电子科技大学
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Circuit Analysis and Design

Academic year 2019/2020 – Semester 1 – Presentation 14

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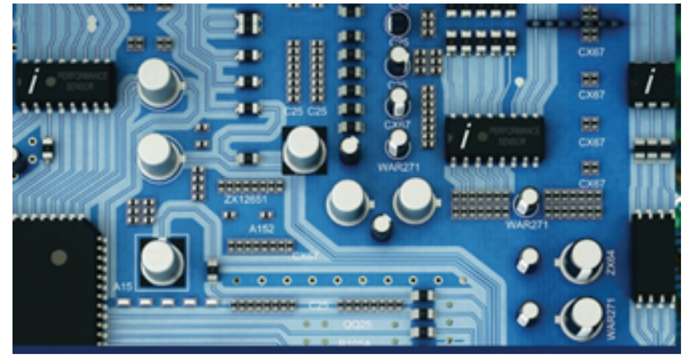
"A good student never steal or cheat"

Agenda



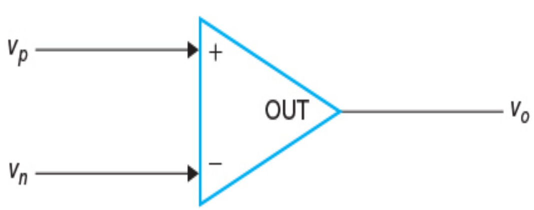
- **Ideal op amp**
- **Sum and difference**
- **Analysis of inverting configuration**
- **Analysis of noninverting configuration**

Introduction

- An operational amplifier (commonly called op amp or opamp*)* is a device that can be used to perform mathematical operations such as addition, subtraction, amplification, attenuation, integration, and differentiation. It is a versatile integrated circuit (IC) chip that is widely used in amplifiers, filters, signal conditioning, and instrumentation circuits. The circuit symbol for an op amp is shown in Figure 5.1.
- Figure 5.2 shows pin configuration for a typical 8-pin package.

FIGURE 5.1

Circuit symbol for an op amp.



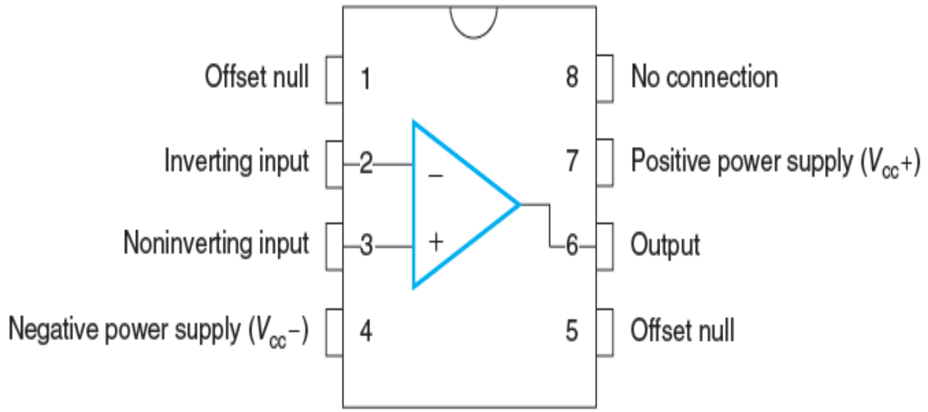


FIGURE 5.2

Ideal Op Amp

- Op amps can be modeled as a voltage-controlled voltage source (VCVS), as shown in Figure 5.3. In the model, v_n is the voltage on the inverting input (pin 2), v_p is the voltage on the noninverting input (pin 3), v_o is the voltage on the output (pin 6), R_i is the input resistance, R_o is the output resistance, and A is the unloaded voltage gain. In general, the input resistance R_i is large, the output resistance R_o is small, and the gain A is large.
- Figure 5.4 shows the inverting configuration of an op amp. The input voltage v_s is applied to the inverting input through a resistor R_1. Resistor R_2 provides a feedback path between the output terminal and the inverting input terminal. When the op amp is replaced by the model shown in Figure 5.3, we obtain the circuit shown in Figure 5.5.

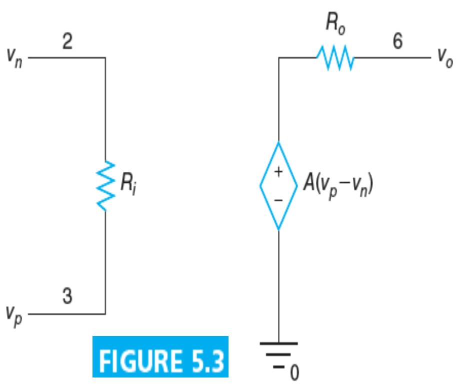


FIGURE 5.3

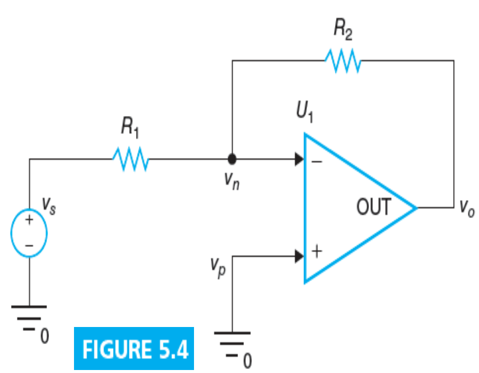


FIGURE 5.4

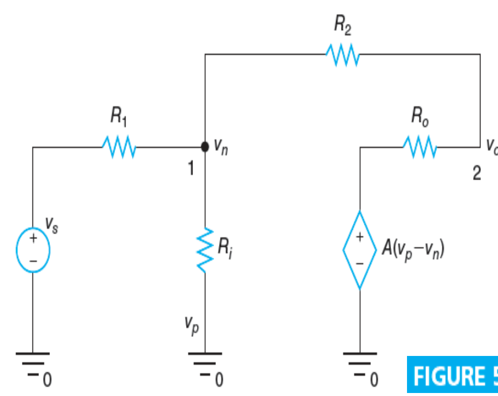


FIGURE 5.5

Summing Amplifier (Inverting Configuration)

- **An inverting amplifier with two inputs is shown in Figure 5.30.**

- **Sum the currents leaving node 1:** $\dfrac{0-v_1}{R_1}+\dfrac{0-v_2}{R_2}+\dfrac{0-v_o}{R_f}=0$

- **Solve for v_o:** $v_o=-\left(\dfrac{R_f}{R_1}v_1+\dfrac{R_f}{R_2}v_2\right)$

- **If** $R_1 = R_f$, $R_2 = R_f$, $v_o = -(v_1 + v_2)$

- **If** $R_1 = R_f/k_1$, $R_2 = R_f/k_2$, **we obtain**

$$v_o=\frac{R_4}{R_3}\left(\frac{R_f}{R_1}v_1+\frac{R_f}{R_2}v_2\right)$$

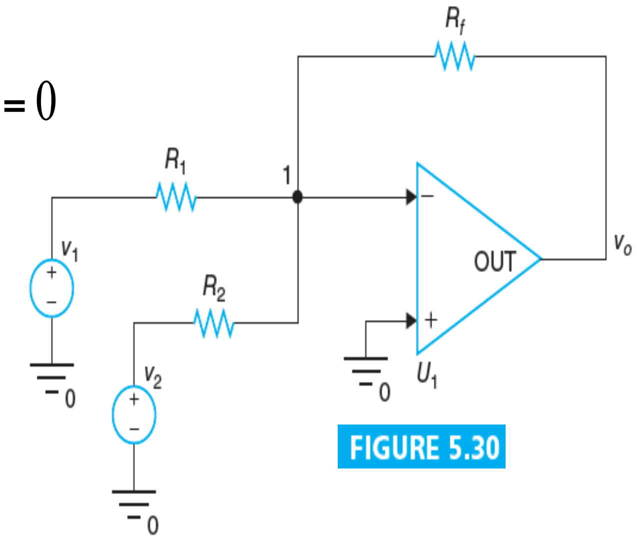


FIGURE 5.30

- **For the circuit shown in Fig.5.31, we get**

$$v_o=-\left(\frac{R_f}{R_1}v_1+\frac{R_f}{R_2}v_2\right)=-\left(k_1v_1+k_2v_2\right)$$

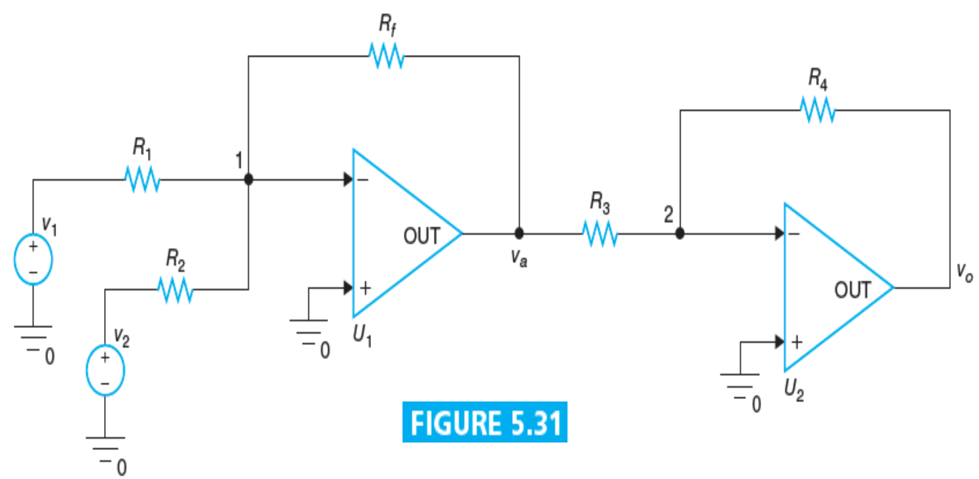


FIGURE 5.31

Summing Amplifier (Inverting Configuration, Continued)

- **An inverting amplifier with N inputs is shown in Figure 5.32.**

- **Sum the currents leaving node 1:** $$\frac{0-v_1}{R_1}+\frac{0-v_2}{R_2}+\ldots+\frac{0-v_N}{R_N}+\frac{0-v_o}{R_f}=0$$

- **Solve for v_o:** $$v_o=-\left(\frac{R_f}{R_1}v_1+\frac{R_f}{R_2}v_2+\ldots+\frac{R_f}{R_N}v_N\right)$$

- **If** $R_1 = R_2 = \ldots = R_N = R_f$**,**

$v_o = -(v_1 + v_2 + \ldots + v_N)$

- **If** $R_1 = R_f/k_1$, $R_2 = R_f/k_2$, …, $R_N = R_f/k_N$**,**

we obtain

$$v_o=-\left(k_1v_1+k_2v_2+\ldots+k_Nv_N\right)$$

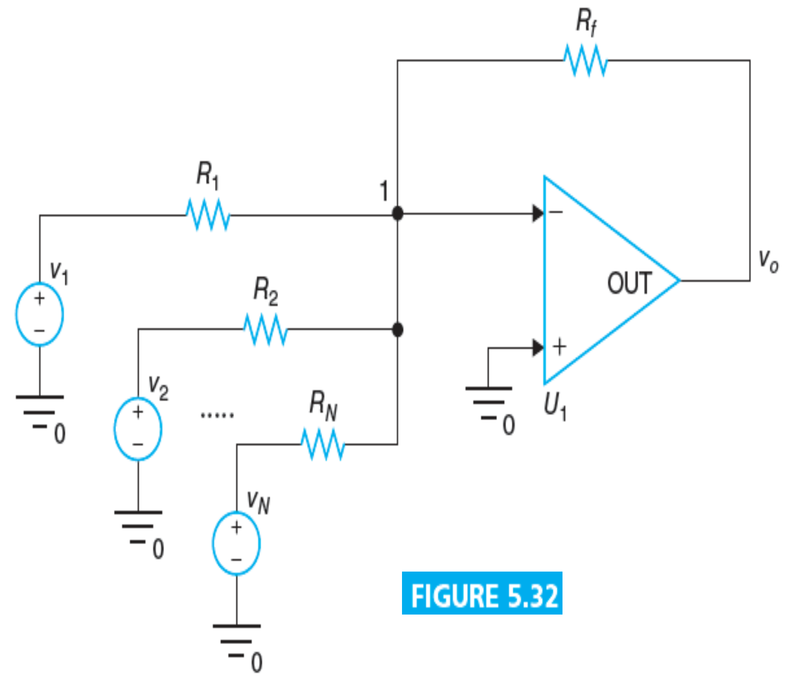


FIGURE 5.32

Summing Amplifier (Noninverting Configuration)

- **A noninverting amplifier with two inputs is shown in Figure 5.33.**

- **Voltage divider rule on R_5-R_4:** $v_n = \dfrac{R_4}{R_4 + R_5} v_o \Rightarrow v_o = \dfrac{R_4 + R_5}{R_4} v_n$

- **Sum the currents leaving node 1:**

$$\frac{v_p - v_1}{R_1} + \frac{v_p - v_2}{R_2} + \frac{v_p}{R_3} = 0 \Rightarrow \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) v_p = \frac{v_1}{R_1} + \frac{v_2}{R_2},\ v_o = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \frac{R_4 + R_5}{R_4} \left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right) \quad (1)$$

- **If** $R_1 = R_2 = R_3 = R_4 = R$ **and** $R_5 = 2R$, v_o **becomes** $v_o = v_1 + v_2$

- **If** $R_3 = R_4 = R$, $R_1 = R/k_1$, $R_2 = R/k_2$, **and** $R_5 = R(k_1 + k_2)$, v_o **becomes** $v_o = k_1 v_1 + k_2 v_2$ (2)

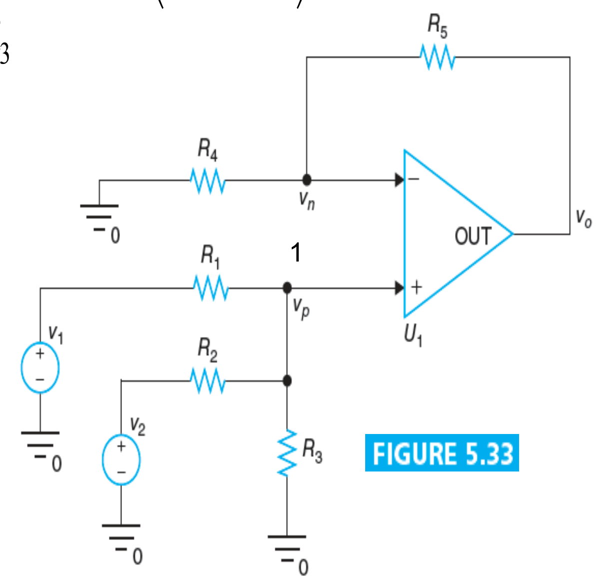


FIGURE 5.33

EXAMPLE 5.7

- **Design an op amp circuit for** $v_o = 0.5v_1 + 3v_2$.
- $k_1 = 0.5$, $k_2 = 3$
- **Let** $R = 3$ kΩ. **Then,**
- $R_3 = R_4 = R = 3$ kΩ
- $R_1 = R/k_1 = 6$ kΩ
- $R_2 = R/k_2 = 1$ kΩ
- $R_5 = R(k_1 + k_2) = 10.5$ kΩ
- **The circuit is shown in Figure 5.34.**

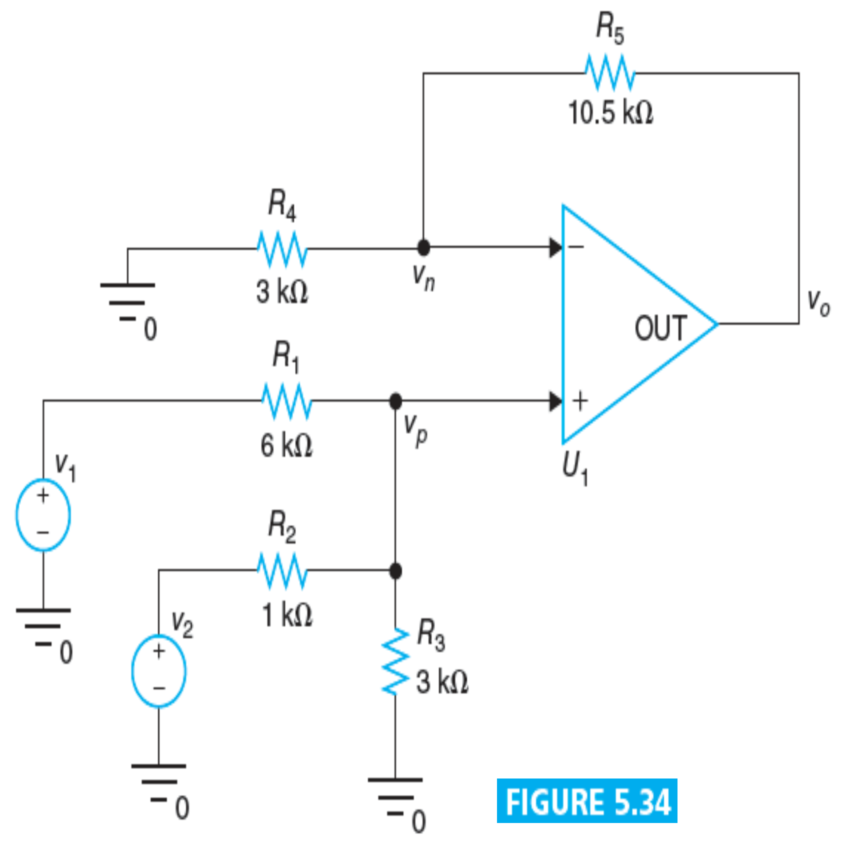


FIGURE 5.34

EXAMPLE 5.8

- **Design a circuit for converting a polar binary signal v_1 (1 is represented by a pulse with 5 V, and 0 is represented by a pulse with – 5 V) to a unipolar binary signal v_o (1 is represented by a pulse with 5 V, and 0 is represented by a pulse with 0 V).**
- **If** $R_1 = R_2 = R_3 = R_5 = R$ **and** $R_4 = 2R$, v_o **becomes**

$$v_o = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \frac{R_4 + R_5}{R_4} \left(\frac{v_1}{R_1} + \frac{v_2}{R_2} \right) = \frac{1}{2}\left(v_1 + v_2\right)$$

- **The circuit is shown in Figure 5.36 (v_2 = 5 V).**
- **Alternate choice:**

  $k_1 = k_2 = 0.5$

  $R = 10\ k\Omega$, $R_3 = R_4 = R = 10\ k\Omega$, $R_1 = R/k_1 = 20\ k\Omega$,

  $R_2 = R/k_2 = 20\ k\Omega$, $R_5 = R(k_1 + k_2) = 10\ k\Omega$
- **Figure 5.37 shows sample waveforms.**

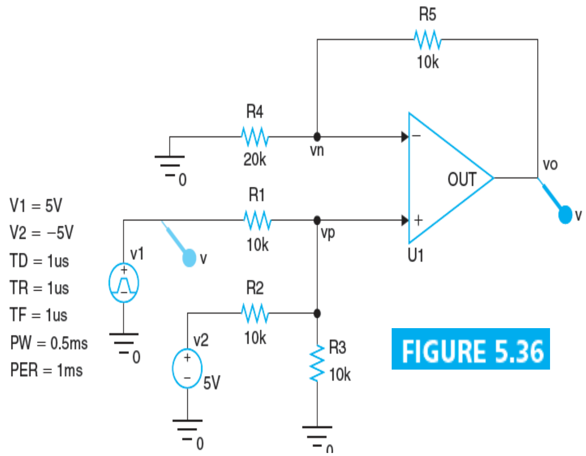


FIGURE 5.36

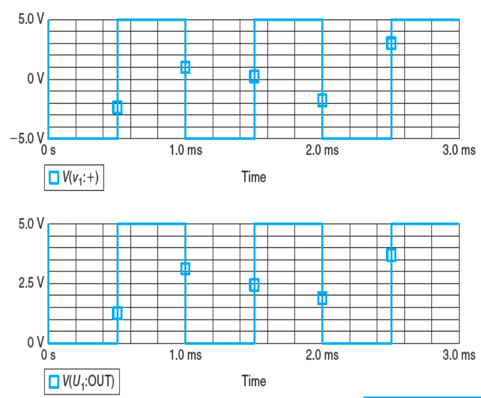


FIGURE 5.37

Summing Amplifier (Noninverting Configuration, N Inputs)

- **A noninverting summing amplifier with N inputs is shown in Figure 5.38.**
- **Voltage divider rule on R_{N+3} - R_{N+2}:** $v_n = \dfrac{R_{N+2}}{R_{N+2}+R_{N+3}} v_o \Rightarrow v_o = \dfrac{R_{N+2}+R_{N+3}}{R_{N+2}} v_n$
- **Sum the currents leaving node 1:**

$$\frac{v_p - v_1}{R_1} + \ldots + \frac{v_p - v_N}{R_N} + \frac{v_p}{R_{N+1}} = 0 \Rightarrow \left(\frac{1}{R_1} + \ldots + \frac{1}{R_{N+1}}\right) v_p = \frac{v_1}{R_1} + \ldots + \frac{v_N}{R_N}$$

$$v_o = \frac{1}{\dfrac{1}{R_1} + \ldots + \dfrac{1}{R_{N+1}}} \frac{R_{N+2}+R_{N+3}}{R_{N+2}} \left(\frac{v_1}{R_1} + \ldots + \frac{v_N}{R_N}\right) \quad (1)$$

- **If** $R_1 = R_2 = \ldots = R_{N+2} = R$ **and** $R_{N+3} = NR$,

v_o **becomes** $v_o = v_1 + v_2 + \ldots + v_N$

- **If** $R_{N+1} = R_{N+2} = R$, $R_1 = R/k_1, \ldots, R_N = R/k_N$, **and**
  $R_{N+3} = R(k_1 + k_2 + \ldots + k_N)$,
  $v_o = k_1 v_1 + k_2 v_2 + \ldots + k_N v_N$ (2)

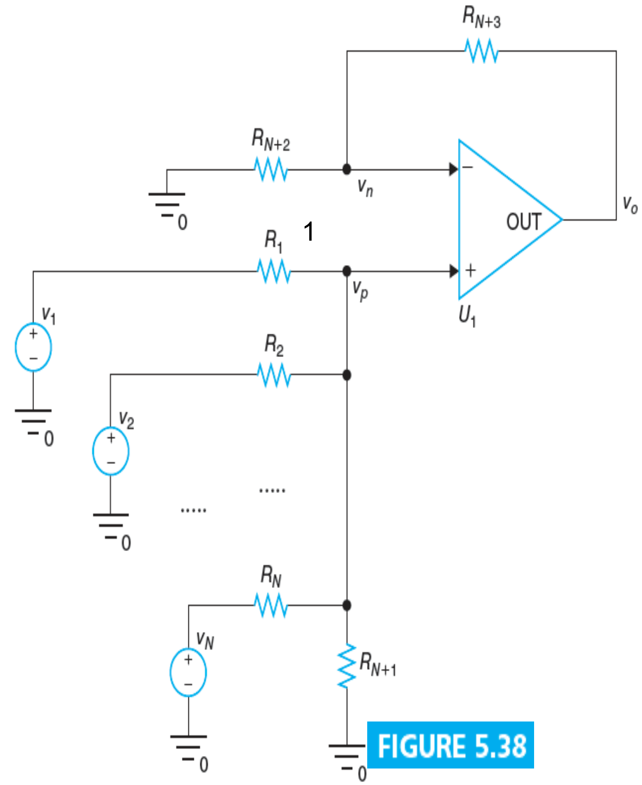


FIGURE 5.38

Difference Amplifier

- **A difference amplifier is shown in Figure 5.41.**
- **Voltage divider rule on R_3-R_4:** $v_p = \frac{R_4}{R_3 + R_4} v_2 \quad (1)$
- **Sum the currents leaving node 1:**

$$\frac{v_n - v_1}{R_1} + \frac{v_n - v_o}{R_2} = 0 \Rightarrow v_o = \frac{R_1 + R_2}{R_1} v_n - \frac{R_2}{R_1} v_1 \quad (2)$$

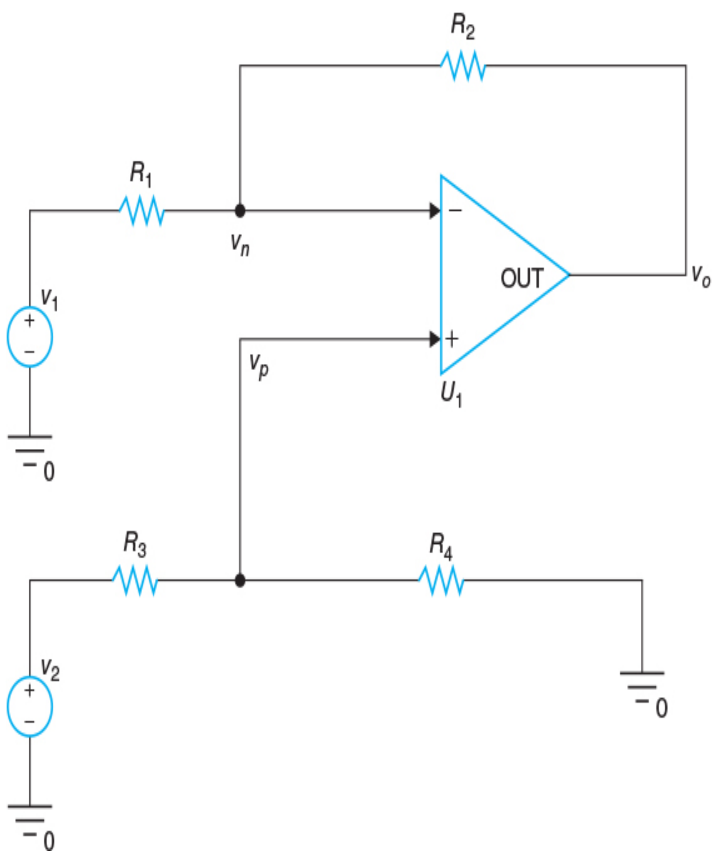
- **Substitute Equation (1) into Equation (2):**

$$v_o = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_2 - \frac{R_2}{R_1} v_1 \quad (3)$$

- **If** $R = R_1 = R_2 = R_3 = R_4$**, Equation (3) becomes** $v_o = v_2 - v_1$
- v_o **is the difference of** v_2 **and** v_1**.**

FIGURE 5.41

Difference amplifier.



EXAMPLE 5.9

- **Design a circuit for converting a unipolar binary signal v_2 (1 is represented by a pulse with 5 V, and 0 is represented by a pulse with 0 V) to a polar binary signal v_o (1 is represented by a pulse with 5 V, and 0 is represented by a pulse with – 5V).**
- $v_o = 2(v_2 - 2.5)$
- **If** $R_3 = R_1$, $R_4 = R_2$, $R_2 = 2R_1$, $v_1 = 2.5$ V, **we get**

$$v_o = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)v_2 - \frac{R_2}{R_1}v_1 = 2\left(v_2 - 2.5\right)$$

- **We choose** $R_1 = R_3 = 10\ \text{k}\Omega$, $R_2 = R_4 = 20\ \text{k}\Omega$ **in the circuit shown in Figure 5.42.**
- **Figure 5.43 shows sample waveforms.**

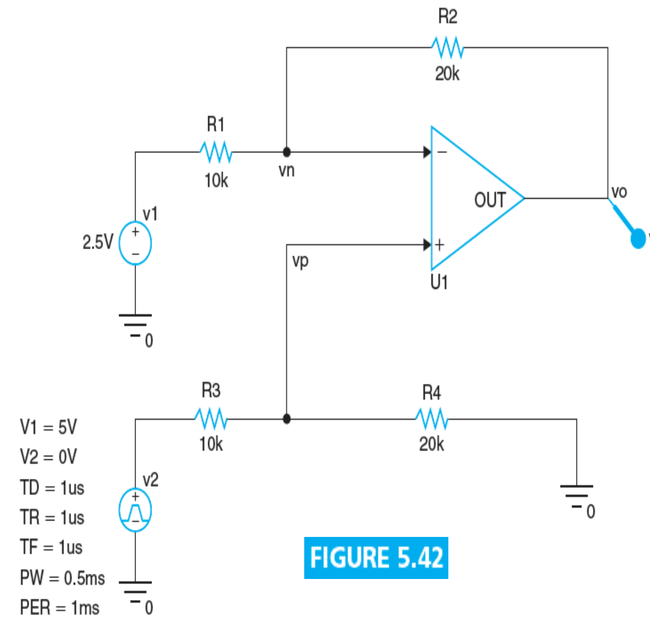


FIGURE 5.42

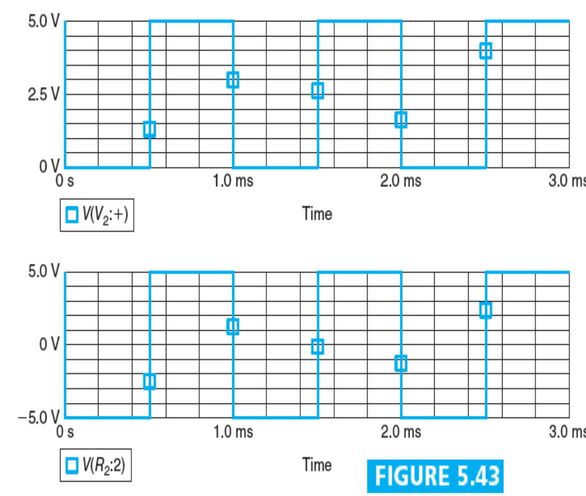


FIGURE 5.43

Op Amp Circuit to Implement $v_o = 7v_1 - 2v_2$

- **We can use the superposition principle to show that the circuit shown in Figure 5.44 provides an output voltage given by** $v_o = 7v_1 - 2v_2$**.**
- **Deactivate** v_2 **by short-circuiting it.** $v_a = 0$**.** U_2 **is configured as a noninverting amplifier. Thus,**

  $v_o = (1 + R_4/R_3)v_1 = (1 + 6)v_1 = 7v_1$
- **Deactivate** v_1 **by short-circuiting it. From the voltage divider rule, the voltage at node 1 is given by** $v_2/3$**. Thus,** $v_a = v_2/3$**.** U_2 **is configured as an inverting amplifier. Thus,**

  $v_o = (-R_4/R_3)v_a = (-6)v_2/3 = -2v_2$
- **Adding the two outputs, we obtain**

  $v_o = 7v_1 - 2v_2$

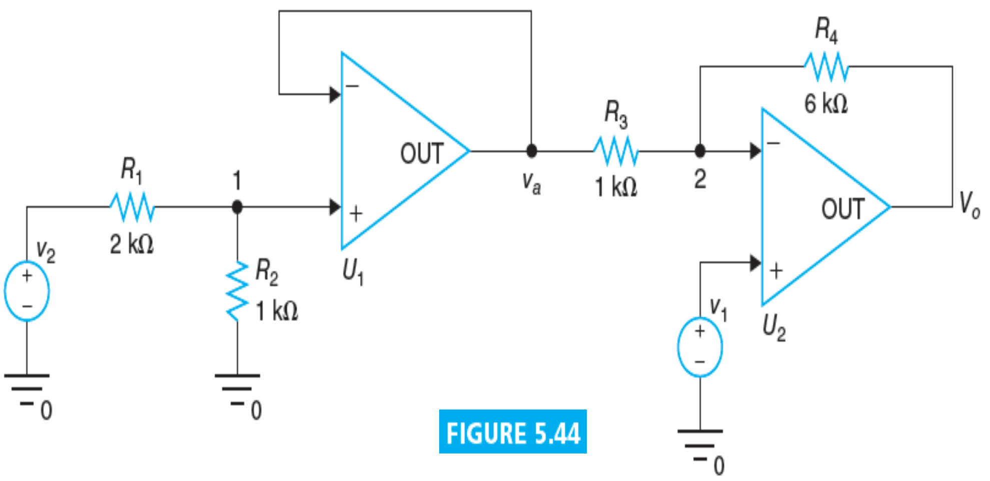


FIGURE 5.44

Analysis of Inverting Configuration

- A model for an inverting configuration is shown in Figure 5.52.

Notice that $v_p = 0$.

- Summing the currents leaving node 2, we obtain

$$\frac{v_o - v_n}{R_2} + \frac{v_o + Av_n}{R_o} = 0 \Rightarrow v_n = \frac{R_o + R_2}{R_o - R_2 A} v_o, \quad v_o = \frac{R_o - R_2 A}{R_o + R_2} v_n \quad (1)$$

- Summing the currents leaving node 1, we obtain

$$\frac{v_n - v_s}{R_1} + \frac{v_n}{R_i} + \frac{v_n - v_o}{R_2} = 0 \Rightarrow \left(\frac{1}{R_1} + \frac{1}{R_i} + \frac{1}{R_2} \right) v_n - \frac{v_o}{R_2} = \frac{v_s}{R_1} \quad (2)$$

- Solving Equations (1) and (2) for v_n and v_o,

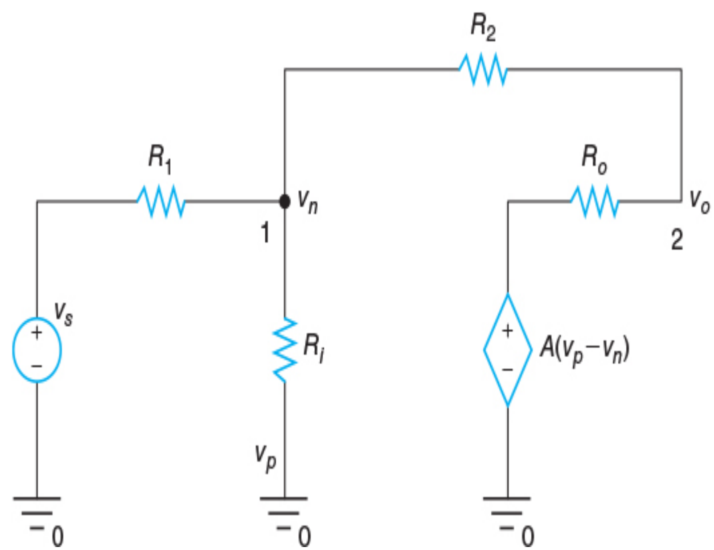
we get

$$v_n = \frac{R_i (R_o + R_2) v_s}{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + A R_1 R_i} \quad (3)$$

$$v_o = \frac{-R_i (-R_o + R_2 A) v_s}{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + A R_1 R_i} \quad (4)$$

FIGURE 5.52

A model for an inverting configuration.



Analysis of Inverting Configuration (Continued)

- **If** $R_o = 0$ **and** $R_i = \infty$**, Equations (3) and (4) become, respectively**

$$v_n = \frac{R_2 v_s}{R_1 + R_2 + AR_1} \cong \frac{R_2}{AR_1} v_s \approx 0 \quad (5)$$

$$v_o = \frac{-R_2 A v_s}{R_1 + R_2 + AR_1} \cong -\frac{R_2}{R_1} v_s \quad (6)$$

- **The current through** R_1 **is given by**

$$i_1 = \frac{v_s - v_n}{R_1} = \frac{R_o + R_2 + R_i + AR_i}{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + AR_1 R_i} v_s$$

- **The input resistance is given by**

$$R_{in} = \frac{v_s}{i_1} = \frac{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + AR_1 R_i}{R_o + R_2 + R_i + AR_i} \approx R_1$$

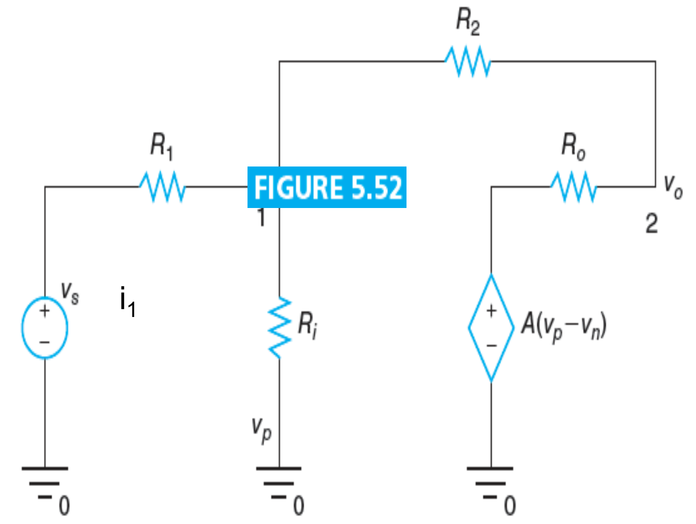


FIGURE 5.52

Analysis of Inverting Configuration (Continued)

- To find the output resistance, we apply test voltage between node 2 and ground as shown in Figure 5.53. From the voltage divider rule, v_n is given by

$$v_n = \frac{R_1 \parallel R_i}{R_2 + (R_1 \parallel R_i)} v_t = \frac{\dfrac{R_1 R_i}{R_1 + R_i}}{R_2 + \dfrac{R_1 R_i}{R_1 + R_i}} v_t = \frac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t$$

- The current out of the test voltage source is

$$i_t = \frac{v_t - v_n}{R_2} + \frac{v_t + A v_n}{R_o} = \frac{v_t - \dfrac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t}{R_2} + \frac{v_t + A \dfrac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t}{R_o}$$

- The output resistance is the ratio of v_t to i_t:

$$R_{out} = \frac{R_o (R_1 R_2 + R_2 R_i + R_1 R_i)}{R_o R_1 + R_o R_i + A R_1 R_i + R_1 R_2 + R_2 R_i + R_1 R_i} \cong \frac{R_o (R_2 + R_1)}{A R_1} \approx 0$$

- The output resistance is close to zero for the inverting configuration.

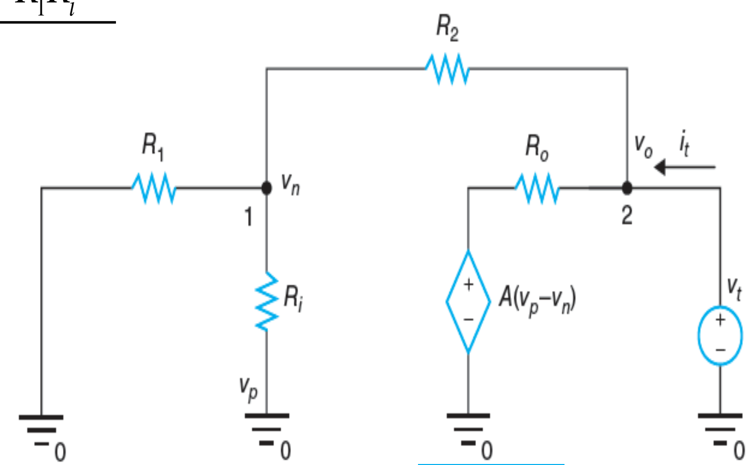


FIGURE 5.53

EXAMPLE 5.10

- **Find V_o in the circuit shown in Figure 5.54.**
- **Summing the currents leaving node 1, we obtain** $$\frac{V_n - 1}{1000} + \frac{V_n}{1000} + \frac{V_n - V_o}{5000} = 0$$
- **Multiplication by 5000 yields**

  $5V_n - 5 + 5V_n + V_n - V_o = 0 \Rightarrow 11V_n - V_o = 5$ (1)

- **Summing the currents leaving node 2, we obtain** $$\frac{V_o - V_n}{5000} + \frac{V_o - 1000(0 - V_n)}{1000} = 0$$
- **Multiplication by 5000 yields**

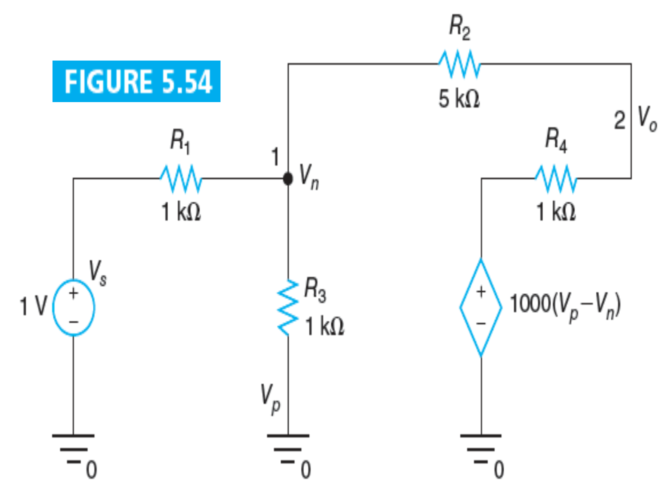
  $V_o - V_n + 5V_o + 5000V_n = 0 \Rightarrow 4999V_n + 6V_o = 0$ (2)

- **Multiply Equation (1) by 6:** $66V_n - 6V_o = 30$ (3)
- **Add Equations (2) and (3):** $5065V_n = 30$
- $V_n = 30/5065 = 0.005923$ V (4)
- **Substitute Equation (4) into Equation (1):**

  $V_o = 11V_n - 5 = -4.934847$ V

- **Due to small value of** A, V_o **is off from** – 5 V **(ideal model).**

FIGURE 5.54



Analysis of Noninverting Configuration

- A model for a noninverting configuration is shown in Figure 5.56.
- Summing the currents leaving node 2, we obtain

$$\frac{v_o - v_n}{R_2} + \frac{v_o - A(v_s - v_n)}{R_o} = 0 \quad (1)$$

- Summing the currents leaving node 1, we obtain

$$\frac{v_n}{R_1} + \frac{v_n - v_s}{R_i} + \frac{v_n - v_o}{R_2} = 0 \Rightarrow \left(\frac{1}{R_1} + \frac{1}{R_i} + \frac{1}{R_2}\right) v_n = \frac{v_s}{R_i} + \frac{v_o}{R_2} \quad (2)$$

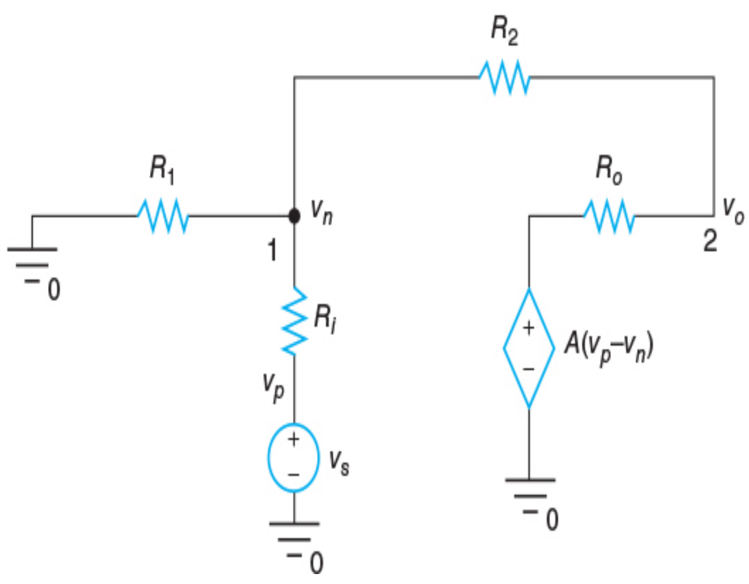
- Solving Equations (1) and (2) for v_n and v_o, we get

$$v_n = \frac{R_1(R_o + R_2 + AR_i)v_s}{R_oR_i + R_oR_1 + R_iR_2 + R_1R_2 + R_1R_i + AR_1R_i} \quad (3)$$

$$v_o = \frac{(R_oR_1 + R_1R_iA + R_2R_iA)v_s}{R_oR_i + R_oR_1 + R_iR_2 + R_1R_2 + R_1R_i + AR_1R_i} \quad (4)$$

FIGURE 5.56

Model of a noninverting configuration.



Analysis of Noninverting Configuration (Continued)

- **The current through** R_i **is given by**

$$i_1 = \frac{v_s - v_n}{R_i} = \frac{v_s}{R_i} - \frac{\left(R_o R_1 + R_1 R_2 + A R_1 R_i\right) v_s}{R_i\left(R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + A R_1 R_i\right)} = \frac{\left(R_o + R_2 + R_1\right) v_s}{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + A R_1 R_i} \approx 0$$

- **The input resistance is given by**

$$R_{in} = \frac{v_s}{i_1} = \frac{R_o R_i + R_o R_1 + R_i R_2 + R_1 R_2 + R_1 R_i + A R_1 R_i}{R_o + R_2 + R_1} \cong \frac{A R_1 R_i}{R_o + R_2 + R_1} \approx \frac{A R_1 R_i}{R_2 + R_1}$$

- **If** $R_o = 0$ **and** $R_i = \infty$**,**

equations (3) and (4) become:

$$v_n = \frac{A R_1 v_s}{R_1 + R_2 + A R_1} \approx v_s \quad (5)$$

$$v_o = \frac{A\left(R_1 + R_2\right) v_s}{R_1 + R_2 + A R_1} \cong \left(1 + \frac{R_2}{R_1}\right) v_s \quad (6)$$

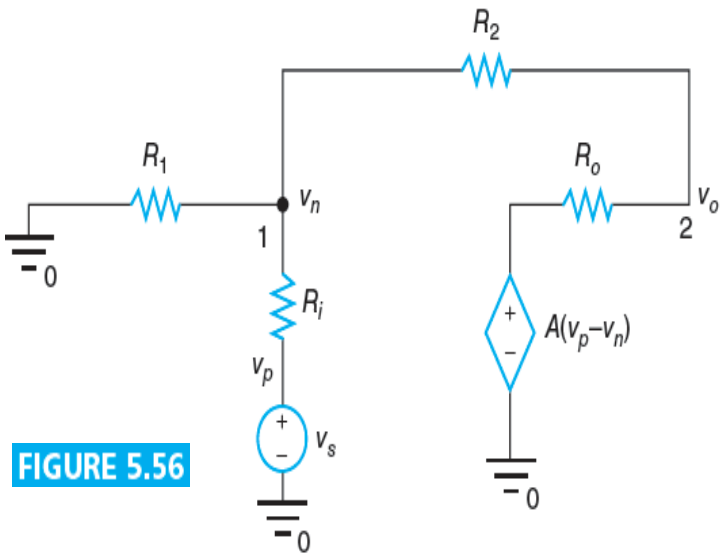


FIGURE 5.56

Analysis of Noninverting Configuration (Continued)

- To find the output resistance, we apply test voltage between node 2 and ground as shown in Figure 5.57. From the voltage divider rule, v_n is given by

$$v_n = \frac{R_1 \| R_i}{R_2 + (R_1 \| R_i)} v_t = \frac{\dfrac{R_1 R_i}{R_1 + R_i}}{R_2 + \dfrac{R_1 R_i}{R_1 + R_i}} v_t = \frac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t$$

- The current out of the test voltage source is

$$i_t = \frac{v_t - v_n}{R_2} + \frac{v_t + A v_n}{R_o} = \frac{v_t - \dfrac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t}{R_2} + \frac{v_t + A \dfrac{R_1 R_i}{R_1 R_2 + R_2 R_i + R_1 R_i} v_t}{R_o}$$

- The output resistance is the ratio of v_t to i_t:

$$R_{out} = \frac{R_o (R_1 R_2 + R_2 R_i + R_1 R_i)}{R_o R_1 + R_o R_i + A R_1 R_i + R_1 R_2 + R_2 R_i + R_1 R_i} \cong \frac{R_o (R_2 + R_1)}{A R_1} \approx 0$$

- The output resistance is close to zero for noninverting configuration.

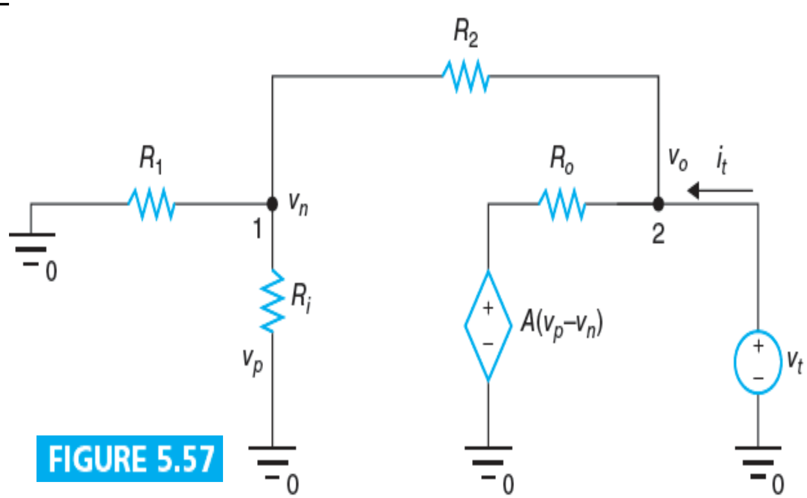


FIGURE 5.57

EXAMPLE 5.11

- **Find V_o in the circuit shown in Figure 5.58.**
- **Summing the currents leaving node 1, we obtain** $$\frac{V_n - 1}{2000} + \frac{V_n}{1000} + \frac{V_n - V_o}{9000} = 0$$
- **Multiplication by** 18000 **yields**

  $9V_n – 9 + 18V_n + 2V_n – 2V_o = 0 \Rightarrow 29V_n – 2V_o = 9$ (1)

- **Summing the currents leaving node 2, we obtain** $$\frac{V_o - V_n}{9000} + \frac{V_o - 2000(1 - V_n)}{3000} = 0$$
- **Multiplication by** 9000 **yields**

  $V_o – V_n + 3V_o – 6000 + 6000V_n = 0 \Rightarrow 5999V_n + 4V_o = 6000$ (2)

- **Multiply Equation (1) by** 2: $58V_n – 4V_o = 1$ (3)
- **Add Equations (2) and (3):** $6057V_n = 6018$
- $V_n = 6018/6057 = 0.99356117$ V (4)
- **Substitute Equation (4) into Equation (1):**

  $V_o = (29/2)V_n – (9/2) = 9.90664$ V

- **Due to small value of** A, V_o **is off**

from 10 V **(ideal model).**

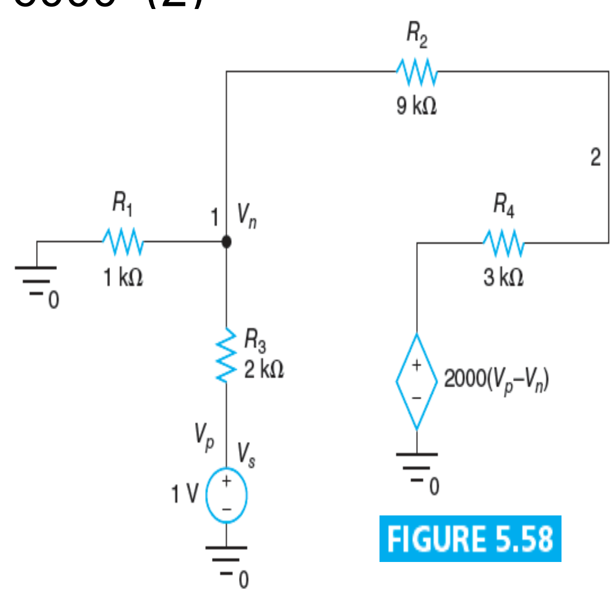


FIGURE 5.58

Summary

- **Without the negative feedback component from the output, the output** v_o **will be large due to large gain** A**. The negative feedback component provides comparable gain in the denominator to offset the effects of large gain in the numerator.**
- **In the ideal op amp model, assume large input resistance (**$R_i = \infty$**), small output resistance (**$R_o = 0$**), and large gain** A**. Then, the current flowing into (or out of) the two input terminals is zero, that is,** $i_p = 0$**, and** $i_n = 0$**. Also, the voltage at the negative input terminal is equal to the voltage at the positive input terminal (**$v_n = v_p$**). This is called virtual short.**
- **In the inverting configuration of op amp,** v_o, v_n, i_{Ri}, R_{in}, R_{out} **are given by**

$$v_o = -\frac{R_2}{R_1}v_s \quad v_n \cong \frac{R_2}{AR_1}v_s \approx 0 \quad i_{R_i} = \frac{v_d}{R_i} = \frac{-v_n}{R_i} \cong -\frac{R_2}{R_1 A R_i}v_s \approx 0 \quad R_{in} = \frac{v_s}{i_1} \approx R_1 \quad R_{out} \cong \frac{R_o(R_2+R_1)}{AR_1} \approx 0$$

- **In the noninverting configuration of op amp,** v_o**,** v_n**,** i_{Ri}**,** R_{in}**,** R_{out} **are given by**

$$v_o \cong \left(1+\frac{R_2}{R_1}\right)v_s \quad v_n = \frac{AR_1 v_s}{R_1+R_2+AR_1} \approx v_s \quad i_{R_i} = \frac{v_s - v_n}{R_i} \approx 0 \quad R_{in} \approx \frac{AR_1R_i}{R_2+R_1} \quad R_{out} \cong \frac{R_o(R_2+R_1)}{AR_1} \approx 0$$

Summary (Continued)

- **A summing amplifier can be designed in inverting configuration or in noninverting configuration.**
- **In the inverting configuration, for N inputs, the output can be**

  $v_o = -(k_1v_1 + k_2v_2 + \ldots + k_Nv_N)$

  In the noninverting configuration, for N inputs, the output can be

  $v_o = k_1v_1 + k_2v_2 + \ldots + k_Nv_N$
- **The output of a difference amplifier is given by**

$$v_o = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)v_2 - \frac{R_2}{R_1}v_1$$

If $R = R_1 = R_2 = R_3 = R_4$**, the output is given by**

$v_o = v_2 - v_1$