fig. 10.52b, using the procedure in step 2 above, gives us

$$A_c = \frac{V_o}{V_c} = \frac{12\ \text{mV}}{1\ \text{mV}} = 12$$

Using Eq. (10.28), we obtain the value of CMRR,

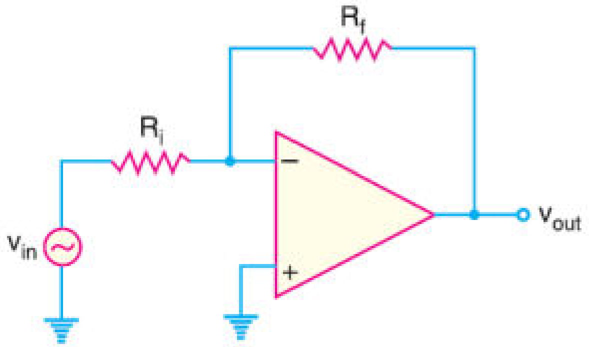
$$\text{CMRR} = \frac{A_d}{A_c} = \frac{8000}{12} = \mathbf{666.7}$$

which can also be expressed as

$$\text{CMRR} = 20 \log_{10} \frac{A_d}{A_c} = 20 \log_{10} 666.7 = \mathbf{56.48\ dB}$$

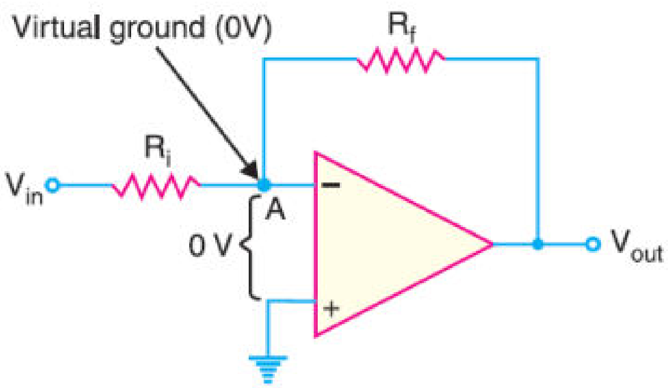
Inverting Amplifier

- An OP amplifier can be operated as an inverting amplifier. An input signal vin is applied through input resistor Ri to the minus input (inverting input). The output is fed back to the same minus input through feedback resistor Rf. The plus input (non-inverting input) is grounded. The resistor Rf provides the negative feedback. Since the input signal is applied to the inverting input (–), the output will be inverted as compared to the input. Hence the name inverting amplifier.

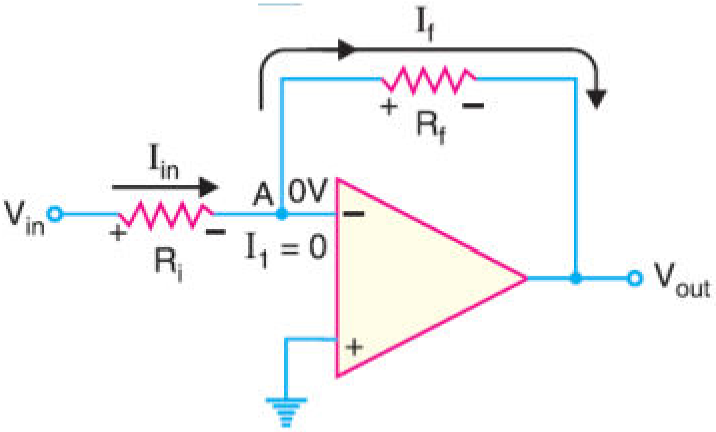


Voltage gain

- 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 because the other input (+) is grounded. The 0V at the inverting input terminal is referred to as virtual ground. The point A is said to be at virtual ground because it is at 0V but is not physically connected to the ground (VA = 0V).

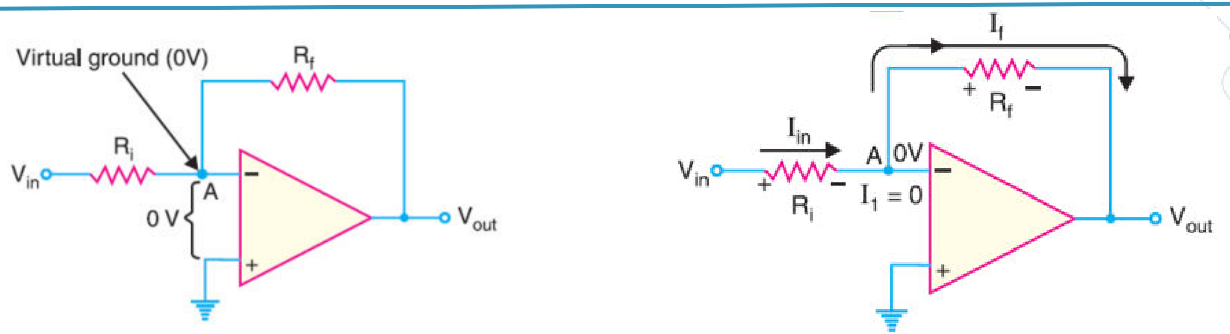


(i)



(ii)

Voltage gain



(i) (ii)

- Referring to Figure (ii), the current I1 to the inverting input is zero. Therefore, current Iin flowing through Ri entirely flows through feedback resistor Rf. In other words, If = Iin.

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

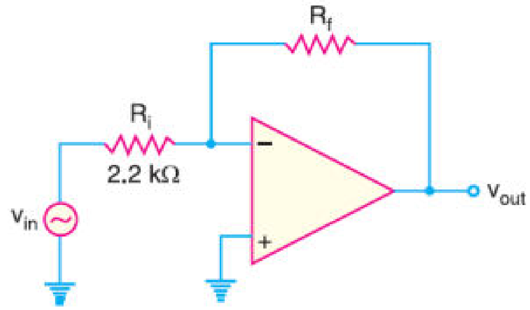
$$\text{And } \ I_f = \frac{Voltage\ \ Across\ R_f}{R_f} = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

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

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

Math Problem

Example 1: Given the OP-amp configuration in Figure, determine the value of Rf required to produce a closed-loop voltage gain of –100.



Solution:

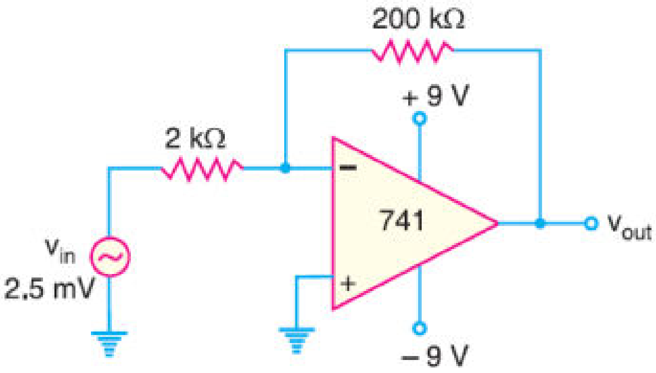
We know, $A_{CL} = \frac{-R_f}{R_i}$

or, $-100 = \frac{-R_f}{2.2}$

$$R_f = 100 \times 2.2 = 220\ k\Omega$$

Math Problem

Example 2: Determine the output voltage for the given circuit.



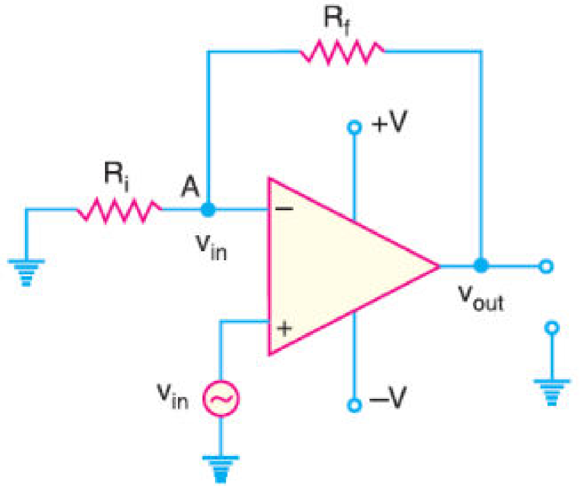
Solution:

We know, $A_{CL} = \frac{-R_f}{R_i} = \frac{-200}{2} = -100$

$\therefore$ Output voltage, $v_{out} = A_{CL} \times v_{in} = (-100) \times (2.5 \text{ mV}) = -250 \text{ mV} = -0.25 \text{ V}$

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. 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 Rf and input resistance Ri. This produces negative feedback in the circuit. Here Ri is grounded. Since the input signal is applied to the non-inverting input (+), the output signal will be non-inverted that is, the output signal will be in phase with the input signal.



Voltage gain

- If we assume that we are not at saturation, the potential at point A is the same as Vin. Since the input impedance of OP-amp is very high, all of the current that flows through Rf also flows through Ri. Keeping these things in mind, we have,

  Voltage across Ri = Vin – 0
  Voltage across Rf = Vout – Vin

  Now, Current through Ri = Current through Rf

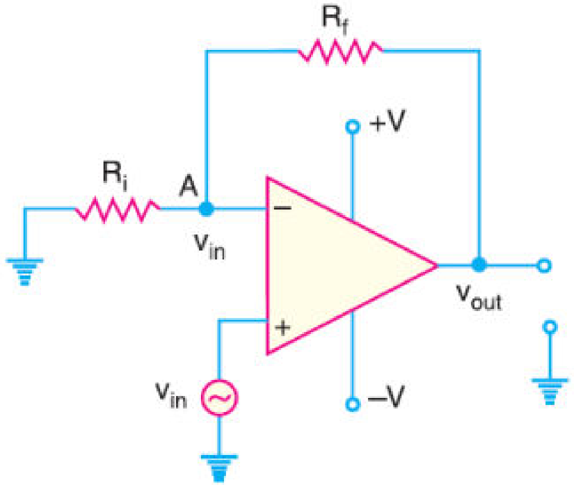
$$\text{or,}\quad \frac{V_{in}-0}{R_i} = \frac{V_{out}-V_{in}}{R_f}$$

$$\text{or,}\quad V_{in}R_f = V_{out}R_i - V_{in}R_i$$

$$\text{or,}\quad V_{in}(R_f+R_i) = V_{out}R_i$$

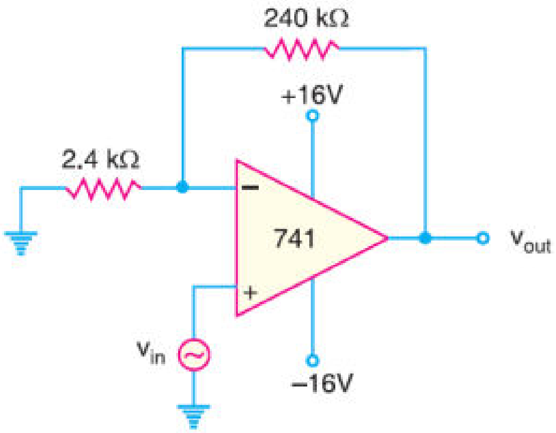
$$\text{or,}\quad \frac{V_{out}}{V_{in}} = \frac{R_f+R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

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



Math Problems

- **Example 1:** Calculate the output voltage from the non-inverting amplifier circuit of the following circuit for an input of 120 µV.



Solution:

We know,

$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{240}{2.4} = 1 + 100 = 101$$

Output voltage, $v_{out} = A_{CL} \times v_{in} = (101) \times (120\ \mu\text{V}) = 12.12\ \text{mV}$