The Ideal Operational Amplifier

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Ideal OP AMP

- The input impedance is infinite. (The input current is zero.)
- The output impedance is zero.
- Terminal (1): inverting input terminal, Terminal (2): noninverting input terminal

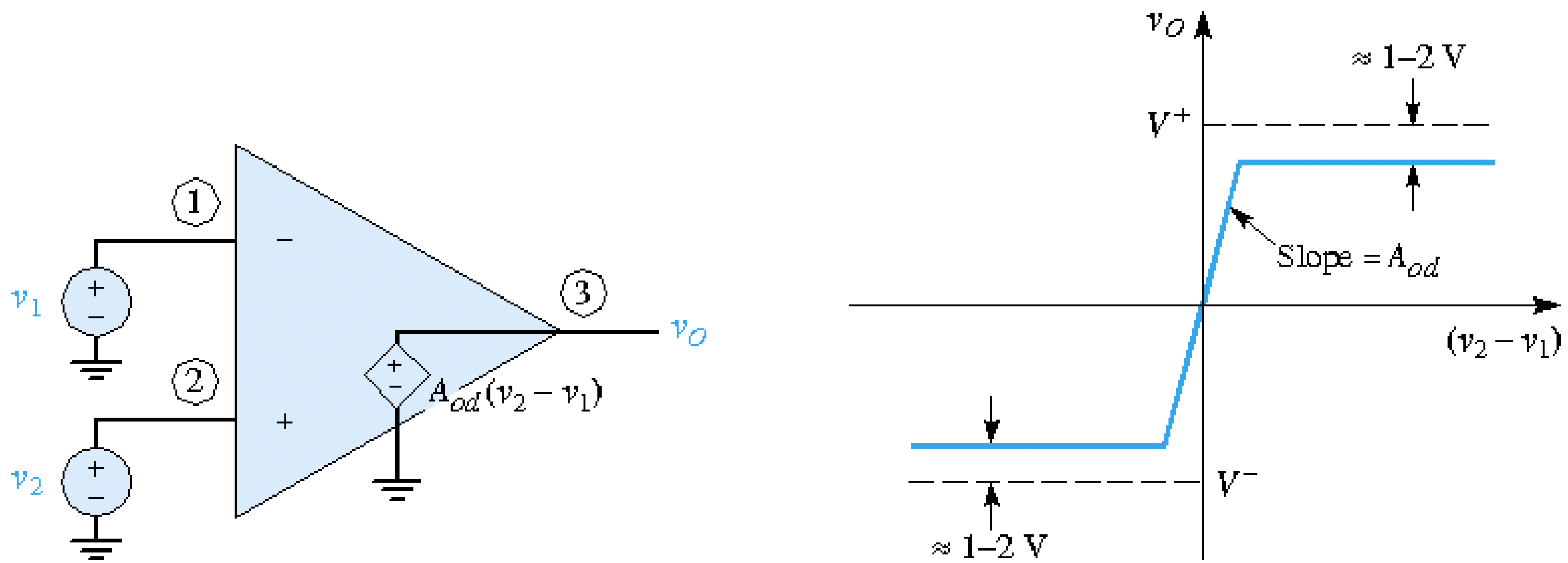


Figure 9.2 (a) Ideal op-amp equivalent circuit and (b) op-amp transfer characteristics

Closed-Loop Voltage Gain

$$\begin{cases} \dfrac{v_I - V_{gs}}{R_I} = \dfrac{v_{gs} - v_O}{R_F} \\ \dfrac{V_{gs} - v_O}{R_F} = g_m V_{gs} \end{cases}$$

$$\begin{cases} \dfrac{v_I}{R_I} + \dfrac{v_O}{R_F} = V_{gs}\left(\dfrac{1}{R_I} + \dfrac{1}{R_F}\right) \\ V_{gs} = \dfrac{V_{gs} - v_O}{g_m R_F} \end{cases}$$

$$\frac{v_O}{v_I} = -\frac{R_F}{R_I} \cdot \frac{(1 - 1/(g_m R_F))}{(1 + 1/(g_m R_F))} = -\frac{R_F}{R_I}$$

As $g_m \to \infty$.

If $g_m \to \infty, V_{gs} \cong 0$. (input terminal virtual ground)

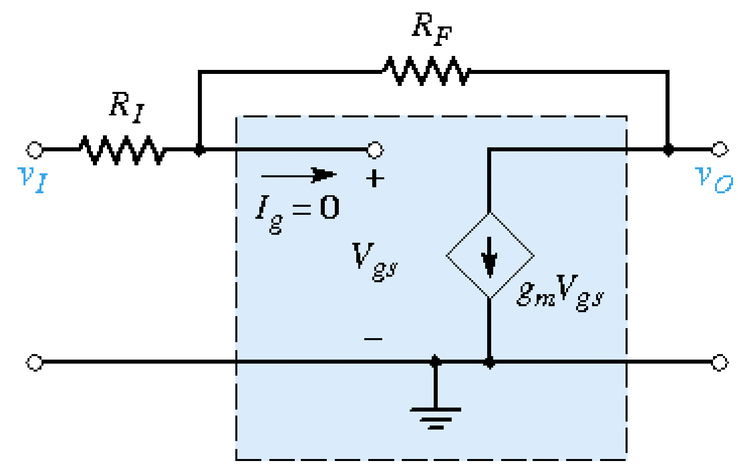


Figure 9.4 Simplified small-signal equivalent circuit of a MOSFET with input and feedback resistors

OP Output Resistance

- The output resistance of the OP circuit with negative feedback included goes to zero.

$$I_x = g_m V_{gs} + \frac{V_x}{R_I + R_F}$$

$$V_{gs} = V_x \cdot \frac{R_I}{R_I + R_F}$$

$$R_o = \frac{V_x}{I_x} = \frac{R_I + R_F}{1 + g_m R_I} \to 0 \quad \text{As } g_m \to \infty$$

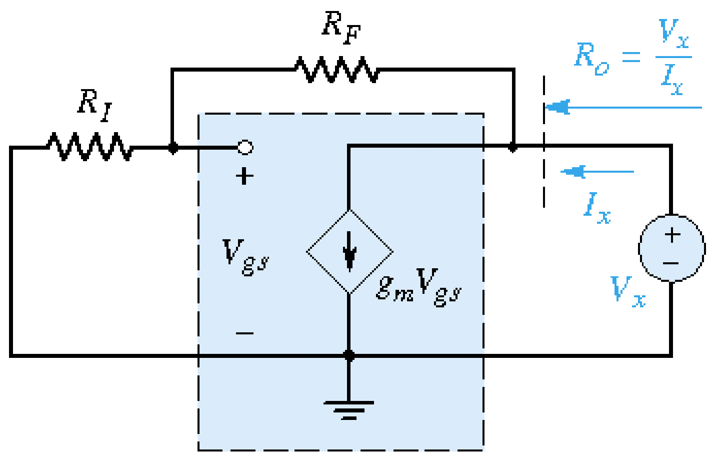


Figure 9.5 Equivalent circuit determining output resistance

Summary of Ideal OP AMP

- The internal differential gain A_{od} is considered to be infinite.
- The differential input voltage $(v_2 - v_1)$ is assumed to be zero. If A_{od} is very large and if the output voltage v_O is finite, then the two input voltages must be nearly equal.
- The effective input impedance to op-amp is assumed to be infinite, so the two input currents, i_1 and i_2, are essentially zero.
- The output resistance R_o is assumed to be zero in the ideal case, so the output voltage is connected directly to the dependent voltage source, and the output voltage is independent of any load connected to the output.

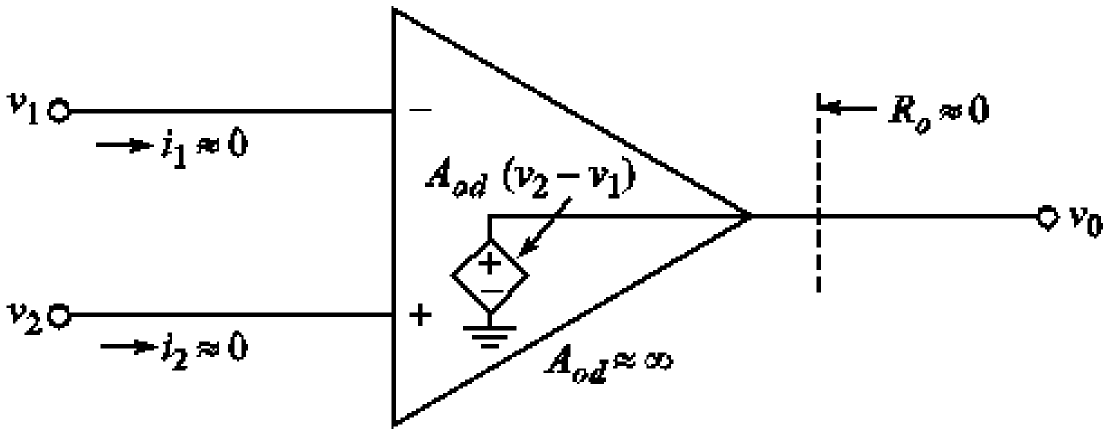


Figure 9.6 Parameters of the ideal op-amp

$\mu A-741$ parameters:

$R_i = 2\text{M}\Omega$

$R_o = 75\Omega$

$A_{od} = 2\times10^5$

Inverting Amplifier

$$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I}{R_1}$$

$$v_o = v_1 - i_2 R_2 = -i_1 R_2 = -\frac{R_2 v_I}{R_1}$$

$$A_v = \frac{v_o}{v_I} = -\frac{R_2}{R_1}$$ (Closed-Loop Voltage Gain)

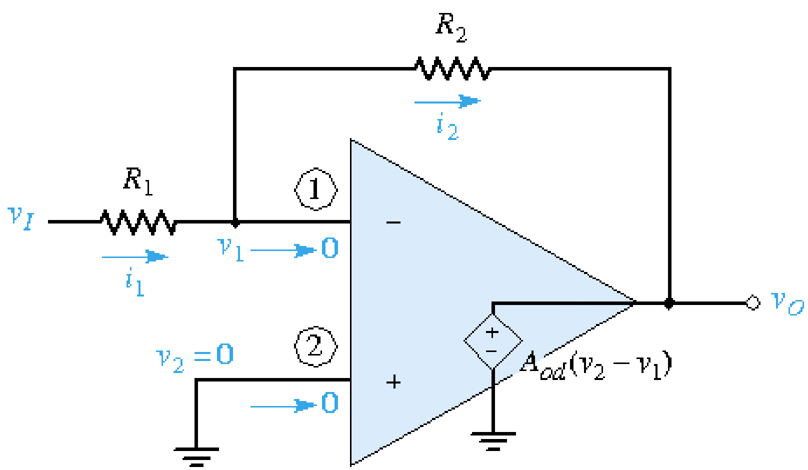


Figure 9.8 Inverting op-amp equivalent circuit

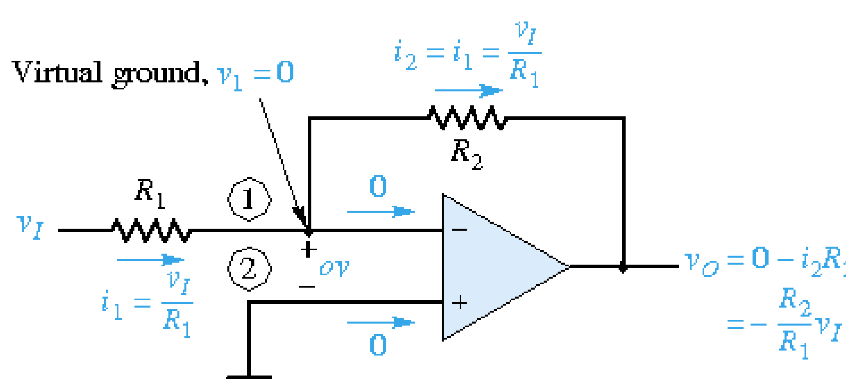


Figure 9.9 Currents and voltages in the inverting op-amp

Amplifier with a T-Network

$$v_x = -i_2 R_2 = -i_1 R_2 = -\frac{R_2}{R_1} v_I$$

$$i_2 + i_4 = i_3$$

$$-\frac{v_x}{R_2} - \frac{v_x}{R_4} = \frac{v_x - v_O}{R_3}$$

$$v_x\left(\frac{1}{R_2} + \frac{1}{R_4} + \frac{1}{R_3}\right) = \frac{v_O}{R_3}$$

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$$

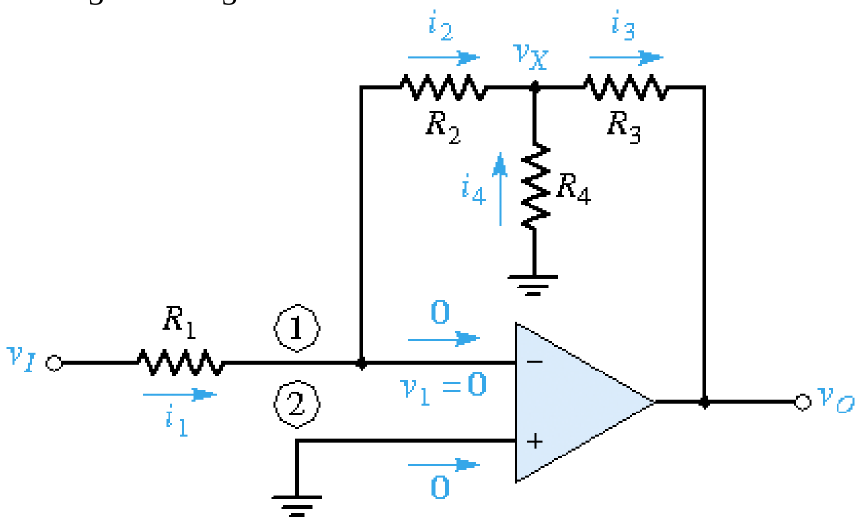


Figure 9.11 Inverting op-amp with T-network

Effect of Finite Gain

$$v_O = A_{od}(v_2 - v_1) = -A_{od} v_1$$

$$\frac{v_I - v_1}{R_1} = \frac{v_1 - v_O}{R_2}$$

$$v_1 = \frac{v_I R_2 + v_O R_1}{R_1 + R_2}$$

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1} \frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)\right]}$$

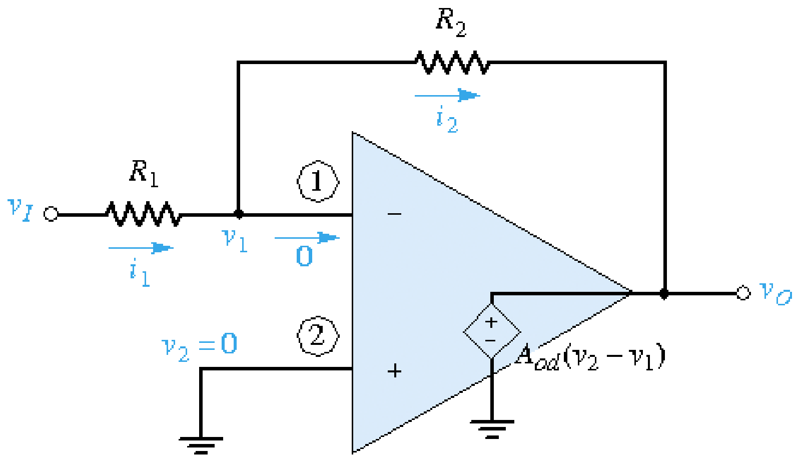


Figure 9.12 Equivalent circuit of the inverting op-amp with a finite differential-mode gain

Example 9.3 **Objective:** Determine the deviation from the ideal due to a finite differential gain.

Consider an inverting op-amp with $R_1 = 10\,\text{k}\Omega$ and $R_2 = 100\,\text{k}\Omega$. Determine the closed-looop gain for: $A_{od} = 10^2$, 10^3, 10^4, 10^5, and 10^6. Calculate the percent deviation from the ideal gain.

Solution: The ideal closed-loop gain is

$$A_v = -\frac{R_2}{R_1} = -\frac{100}{10} = -10$$

If $A_{od} = 10^2$, we have, from Equation (9.3),

$$A_v = -\frac{100}{10} \cdot \frac{1}{\left[1 + \frac{1}{10^2}\left(1 + \frac{100}{10}\right)\right]} = \frac{-10}{(1 + 0.11)} = -9.01$$

which is a 9.9 percent deviation from the ideal. For the other differential gain values we have the following results:

A_{od}	A_v	Deviation (%)
10^2	−9.01	9.9
10^3	−9.89	1.1
10^4	−9.989	0.11
10^5	−9.999	0.01
10^6	−9.9999	0.001

Summing Amplifier

$$v_O = -R_F\left(\frac{1}{R_1}v_{I1} + \frac{1}{R_2}v_{I2} + \frac{1}{R_3}v_{I3}\right)$$

If $R_1 = R_2 = R_3 = R$, then

$$v_O = -\frac{R_F}{R}\left(v_{I1} + v_{I2} + v_{I3}\right)$$

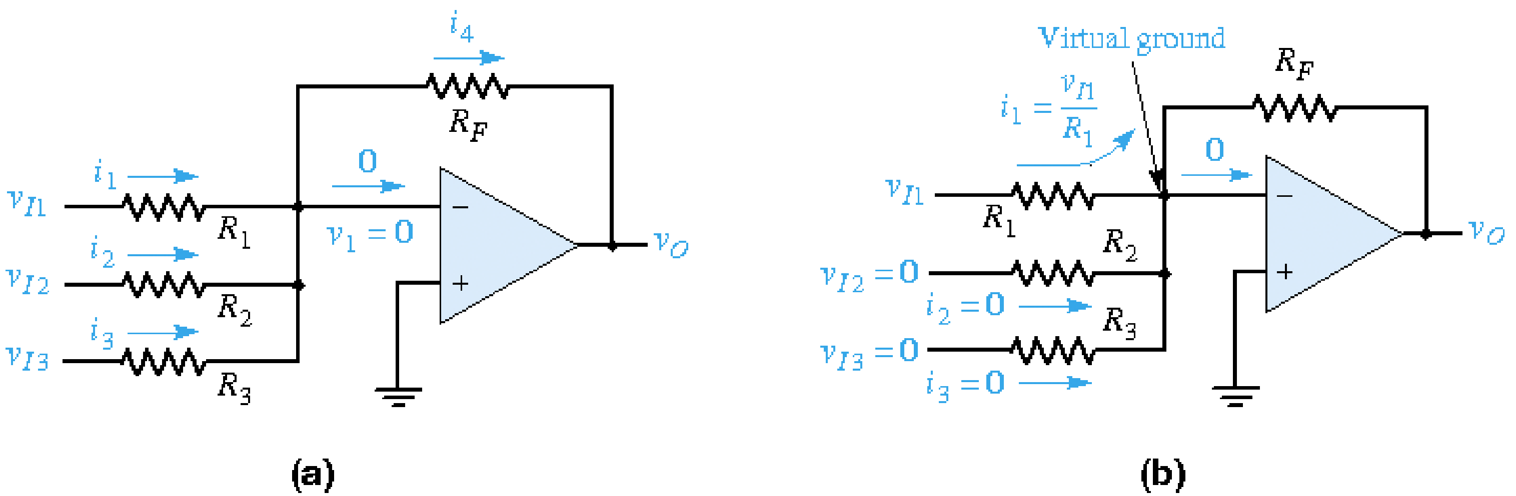


Figure 9.13 (a) Summing op-amp amplifier circuit and (b) currents and voltages in the summing amplifier

Noninverting Amplifier

$$i_1 = -\frac{v_I}{R_1}$$

$$i_2 = \frac{v_I - v_O}{R_2} = -\frac{v_I}{R_1}$$

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

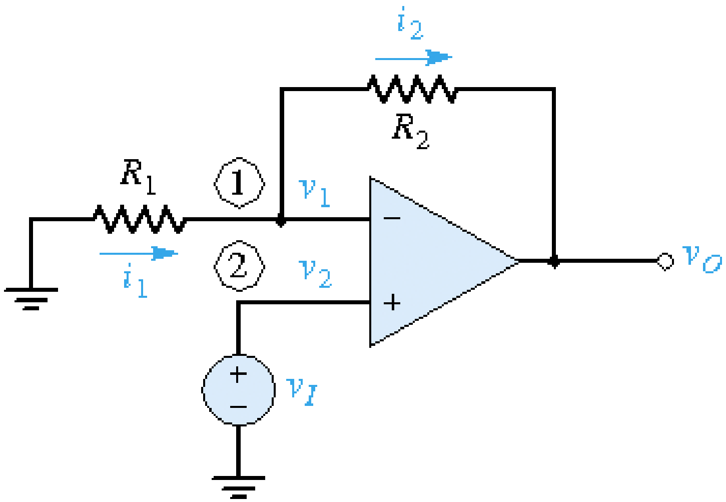


Figure 9.14 Noninverting op-amp circuit

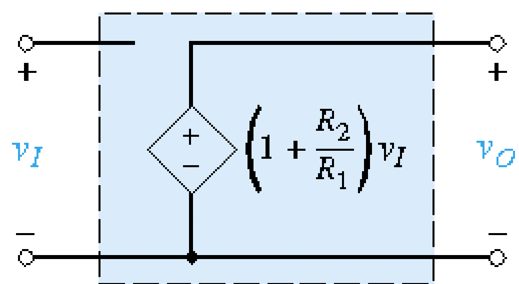


Figure 9.15 Equivalent circuit of ideal noninverting op-amp

Voltage Follower

- The output voltage follows the input, this kind of op-amp circuit is called a voltage follower.
- Impedance Transformer (buffer): The input impedance is essentially infinite, and the output impedance is essentially zero.

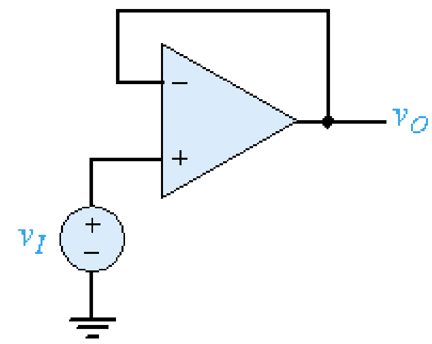


Figure 9.16 Voltage-follower op-amp

$$(a)\ \frac{v_O}{v_I} = \frac{R_L}{R_L + R_S} = \frac{1}{1+100} \approx 0.01 \qquad (b)\ v_O \approx v_I$$

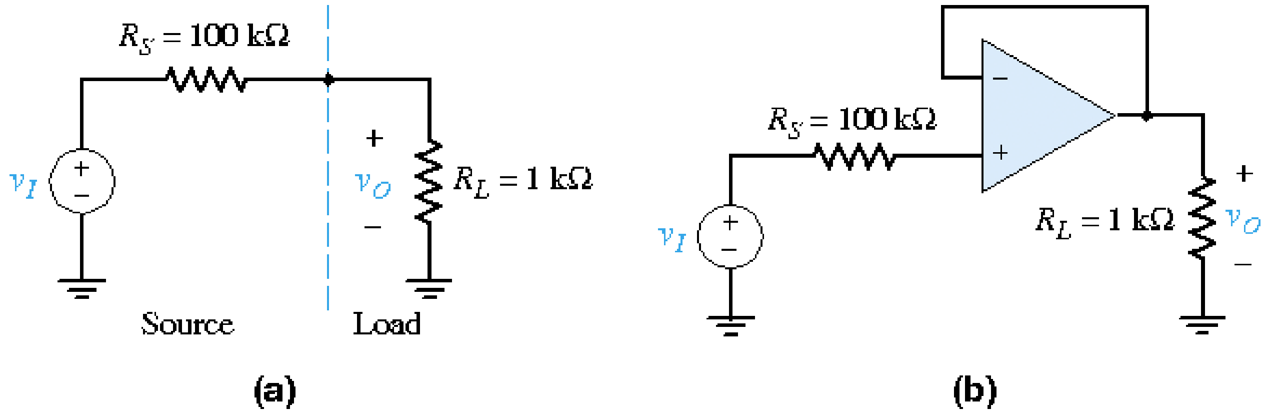


Figure 9.17 (a) Source with a 100 kΩ output resistance driving a 1 kΩ load and (b) source with a 100 kΩ output resistance, voltage follower, and 1 kΩ load

Current-to-Voltage Converter

$$R_i = \frac{v_1}{i_1} \approx 0$$

$$i_2 = i_1 = i_S$$

$$v_O = -i_2 R_F = -i_S R_F$$

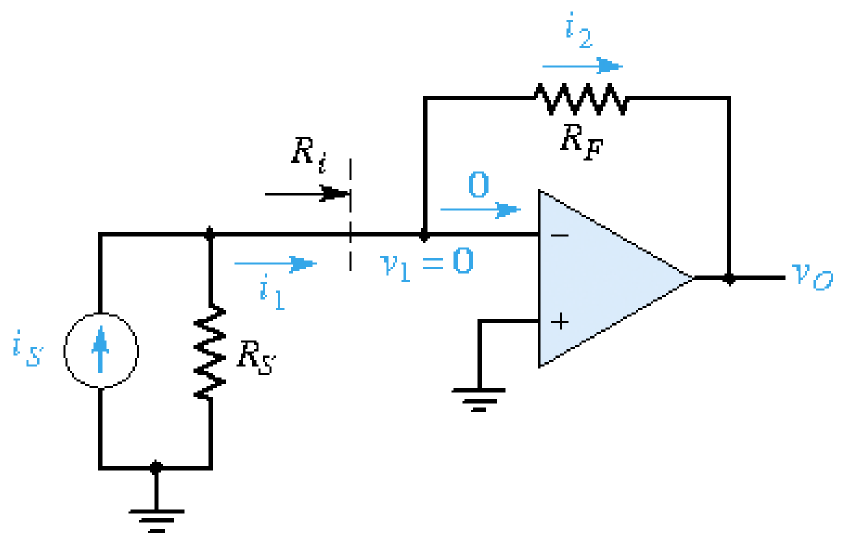


Figure 9.19 Current-to-voltage converter

Voltage-to-Current Converter

$$\begin{cases} \dfrac{v_I - i_L Z_L}{R_1} = \dfrac{i_L Z_L - v_O}{R_F} \\ \dfrac{v_O - i_L Z_L}{R_3} = i_L + \dfrac{i_L Z_L}{R_2} \end{cases}$$

$$\begin{cases} \dfrac{v_I}{R_1} + \dfrac{v_O}{R_F} = \left(\dfrac{1}{R_1} + \dfrac{1}{R_F}\right) Z_L \cdot i_L \\ v_O = R_3\left(1 + \dfrac{Z_L}{R_2} + \dfrac{Z_L}{R_3}\right) \cdot i_L \end{cases}$$

$$-\frac{v_I}{R_1} = i_L \cdot \left(\frac{R_3}{R_F} + Z_L \cdot \left(\frac{R_3}{R_2 R_F} + \frac{R_3}{R_3 R_F} - \frac{1}{R_1} - \frac{1}{R_F}\right)\right)$$

$$= i_L \cdot \left(\frac{R_3}{R_F} + Z_L \cdot \left(\frac{R_3}{R_2 R_F} - \frac{1}{R_1}\right)\right)$$

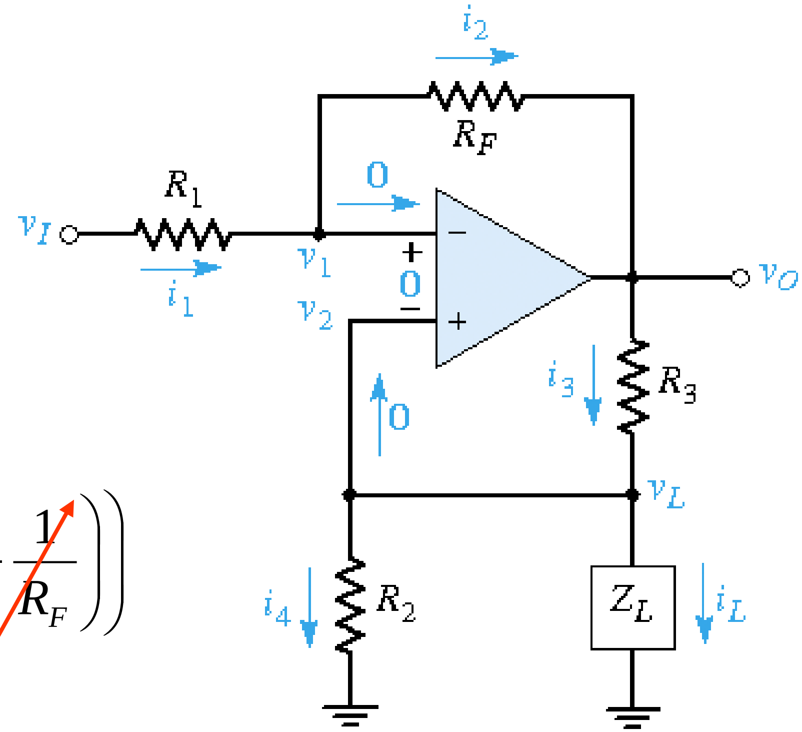


Figure 9.21 Voltage-to-current converter

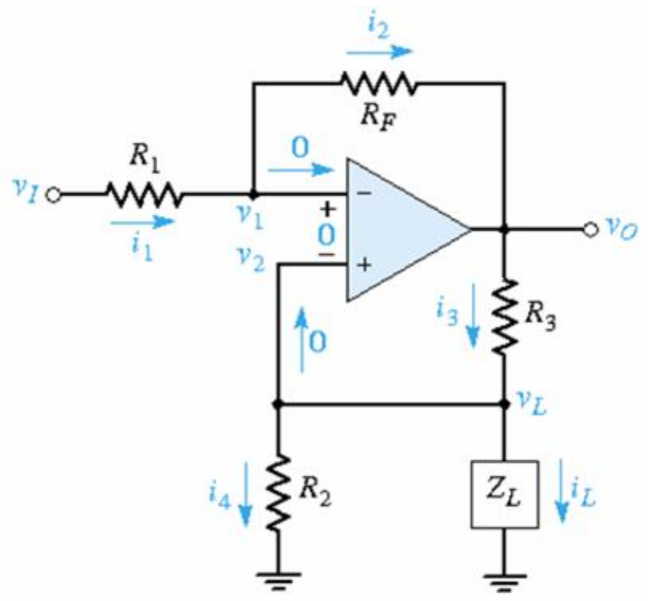
Let $R_1 R_3 = R_2 R_F$, $i_L = -\dfrac{R_F}{R_1 R_3} \cdot v_I = -\dfrac{v_I}{R_2}$ (independent of Z_L)

Example 9.5 **Objective:** Determine a load current in a voltage-to-current converter.

Consider the circuit in Figure 9.21. Let $Z_L = 100\,\Omega$, $R_1 = 10\,\text{k}\Omega$, $R_2 = 1\,\text{k}\Omega$, $R_3 = 1\,\text{k}\Omega$, and $R_F = 10\,\text{k}\Omega$. If $v_I = -5\,\text{V}$, determine the load current i_L and the output voltage v_O.

Solution: We note first that the condition expressed by Equation (9.44) is satisfied; that is,

$$\frac{1}{R_2} = \frac{R_F}{R_1 R_3} = \frac{10}{(10)(1)} \rightarrow \frac{1}{1}$$



The load current is

$$i_L = \frac{-v_I}{R_2} = \frac{-(-5)}{1\,\text{k}\Omega} = 5\,\text{mA}$$

and the voltage across the load is

$$v_L = i_L Z_L = (5 \times 10^{-3})(100) = 0.5\,\text{V}$$

Currents i_4 and i_3 are

$$i_4 = \frac{v_L}{R_2} = \frac{0.5}{1} = 0.5\,\text{mA}$$

and

$$i_3 = i_4 + i_L = 0.5 + 5 = 5.5\,\text{mA}$$

The output voltage is then

$$v_O = i_3 R_3 + v_L = (5.5 \times 10^{-3})(10^3) + 0.5 = 6\,\text{V}$$

We could also calculate i_1 and i_2 as

$$i_1 = i_2 = -0.55\,\text{mA}$$

Difference Amplifier

- An ideal difference amplifier amplifies only the difference between two signals, it rejects any common signals to the two input terminals.
- For example, a microphone system amplifies an audio signal applied to one terminal of a difference amplifier, and rejects any 60 Hz noise signal or "hum" existing on both terminals.
- To analyze the circuit (a), we use the superposition of (b) and (c) with virtual short concept.

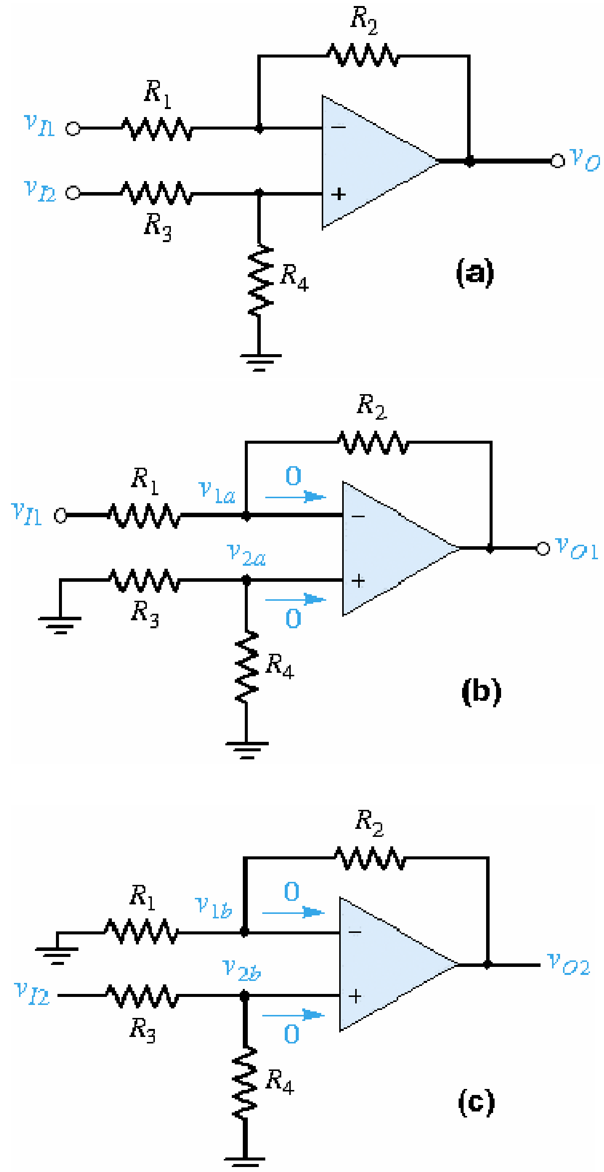
$$v_{O1} = -\frac{R_2}{R_1} v_{I1}$$

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right) v_{2b} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_{I2}$$

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

Let $v_O = 0$ when $v_{I1} = v_{I2}$, then $R_4 / R_3 = R_2 / R_1$.

$$v_O = \frac{R_2}{R_1}(v_{I2} - v_{I1}), \qquad \text{closed loop gain } A_d = R_2 / R_1$$



Difference Amplifier

- Differential Input Resistance

$$R_i = 2R_1$$

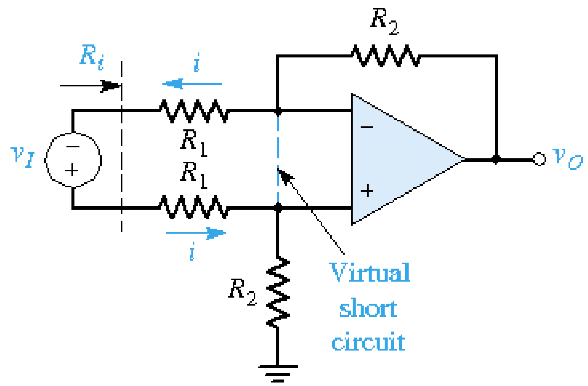


Figure 9.24 Circuit for measuring differential input resistance of op-amp difference amplifier

- Common-Mode Rejection Ratio (CMRR)

Common-mode input signal: $v_{cm} = (v_{I1} + v_{I2})/2$

Common-mode gain: $A_{cm} = \dfrac{v_O}{v_{cm}}$

CMRR: $CMRR = \left|\dfrac{A_d}{A_{cm}}\right| = 20\log_{10}\left|\dfrac{A_d}{A_{cm}}\right|$ (dB)

Example 9.7 **Objective:** Calculate the common-mode rejection ratio of a difference amplifier.

Consider the difference amplifier shown in Figure 9.23(a). Let $R_2/R_1 = 10$ and $R_4/R_3 = 11$. Determine CMRR(dB).

Solution: From Equation (9.50(b)), we have

$$v_O = (1+10)\left(\frac{11}{1+11}\right)v_{I2} - (10)v_{I1}$$

or

$$v_O = 10.0833v_{I2} - 10v_{I1} \tag{9.60}$$

The differential-mode input voltage is defined as

$$v_d = v_{I2} - v_{I1}$$

and the common-mode input voltage is defined as

$$v_{cm} = (v_{I1} + v_{I2})/2$$

Combining these two equations produces

$$v_{I1} = v_{cm} - \frac{v_d}{2} \tag{9.61(a)}$$

and

$$v_{I2} = v_{cm} + \frac{v_d}{2} \tag{9.61(b)}$$

If we substitute Equations (9.61(a)) and (9.61(b)) in Equation (9.60), we obtain

$$v_O = (10.0833)\left(v_{cm} + \frac{v_d}{2}\right) - (10)\left(v_{cm} - \frac{v_d}{2}\right)$$

or

$$v_O = 10.042v_d + 0.0833v_{cm} \tag{9.62}$$

The output voltage is also

$$v_O = A_d v_d + A_{cm} v_{cm} \tag{9.63}$$

If we compare Equations (9.62) and (9.63), we see that

$$A_d = 10.042 \quad \text{and} \quad A_{cm} = 0.0833$$

Therefore, from Equation (9.59), the common-mode rejection ratio, is

$$\text{CMRR(dB)} = 20\log_{10}\left(\frac{10.042}{0.0833}\right) = 41.6\text{ dB}$$

Instrumentation Amplifier

- To obtain high input impedance and a high gain

$$i_1 = \frac{v_{I1} - v_{I2}}{R_1}$$

$$v_{O1} = v_{I1} + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I1} - \frac{R_2}{R_1} v_{I2}$$

$$v_{O2} = v_{I2} - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1})$$

$$= \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_{I2} - v_{I1})$$

$$R_i \to \infty$$

The differential gain is a function of resistance R_1.

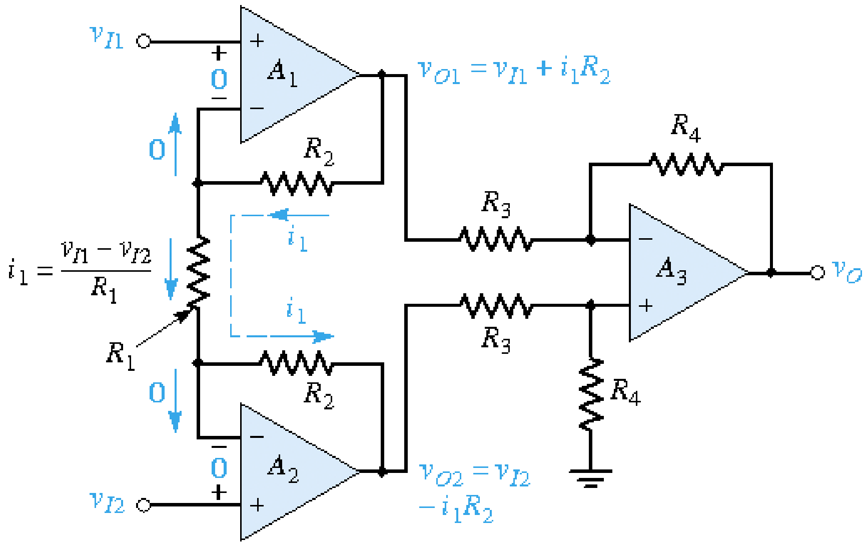


Figure 9.26 Voltages and currents in instrumentation amplifier

Integrator and Differentiator

- Integrator

$$v_O = -\frac{Z_2}{Z_1} v_I = \frac{-1}{sR_1C_2} v_I$$

$$v_O(t) = V_C - \frac{1}{R_1C_2}\int_0^t v_I(\tau)d\tau$$

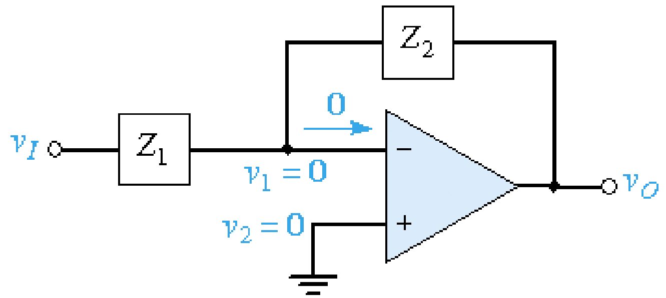


Figure 9.28 Generalized inverting amplifier

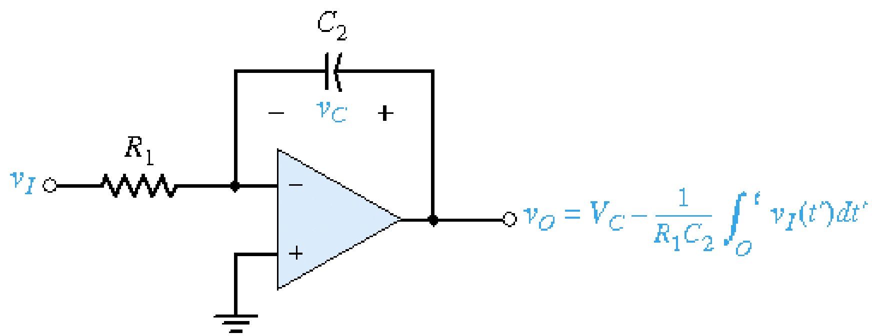


Figure 9.29 Op-amp integrator

- Differentiator

$$v_O = -\frac{Z_2}{Z_1} v_I = -sR_2C_1 v_I$$

$$v_O(t) = -R_1C_2 \frac{dv_I(t)}{dt}$$

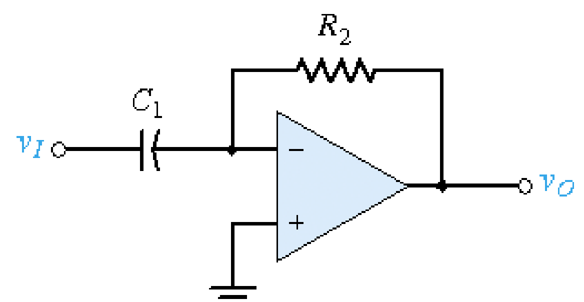


Figure 9.30 Op-amp differentiator

Precision Half-Wave Rectifier

(i) $v_I > 0,$

$$i_D = i_L, v_O = v_I$$

(ii) $v_I < 0,$

$$i_D = i_L = 0, v_O = 0$$

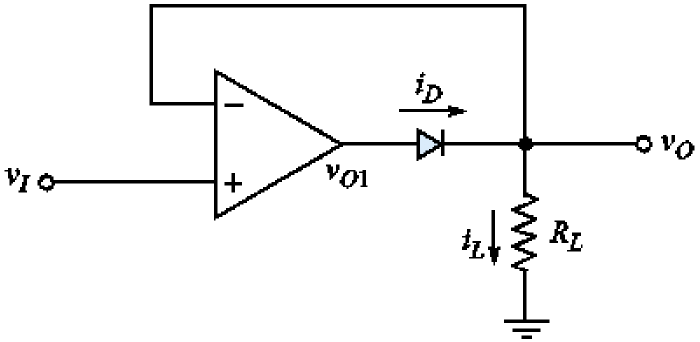


Figure 9.33 Precision half-wave rectifier circuit

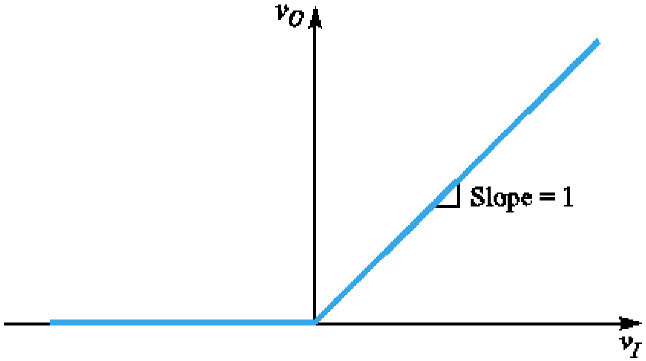


Figure 9.34 Voltage transfer characteristics of precision half-wave rectifier

Log and Antilog Amplifiers

- Log Amplifier

$$i_D = I_S(e^{v_D/V_T} - 1) \approx I_S e^{v_D/V_T}$$

$$= \frac{v_I}{R_1}$$

$$v_D = -v_O$$

$$I_S e^{-v_O/V_T} = \frac{v_I}{R_1} \qquad v_O = -V_T \ln\left(\frac{v_I}{I_S R_1}\right)$$

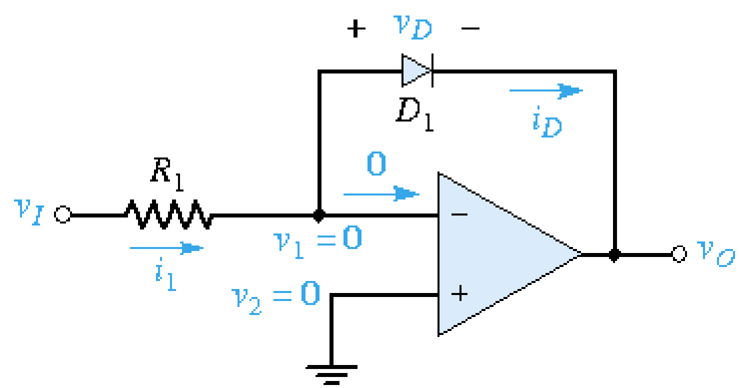


Figure 9.35 Simple log amplifier

- Antilog or Exponential Amplifier

$$i_D \approx I_S e^{v_D/V_T}$$

$$v_O = -i_D R = -I_S R \cdot e^{v_D/V_T}$$

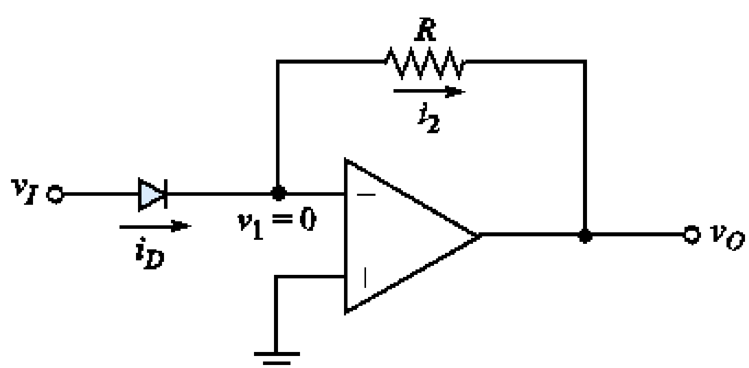


Figure 9.36 A simple antilog, or exponential, amplifier

Summing Op-Amp Circuit Design

$$v_O(v_{I1}) = -\frac{R_F}{R_1} v_{I1} \qquad v_O(v_{I2}) = -\frac{R_F}{R_2} v_{I2}$$

$$v_O = -a_1 v_{I1} - a_2 v_{I2} + a_3 v_{I3} + a_4 v_{I4}$$

$$v_2(v_{I3}) = \frac{R_B // R_C}{R_A + R_B // R_C} v_{I3}$$

$$v_O(v_{I3}) = \left(1 + \frac{R_F}{R_1 // R_2}\right) v_2(v_{I3})$$

$$= \left(1 + \frac{R_F}{R_1 // R_2}\right)\left(\frac{R_B // R_C}{R_A + R_B // R_C}\right) v_{I3}$$

$$= \left(1 + \frac{R_F}{R_1 // R_2}\right)\left(\frac{R_A // R_B // R_C}{R_A}\right) v_{I3}$$

$$v_O(v_{I4}) = \left(1 + \frac{R_F}{R_1 // R_2}\right)\left(\frac{R_A // R_B // R_C}{R_B}\right) v_{I4}$$

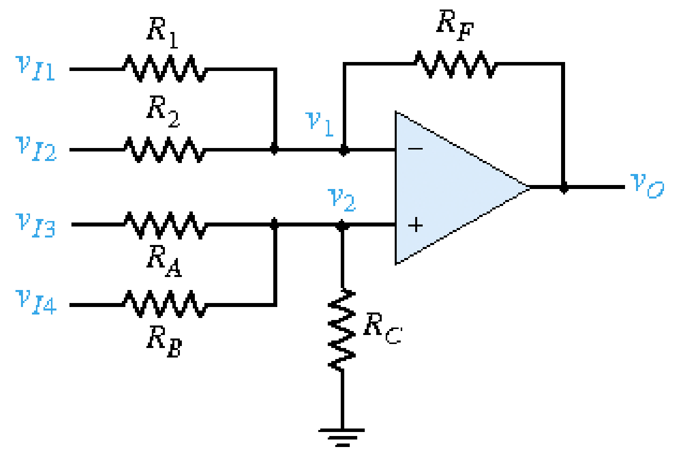


Figure 9.37 Generalized op-amp summing amplifier

$$v_O = v_O(v_{I1}) + v_O(v_{I2}) + v_O(v_{I3}) + v_O(v_{I4})$$

Design Example 9.10 **Objective:** Design a summing op-amp to produce the output

$$v_O = -10v_{I1} - 4v_{I2} + 5v_{I3} + 2v_{I4}$$

The smallest resistor value allowable is 20 kΩ.

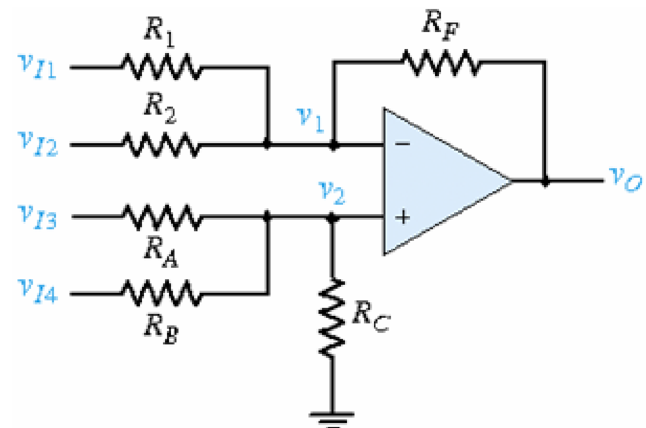
Solution: First we determine the values of resistors R_1, R_2, and R_F, and then we can determine the inverting terms. We know that

$$\frac{R_F}{R_1} = 10 \qquad \text{and} \qquad \frac{R_F}{R_2} = 4$$

Resistor R_1 will be the smallest value, so we can set $R_1 = 20\,\text{k}\Omega$. Then,

$$R_F = 200\,\text{k}\Omega \qquad \text{and} \qquad R_2 = 50\,\text{k}\Omega$$

The multiplying factor in the noninverting terms becomes



$$\left(1 + \frac{R_F}{R_1 \| R_2}\right) = \left(1 + \frac{200}{20\|50}\right) = 15$$

We then need

$$(15)\left(\frac{R_P}{R_A}\right) = 5 \qquad \text{and} \qquad (15)\left(\frac{R_P}{R_B}\right) = 2$$

If we take the ratio of these two expressions, we have

$$\frac{R_B}{R_A} = \frac{5}{2}$$

If we choose $R_A = 80\,\text{k}\Omega$, then $R_B = 200\,\text{k}\Omega$, $R_P = 26.67\,\text{k}\Omega$, and R_C becomes $R_C = 50\,\text{k}\Omega$.

Reference Voltage Source Design

$$V_O = \left(1 + \frac{R_2}{R_1}\right) V_Z$$

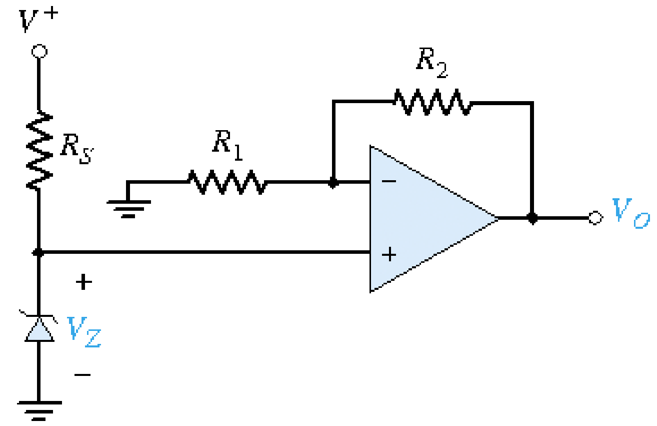


Figure 9.38 Simple op-amp voltage reference circuit

V_S Is used only to start up the circuit.

The Zener diode begins to conduct when

$$\frac{R_4}{R_3 + R_4} V_S > V_Z + V_D \approx V_Z + 0.7$$

$$V_O = \left(1 + \frac{R_2}{R_1}\right) V_Z > V_Z$$

$$I_F = \frac{V_O - V_Z}{R_F} = \frac{R_2 V_Z}{R_1 R_F}$$

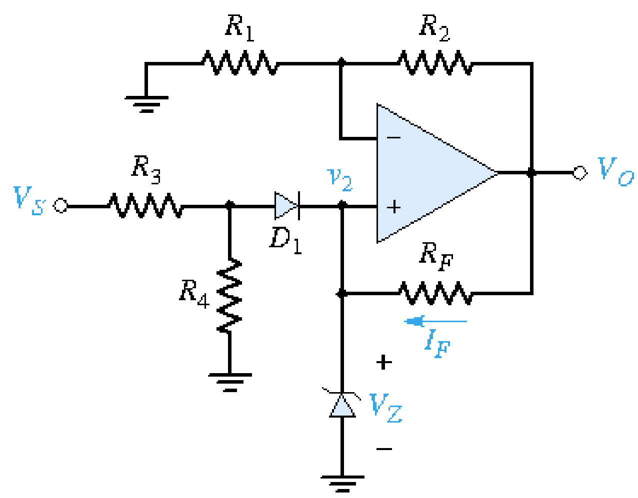
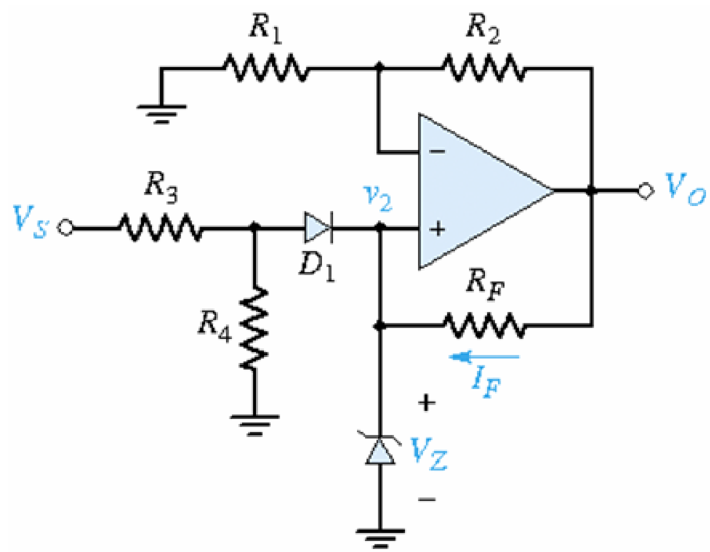


Figure 9.39 Op-amp voltage reference circuit

Design Example 9.11 Objective: Design a voltage reference source with an output of 10.0 V. Use a Zener diode with a breakdown voltage of 5.6 V. Assume the voltage regulation will be within specifications if the Zener diode is biased between 1–1.2 mA.

Solution: Consider the circuit shown in Figure 9.39. For this example, we need



$$\frac{V_O}{V_Z} = \left(1 + \frac{R_2}{R_1}\right) = \frac{10.0}{5.6}$$

Therefore,

$$\frac{R_2}{R_1} = 0.786$$

We know that

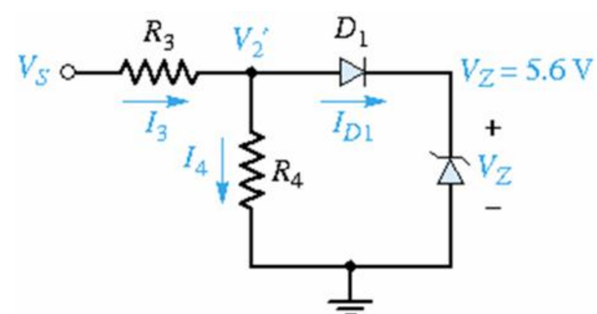
$$I_F = \frac{V_O - V_Z}{R_F}$$

If we set I_F equal to the minimum bias current, we have

$$1\,\text{mA} = \frac{10 - 5.6}{R_F}$$

which means that $R_F = 4.4\,\text{k}\Omega$. If we choose $R_2 = 30\,\text{k}\Omega$, then $R_1 = 38.17\,\text{k}\Omega$.

Resistors R_3 and R_4 can be determined from Figure 9.40. The maximum Zener current supplied by V_S, R_3, and R_4 should be no more than 0.2 mA. We set the current through D_1 equal to 0.2 mA, for $V_S = 10\,\text{V}$. We then have



$$V_2' = V_Z + 0.7 = 5.6 + 0.7 = 6.3\,\text{V}$$

Also,

$$I_4 = \frac{V_2'}{R_4} = \frac{6.3}{R_4}$$

and

$$I_3 = \frac{V_S - V_2'}{R_3} = \frac{10 - 6.3}{R_3} = \frac{3.7}{R_3}$$

If we set $I_4 = 0.2\,\text{mA}$, then

$$I_3 = 0.4\,\text{mA} \qquad R_3 = 9.25\,\text{k}\Omega \qquad R_4 = 31.5\,\text{k}\Omega$$

Difference Amplifier and Bridge Circuit Design

- A transducer is a device that transforms one form of energy into another form.
  - ✓ Ex. A microphone converts acoustical energy to produce electrical outputs.
- Bridge Circuit

  Resistance R_3 represents the transducer, and parameter δ is the deviation of R_3 from R_2 due to the input response of the transducer.

$$v_{O1} = \left[\frac{R_2(1+\delta)}{R_2(1+\delta)+R_1} - \frac{R_2}{R_1+R_2} \right] V^+$$

$$\approx \delta \left(\frac{R_1 // R_2}{R_1+R_2} \right) V^+$$

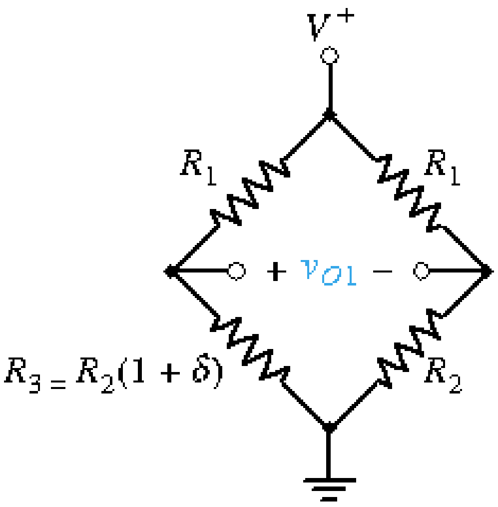


Figure 9.41 Bridge circuit

Design Example 9.12 **Objective:** Design an amplifier system that will produce an output voltage of ±5 V when the resistance R_3 deviates by ±1% from the value of R_2. This would occur, for example, in a system where R_3 is a thermistor whose resistance is given by

$$R_3 = 200\left[1 + \frac{(0.040)(T - 300)}{300}\right] \text{k}\Omega$$

where T is the absolute temperature. For R_3 to vary by ±1% means the temperature is in the range $225 \le T \le 375\,°\text{K}$.

Consider biasing the bridge circuit at $V^+ = 7.5$ V using a 5.6 V Zener diode. Assume ±10 V is available for biasing the op-amp and reference voltage source, and that $R_1 = R_2 = 200\,\text{k}\Omega$.

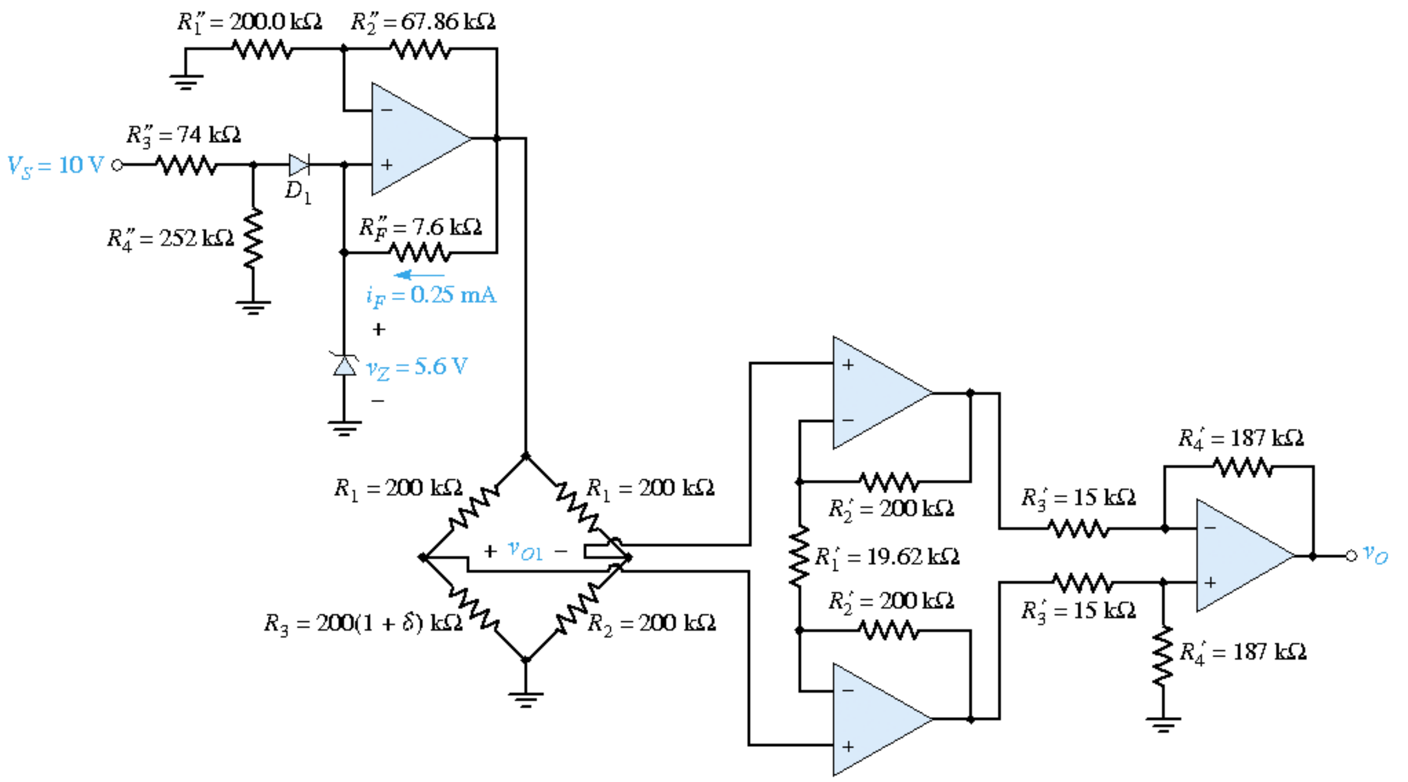


Figure 9.42 Complete amplifier system

Solution: With $R_1 = R_2$, from Equation (9.93), we have

$$v_{O1} = \left(\frac{\delta}{4}\right) V^+$$

For $V^+ = 7.5\,\text{V}$ and $\delta = 0.01$, the maximum output of the bridge circuit is $v_{O1} = 0.01875\,\text{V}$. If the output of the amplifier system is to be $+5\,\text{V}$, the gain of the instrumentation amplifier must be $5/0.01875 = 266.7$. Consider the instrumentation amplifier shown in Figure 9.25. The output voltage is given by Equation (9.67), which can be

$$\frac{v_O}{v_{O1}} = \frac{R_4'}{R_3'}\left(1 + \frac{2R_2'}{R_1'}\right) = 266.7$$

We would like the ratios R_4'/R_3' and R_2'/R_1' to be the same order of magnitude. If we let $R_3' = 15.0\,\text{k}\Omega$ and $R_4' = 187.0\,\text{k}\Omega$, then $R_4'/R_3' = 12.467$ and $R_2'/R_1' = 10.195$. If we set $R_2' = 200.0\,\text{k}\Omega$, then $R_1' = 19.62\,\text{k}\Omega$.

Resistance R_1' can be a combination of a fixed resistance in series with a potentiometer, to permit adjustment of the gain.

Comment: The complete design of this instrumentation amplifier is shown in Figure 9.42. Correlation of the reference voltage source design is left as an exercise.