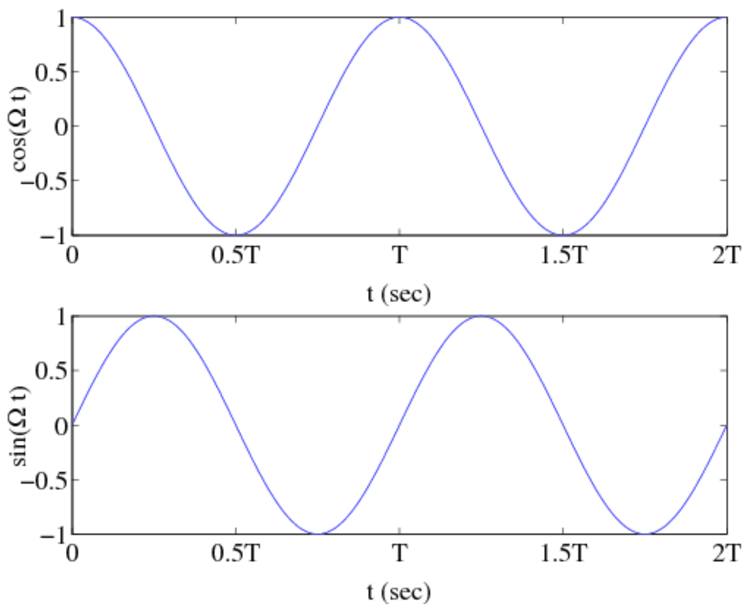
EE 2010 Circuit Analysis

Module 18: Active Filters: Op-Amps with Dynamic Elements Notes

These notes are drawn from *Alexander and Sadiku*, 2013, *O'Malley*, 2011, and other sources. They are intended to offer a summary of topics to guide you in focused studies. You should augment this handout with notes taken in class, reading textbook(s), and working additional example problems.

Recall **Definition:** A *sinusoid* is a continuous function (of t) having the form of a cosine $A\cos(2\pi f t + \phi)$ or a sine $A\sin(2\pi f t + \theta)$, where A is the amplitude, f is the *frequency* in cycles/s or Hz, $\omega = 2\pi f$ is the *angular frequency* in radians/s, and ϕ and θ are the phases in radians. The *period* of the sinusoid is $T = \frac{1}{f} = \frac{2\pi}{2\pi f} = \frac{2\pi}{\omega}$. In what follows, we will interchangeably reference frequencies f in Hz and ω in Rad/Sec.



The phase of a continuous-time sinusoid manifests as a kind of "time delay." Notice that $\sin(2\pi f t)$ can be written as $\cos(2\pi f t - \pi/2)$ – a time *delay* and that $\cos(2\pi f t)$ can be written as $\sin(2\pi f t + \pi/2)$ – a time *advance*. In what follows, we will typically express sinusoidal waveforms in their $\cos(\cdot)$ form.

And recall: For any linear operation or system, we have **sinusoidal in → sinusoidal out!** and at exactly the same frequency.

$$A\cos(\omega_0 t + \theta) \longrightarrow \boxed{\mathcal{L}} \text{———} (|H(j\omega_0)| \cdot A)\cos(\omega_0 t + \theta + \angle H(j\omega_0))$$

That is, the effect of *any linear operation on a sinusoid* is a change of *amplitude* $A \to (|H(j\omega_0)| \cdot A)$ and/or a change of *phase* $\theta \to \theta + \angle H(j\omega_0)$. Then to analyze the operation of a linear system (circuit) on sinusoidal signals, we need only determine, as a function of frequency ω (or f with $\omega = 2\pi f$), the affect of the system on the *amplitude* (i.e, find $|H(j\omega)|$) and the *phase* (i.e., find

$\angle H(j\omega)$) on the input signal, and these are the **magnitude and phase of the Transfer Function** of the system!

The Concept of Filters The sinusoidal steady-state frequency responses of circuits are of significance in many applications, especially in communications and control systems. A specific application is in electric filters that block out or eliminate signals with unwanted frequencies and pass signals with the desired frequencies. Filters are used in all sorts of instrumentation, radio, TV, and telephone systems to separate one broadcast frequency from another.

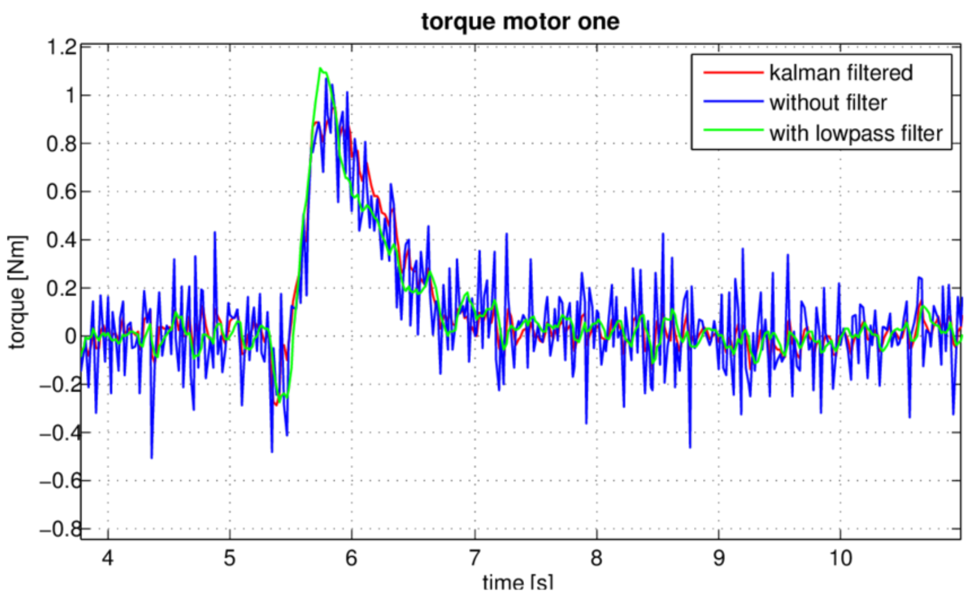


Figure 1: Filtering in a Mechanical Application

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Procedures for the Analysis of Active (Op-Amp) Filters:

Using the s-domain steady-state impedance models:

s-domain	**Steady State @ ω R/s**	**Steady State @ f Hz**
$Z_R = R$	$Z_R = R$	$Z_R = R$
$Z_C = \frac{1}{s \cdot C}$	$Z_C = \frac{1}{j\omega \cdot C}$	$Z_C = \frac{1}{j2\pi f \cdot C}$
$Z_L = s \cdot L$	$Z_L = j\omega \cdot L$	$Z_L = j2\pi f \cdot L$

Table 1: Steady-State Impedance Models for R, C, and L

1. Replace *all independent sources with symbolic representations such as* $V_{in}(s)$
2. Employ s-domain impedance models
3. Analyze the circuit incorporating appropriate Op-Amp properties

4. Use algebra or an algebra solver to find the output: $V_{out}(s)$, or whatever output function is dictated by the problem

5. Find the transfer function: $H(s) = \frac{V_{out}(s)}{V_{in}(s)}$, or whatever input-output function is dictated by the problem

6. We immediately have the steady-state transfer function $H(f)$ by letting $s = j2\pi f$ or $H(\omega)$ by letting $s = j\omega$

7. When asked plot $|H(\cdot)|$ and $\angle H(\cdot)$ as a function of f or ω to gain insight as to the operation of the active circuit.

8. In general, we can now compute $V_{out}(\cdot) = H(\cdot)V_{in}(\cdot)$ where $H(\cdot)$ at any particular f or ω is a complex number accounting for both the change in amplitude (through $|H(\cdot)|$) and change of phase (through $\angle H(\cdot)$)

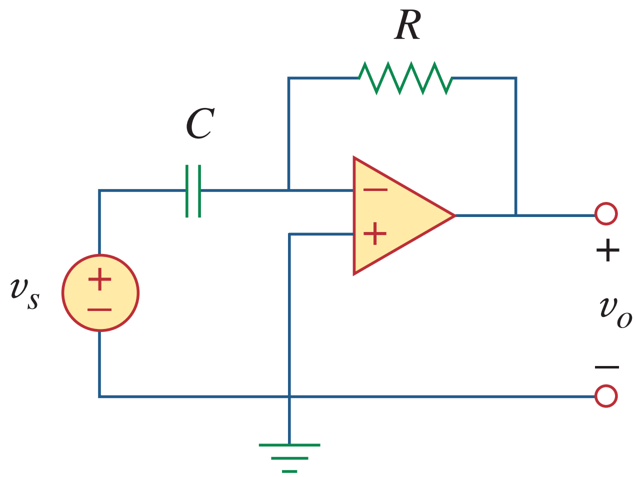
   For example, for a sinusoidal input at a particular frequency, ω_0, with

   $$v_{in}(t) = A\cos(\omega_0 t + \theta)$$

   the output is found as:

   $$v_{out}(t) = A|H(\omega_0)|\cos(\omega_0 t + \theta + \angle H(\omega_0))$$

Example 1: Find the transfer function:



Writing a node equation at the inverting input, we have:

$$\frac{(0 - V_s)}{\frac{1}{Cs}} + \frac{(0 - V_o)}{R} = 0$$

or

$$V_o = -V_s RCs$$

which, in time-domain yields:

$$v_o(t) = -RC\frac{dv_s(t)}{dt}$$

that is, a time-derivative.

The transfer function $H(s)$ of this inverting derivative is immediately observed as

$$\frac{V_o}{V_s} = H(s) = -RCs$$

which we will later recognize as a one-pole high-pass filter.

This analysis is applicable for any input. As a special case, the operation of a derivative for sinusoidal steady-state (at frequency ω) is specified by the transfer function:

$$H(\omega) = -j\omega RC$$

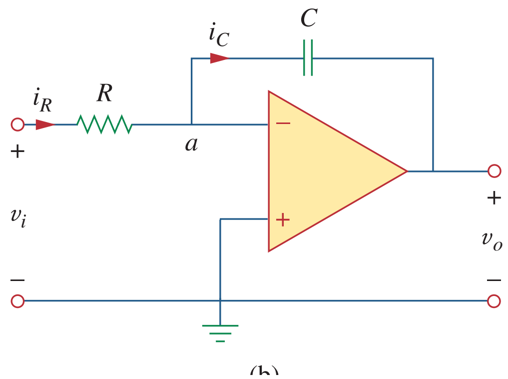
so that if

$$v_s(t) = A\cos(\omega t),$$

then $v_o(t) = A\omega RC\sin(\omega t)$ or

$$v_o(t) = A\omega RC\cos(\omega t - \frac{\pi}{2})$$

Example 2: Find the transfer function:



Again, writing a node equation at the inverting input, we have:

$$\frac{(0 - V_i)}{R} + \frac{(0 - V_o)}{\frac{1}{Cs}} = 0$$

or

$$V_o = -\frac{V_i}{RCs}$$

which, in time-domain yields:

$$v_o(t) = -\frac{1}{RC}\int v_i(t)dt$$

that is, an integrator.

The transfer function $H(s)$ of this inverting integrator is immediately observed as

$$\frac{V_o}{V_i} = H(s) = -\frac{1}{RCs}$$

which we will later recognize as a one-pole low-pass filter.

Integrators (when carefully applied to avoid saturation) can be very useful in many situations and applicable to any input.

As a special case, the operation of an integrator for sinusoidal steady-state (at frequency ω) yields:

$$V_o(\omega) = -\frac{1}{j\omega RC}V_i(\omega)$$

so that if

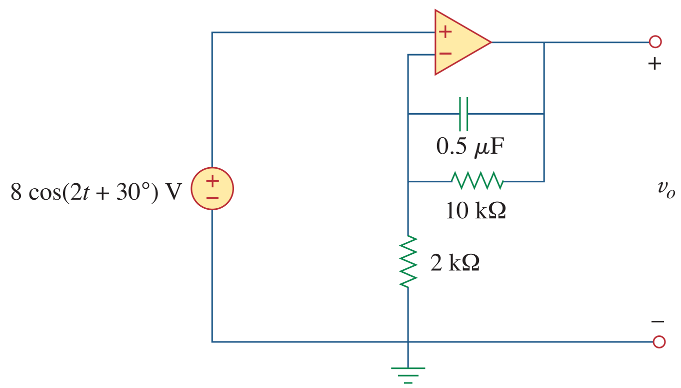
$$v_i(t) = A\cos(\omega t),$$

then $v_o(t) = \frac{A}{\omega RC}\sin(\omega t)$ or

$$v_o(t) = \frac{A}{\omega RC}\cos(\omega t - \frac{\pi}{2})$$

Problem 10.71

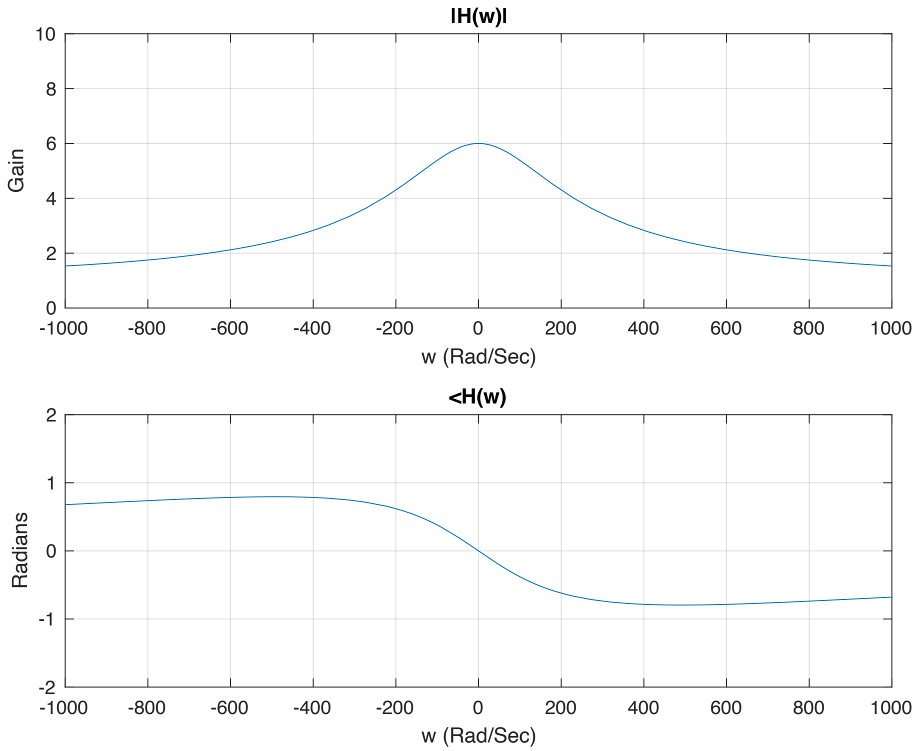
1. Find the transfer function.
2. Plot the magnitude and phase of the transfer function.
3. Evaluate the magnitude and phase of the transfer function at the specified input frequency.
4. Find the output due to the specified input.




```
%% Problem 10.71
clear all
polarForm = @(z) double([abs(z)  angle(z)]); % Function to give polar form
syms Vin Vout H s w
Vout = solve(Vin/2000 + (Vin-Vout)/10000 + (Vin-Vout)*s*0.5e-6 ,Vout)
% 1) Find the transfer function
H(s) = simplify(Vout/Vin)
% 2) Plot the magnitude and phase of the transfer function.
wmax = 1000; % Frequency limit for plotting
figure(71)
subplot(2,1,1)
fplot(abs(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, 0, 10])
title('|H(w)|'); xlabel('w (Rad/Sec)'); ylabel('Gain')
subplot(2,1,2)
fplot(angle(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, -pi, pi])
title('<H(w)'); xlabel('w (Rad/Sec)'); ylabel('Radians')
snapnow;
% 3) Evaluate the magnitude and phase at the specified input frequency.
w = 2
% Find the polar form of the transfer function at the specified frequency
HPolar=polarForm(H(j*w))
% 4) Find the output due to the specified input.
fprintf('Vout(t) = %0.2g *8*cos(%0.2f*t + 30*2*pi/360 %+0.2f )\n',HPolar(1), w,
    HPolar(2))
%
```

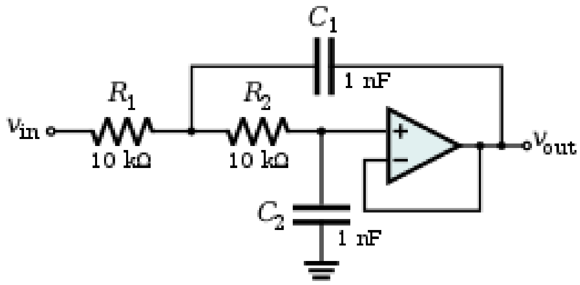
which yields:

```
H(s) = (s + 1200)/(s + 200)
w =      2
HPolar =     5.9997   —0.0083
Vout(t) = 6 *8*cos(2.00*t + 30*2*pi/360 —0.01 )
```



Which is a first-order low-pass filter.

A popular filter class from WIKIPEDIA:



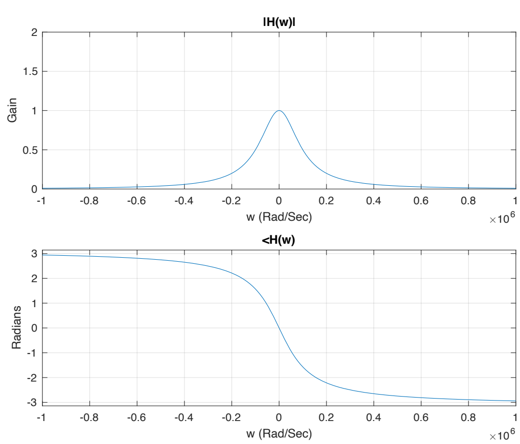
The Sallen-Key Lowpass:

This is a voltage-follower, so $V_{out} = V_+ = V_-$.

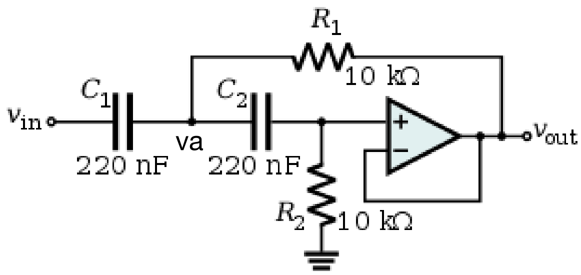
```
%% Sallen-Key Lowpass
clear all
syms Vin va Vout H s w
[Vin,Vout] = solve((va-Vin)/10000 + (va-Vout)/10000 + (va-Vout)*s*1e-9 ==0,...
              Vout == (va/(s*(1e-9)))/(10000+1/(s*1e-9)) ,Vin,Vout);
H(s) = simplify(Vout/Vin)
wmax = 1000000;  % Frequency limit for plotting
figure(5)
subplot(2,1,1)
fplot(abs(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, 0, 2])
title('|H(w)|'); xlabel('w (Rad/Sec)'); ylabel('Gain')
subplot(2,1,2)
fplot(angle(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, -pi, pi])
title('<H(w)'); xlabel('w (Rad/Sec)'); ylabel('Radians')
snapnow;
```

which yields

```
H(s) = 1.0000e+10/(s + 100000)^2
```



A high-pass configuration from WIKIPEDIA:



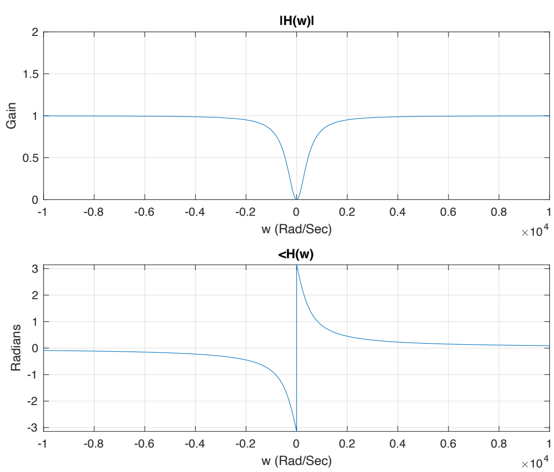
Sallen-Key Highpass:

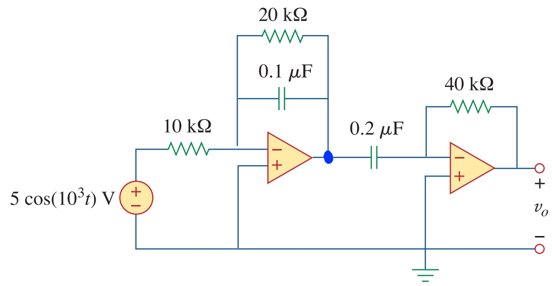
This is a voltage-follower, so $V_{out} = V_{+} = V_{-}$.

```
%% Sallen-Key Highpass
clear all
syms Vin va Vout H s w
[Vin,Vout] = solve((va-Vin)*s*220e-9 + (va-Vout)/10000 + (va-Vout)*s*220e-9 ==0,...
              Vout == (va*10000)/(10000+1/(s*220e-9)) ,Vin,Vout);
H(s) = simplify(Vout/Vin)
wmax = 10000;  % Frequency limit for plotting
figure(5)
subplot(2,1,1)
fplot(abs(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, 0, 2])
title('|H(w)|'); xlabel('w (Rad/Sec)'); ylabel('Gain')
subplot(2,1,2)
fplot(angle(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, -pi, pi])
title('<H(w)'); xlabel('w (Rad/Sec)'); ylabel('Radians')
snapnow;
```

which yields

```
H(s) = (1.0541e+35*s^2)/(3.2466e+17*s + 1.4757e+20)^2
```





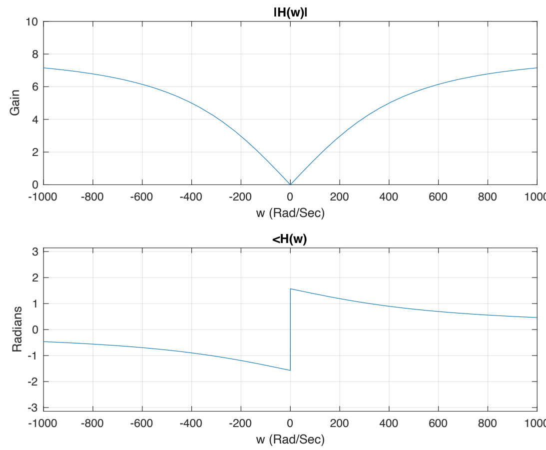
Problem 10.79:

We'll label the intermediate voltage as va.

```
%% Problem 10.79
clear all
syms Vin va Vout H s w
[Vin,Vout] = solve((0-Vin)/10000 + (0-va)/20000 + (0-va)*s*1e-7 == 0,...
              (0-va)*s*2e-7 + (0-Vout)/40000 == 0, Vin, Vout);
H(s) = simplify(Vout/Vin)
wmax = 1000; % Frequency limit for plotting
figure(79)
subplot(2,1,1)
fplot(abs(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, 0, 10])
title('|H(w)|'); xlabel('w (Rad/Sec)'); ylabel('Gain')
subplot(2,1,2)
fplot(angle(H(i*w)),[-wmax,wmax]), grid
axis([-wmax,wmax, -pi, pi])
title('<H(w)'); xlabel('w (Rad/Sec)'); ylabel('Radians')
snapnow;
%
```

which yields

```
H(s) = (8.0000*s)/(s + 500)
```



Homework: Ch. 10 # 72, 78, 80; Ch. 14 # 65, 83

10.67 Find the Thevenin and Norton equivalent circuits at terminals *a-b* in the circuit of Fig. 10.110.

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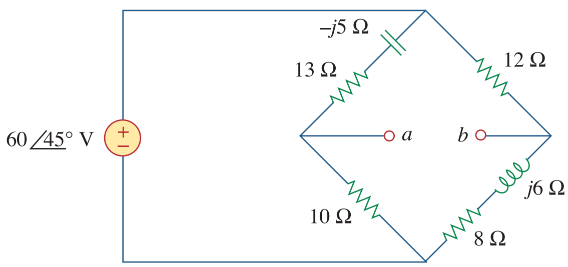

Figure 10.110
For Prob. 10.67.

10.68 Find the Thevenin equivalent at terminals *a-b* in the circuit of Fig. 10.111.

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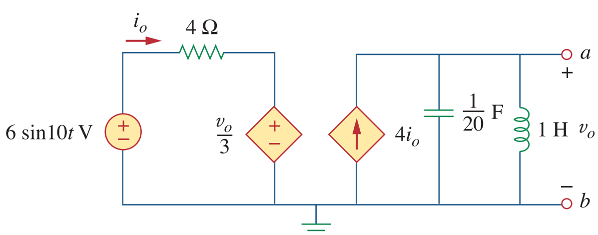

Figure 10.111
For Prob. 10.68.

Section 10.7 Op Amp AC Circuits

10.69 For the differentiator shown in Fig. 10.112, obtain $\mathbf{V}_o/\mathbf{V}_s$. Find $v_o(t)$ when $v_s(t) = \mathbf{V}_m \sin \omega t$ and $\omega = 1/RC$.

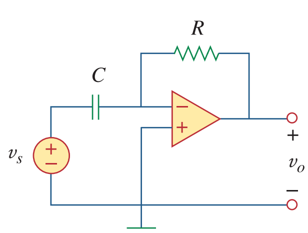

Figure 10.112
For Prob. 10.69.

10.70 Using Fig. 10.113, design a problem to help other students better understand op amps in AC circuits.

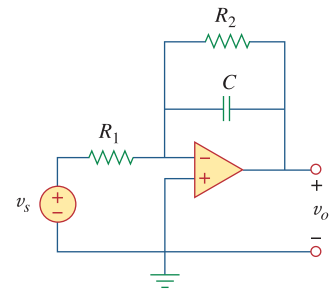

Figure 10.113
For Prob. 10.70.

10.71 Find v_o in the op amp circuit of Fig. 10.114.

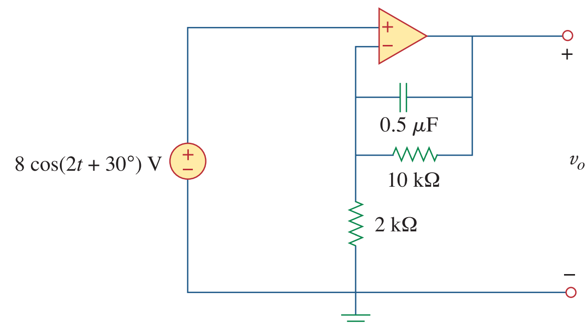

Figure 10.114
For Prob. 10.71.

10.72 Compute $i_o(t)$ in the op amp circuit in Fig. 10.115 if $v_s = 4\cos(10^4 t)$ V.

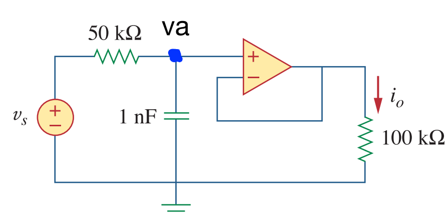

Figure 10.115
For Prob. 10.72.

10.73 If the input impedance is defined as $\mathbf{Z}_{in} = \mathbf{V}_s/\mathbf{I}_s$, find the input impedance of the op amp circuit in Fig. 10.116 when $R_1 = 10$ kΩ, $R_2 = 20$ kΩ, $C_1 = 10$ nF, $C_2 = 20$ nF, and $\omega = 5000$ rad/s.

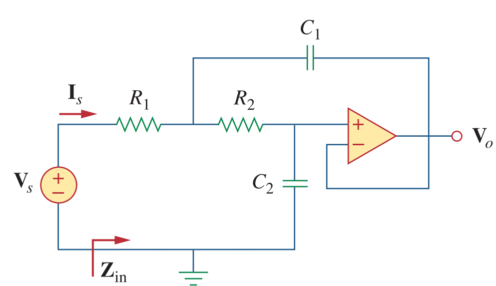

Figure 10.116
For Prob. 10.73.

10.74 Evaluate the voltage gain $\mathbf{A}_v = \mathbf{V}_o/\mathbf{V}_s$ in the op amp circuit of Fig. 10.117. Find $\mathbf{A}_v$ at $\omega = 0$, $\omega \to \infty$, $\omega = 1/R_1C_1$, and $\omega = 1/R_2C_2$.

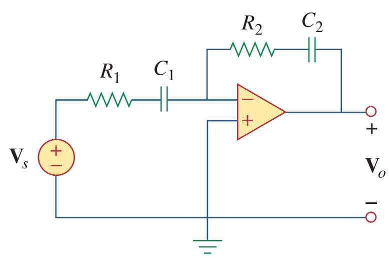

Figure 10.117
For Prob. 10.74.

10.75 In the op amp circuit of Fig. 10.118, find the closed-loop gain and phase shift of the output voltage with respect to the input voltage if $C_1 = C_2 = 1$ nF, $R_1 = R_2 = 100$ kΩ, $R_3 = 20$ kΩ, $R_4 = 40$ kΩ, and $\omega = 2000$ rad/s.

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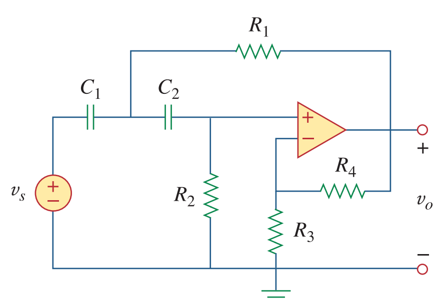

Figure 10.118
For Prob. 10.75.

10.76 Determine $\mathbf{V}_o$ and $\mathbf{I}_o$ in the op amp circuit of Fig. 10.119.

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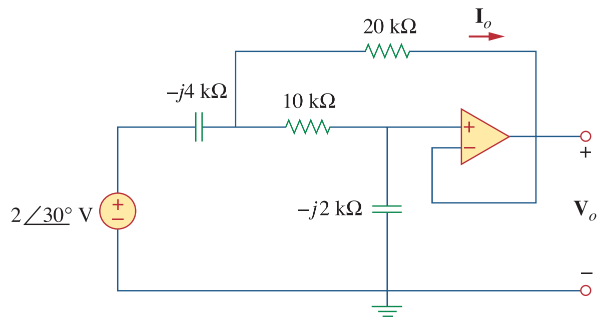

Figure 10.119
For Prob. 10.76.

10.77 Compute the closed-loop gain $\mathbf{V}_o/\mathbf{V}_s$ for the op amp circuit of Fig. 10.120.

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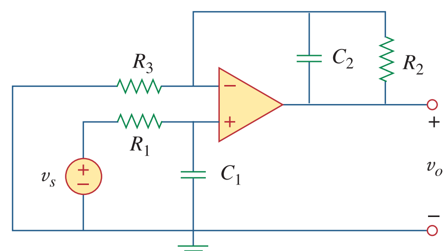

Figure 10.120
For Prob. 10.77.

10.78 Determine $v_o(t)$ in the op amp circuit in Fig. 10.121 below.

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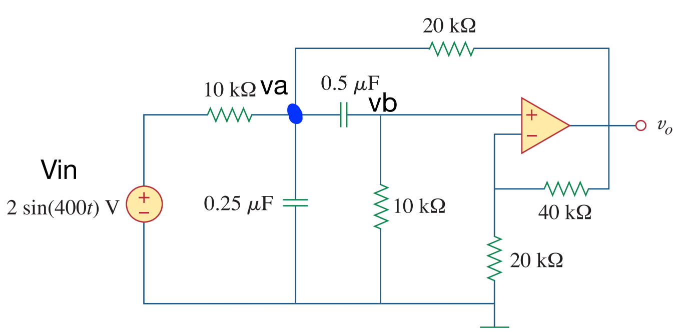

Figure 10.121
For Prob. 10.78.

10.79 For the op amp circuit in Fig. 10.122, obtain $v_o(t)$.

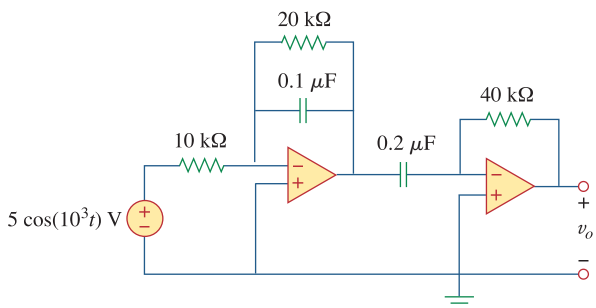

Figure 10.122
For Prob. 10.79.

10.80 Obtain $v_o(t)$ for the op amp circuit in Fig. 10.123 if $v_s = 4\cos(1000t - 60°)$ V.

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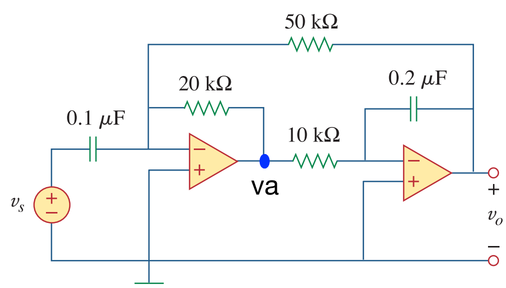

Figure 10.123
For Prob. 10.80.

Section 10.8 AC Analysis Using *PSpice*

10.81 Use *PSpice or MultiSim* to determine $\mathbf{V}_o$ in the circuit of Fig. 10.124. Assume $\omega = 1$ rad/s.

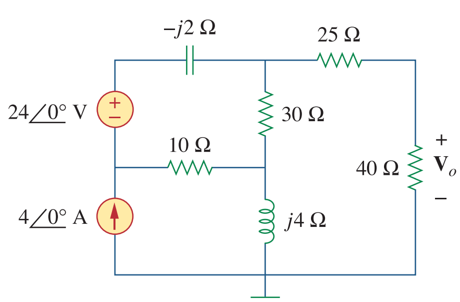

Figure 10.124
For Prob. 10.81.

10.82 Solve Prob. 10.19 using *PSpice or MultiSim*.

10.83 Use *PSpice or MultiSim* to find $v_o(t)$ in the circuit of Fig. 10.125. Let $i_s = 2\cos(10^3 t)$ A.

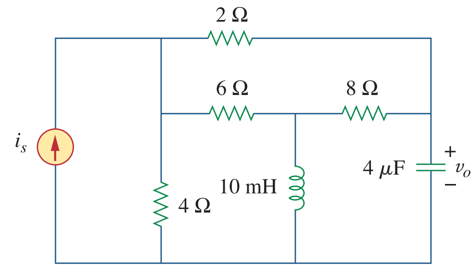

Figure 10.125
For Prob. 10.83.

10.84 Obtain $\mathbf{V}_o$ in the circuit of Fig. 10.126 using *PSpice or MultiSim*.

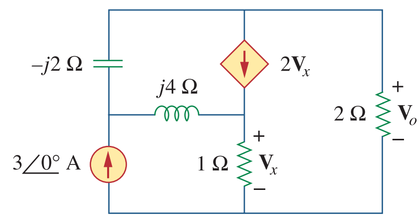

Figure 10.126
For Prob. 10.84.

10.85 Using Fig. 10.127, design a problem to help other students better understand performing AC analysis with *PSpice or MultiSim*.

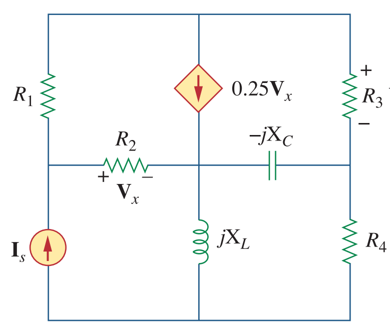

Figure 10.127
For Prob. 10.85.

10.86 Use *PSpice or MultiSim* to find $\mathbf{V}_1$, $\mathbf{V}_2$, and $\mathbf{V}_3$ in the network of Fig. 10.128.

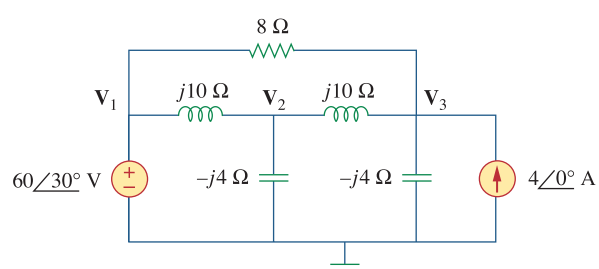

Figure 10.128
For Prob. 10.86.

10.87 Determine $\mathbf{V}_1$, $\mathbf{V}_2$, and $\mathbf{V}_3$ in the circuit of Fig. 10.129 using *PSpice or MultiSim.*

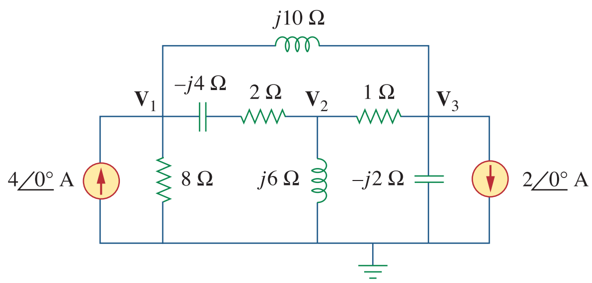

Figure 10.129
For Prob. 10.87.

10.88 Use *PSpice or MultiSim* to find v_o and i_o in the circuit of Fig. 10.130 below.

10.90 Figure 10.132 shows a Wien-bridge network. Show that the frequency at which the phase shift between the input and output signals is zero is $f = \frac{1}{2}\pi\ RC$, and that the necessary gain is $\mathbf{A}_v = \mathbf{V}_o/\mathbf{V}_i = 3$ at that frequency.

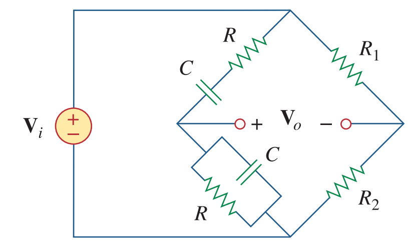

Figure 10.132
For Prob. 10.90.

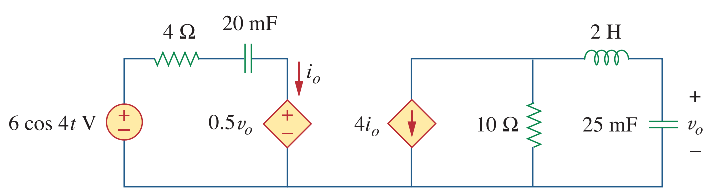

Figure 10.130
For Prob. 10.88.

Section 10.9 Applications

10.89 The op amp circuit in Fig. 10.131 is called an *inductance simulator*. Show that the input impedance is given by

$$\mathbf{Z}_{\text{in}} = \frac{\mathbf{V}_{\text{in}}}{\mathbf{I}_{\text{in}}} = j\omega L_{\text{eq}}$$

where

$$L_{\text{eq}} = \frac{R_1 R_3 R_4}{R_2} C$$

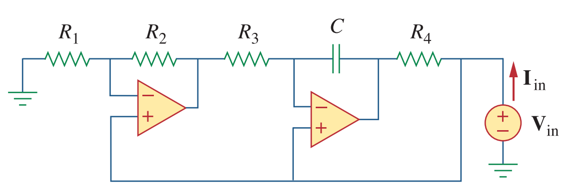

Figure 10.131
For Prob. 10.89.

10.91 Consider the oscillator in Fig. 10.133.

(a) Determine the oscillation frequency.

(b) Obtain the minimum value of R for which oscillation takes place.

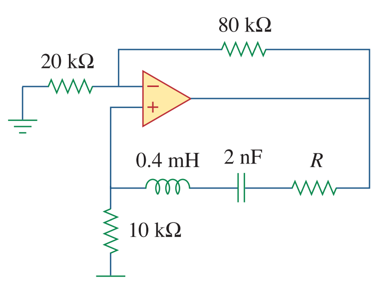

Figure 10.133
For Prob. 10.91.

14.51 Design an *RL* lowpass filter that uses a 40-mH coil and has a cutoff frequency of 5 kHz.
e2d

14.52 Design a problem to help other students better understand passive highpass filters.
e2d

14.53 Design a series *RLC* type bandpass filter with cutoff frequencies of 10 kHz and 11 kHz. Assuming $C = 80$ pF, find R, L, and Q.
e2d

14.54 Design a passive bandstop filter with $\omega_0 = 10$ rad/s and $Q = 20$.
e2d

14.55 Determine the range of frequencies that will be passed by a series *RLC* bandpass filter with $R = 10\ \Omega$, $L = 25$ mH, and $C = 0.4\ \mu$F. Find the quality factor.

14.56 (a) Show that for a bandpass filter,

$$\mathbf{H}(s) = \frac{sB}{s^2 + sB + \omega_0^2}, \qquad s = j\omega$$

where B = bandwidth of the filter and ω_0 is the center frequency.

(b) Similarly, show that for a bandstop filter,

$$\mathbf{H}(s) = \frac{s^2 + \omega_0^2}{s^2 + sB + \omega_0^2}, \qquad s = j\omega$$

14.57 Determine the center frequency and bandwidth of the bandpass filters in Fig. 14.88.

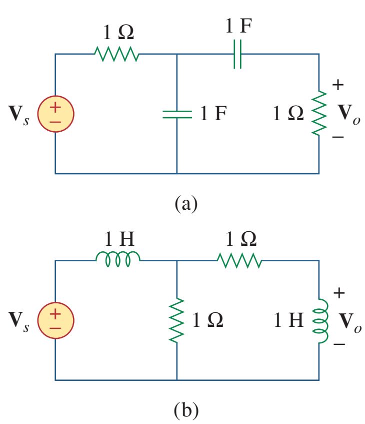

Figure 14.88
For Prob. 14.57.

14.58 The circuit parameters for a series *RLC* bandstop filter are $R = 2$ kΩ, $L = 0.1$ H, $C = 40$ pF. Calculate:

(a) the center frequency

(b) the half-power frequencies

(c) the quality factor

14.59 Find the bandwidth and center frequency of the bandstop filter of Fig. 14.89.

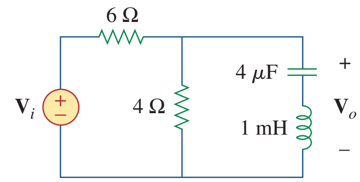

Figure 14.89
For Prob. 14.59.

Section 14.8 Active Filters

14.60 Obtain the transfer function of a highpass filter with a passband gain of 10 and a cutoff frequency of 50 rad/s.

14.61 Find the transfer function for each of the active filters in Fig. 14.90.

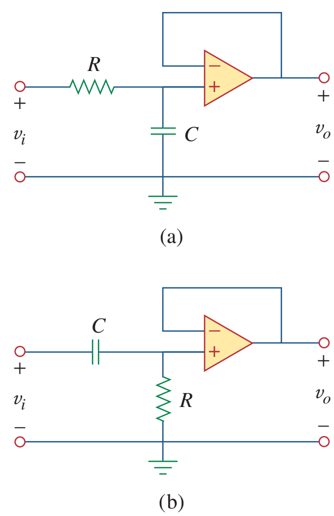

Figure 14.90
For Probs. 14.61 and 14.62.

14.62 The filter in Fig. 14.90(b) has a 3-dB cutoff frequency at 1 kHz. If its input is connected to a 120-mV variable frequency signal, find the output voltage at:

(a) 200 Hz (b) 2 kHz (c) 10 kHz

14.63 Design an active first-order highpass filter with
e2d

$$\mathbf{H}(s) = -\frac{100s}{s + 10}, \qquad s = j\omega$$

Use a 1-μF capacitor.

14.64 Obtain the transfer function of the active filter in Fig. 14.91 on the next page. What kind of filter is it?

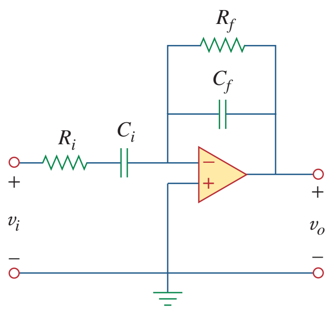

Figure 14.91
For Prob. 14.64.

14.65 A highpass filter is shown in Fig. 14.92. Show that the transfer function is

$$\mathbf{H}(\omega) = \left(1 + \frac{R_f}{R_i}\right)\frac{j\omega RC}{1 + j\omega RC}$$

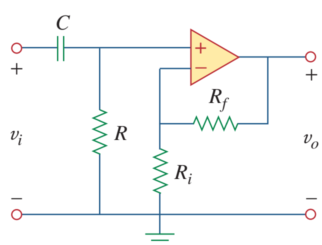

Figure 14.92
For Prob. 14.65.

14.66 A "general" first-order filter is shown in Fig. 14.93.

(a) Show that the transfer function is

$$\mathbf{H}(s) = \frac{R_4}{R_3 + R_4} \times \frac{s + (1/R_1C)[R_1/R_2 - R_3/R_4]}{s + 1/R_2C},$$

$s = j\omega$

(b) What condition must be satisfied for the circuit to operate as a highpass filter?

(c) What condition must be satisfied for the circuit to operate as a lowpass filter?

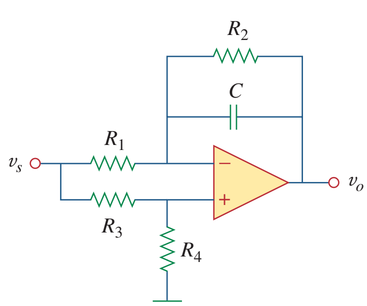

Figure 14.93
For Prob. 14.66.

14.67 Design an active lowpass filter with dc gain of 0.25 and a corner frequency of 500 Hz.
e⁄d

14.68 Design a problem to help other students better understand the design of active highpass filters when specifying a high-frequency gain and a corner frequency.
e⁄d

14.69 Design the filter in Fig. 14.94 to meet the following requirements:
e⁄d

(a) It must attenuate a signal at 2 kHz by 3 dB compared with its value at 10 MHz.

(b) It must provide a steady-state output of $v_o(t) = 10 \sin(2\pi \times 10^8 t + 180°)$ V for an input $v_s(t) = 4 \sin(2\pi \times 10^8 t)$ V.

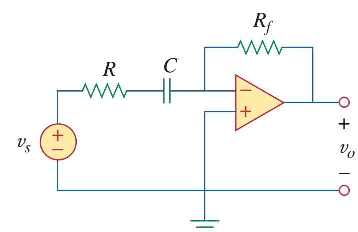

Figure 14.94
For Prob. 14.69.

***14.70** A second-order active filter known as a Butterworth filter is shown in Fig. 14.95.
e⁄d

(a) Find the transfer function $\mathbf{V}_o/\mathbf{V}_i$.

(b) Show that it is a lowpass filter.

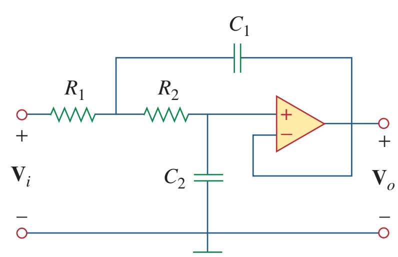

Figure 14.95
For Prob. 14.70.

Section 14.9 Scaling

14.71 Use magnitude and frequency scaling on the circuit of Fig. 14.79 to obtain an equivalent circuit in which the inductor and capacitor have magnitude 1 H and 1 F respectively.

14.72 Design a problem to help other students better understand magnitude and frequency scaling.
e⁄d

14.73 Calculate the values of R, L, and C that will result in $R = 12$ kΩ, $L = 40$ μH, and $C = 300$ nF respectively when magnitude-scaled by 800 and frequency-scaled by 1000.

14.74 A circuit has $R_1 = 3\ \Omega$, $R_2 = 10\ \Omega$, $L = 2\text{H}$, and $C = 1/10$ F. After the circuit is magnitude-scaled by 100 and frequency-scaled by 10^6, find the new values of the circuit elements.

14.75 In an *RLC* circuit, $R = 20\ \Omega$, $L = 4$ H, and $C = 1$ F. The circuit is magnitude-scaled by 10 and frequency-scaled by 10^5. Calculate the new values of the elements.

14.76 Given a parallel *RLC* circuit with $R = 5\ \text{k}\Omega$, $L = 10$ mH, and $C = 20\ \mu\text{F}$, if the circuit is magnitude-scaled by $K_m = 500$ and frequency-scaled by $K_f = 10^5$, find the resulting values of R, L, and C.

14.77 A series *RLC* circuit has $R = 10\ \Omega$, $\omega_0 = 40$ rad/s, and $B = 5$ rad/s. Find L and C when the circuit is scaled:

(a) in magnitude by a factor of 600,

(b) in frequency by a factor of 1,000,

(c) in magnitude by a factor of 400 and in frequency by a factor of 10^5.

14.78 Redesign the circuit in Fig. 14.85 so that all resistive elements are scaled by a factor of 1,000 and all frequency-sensitive elements are frequency-scaled by a factor of 10^4.

***14.79** Refer to the network in Fig. 14.96.

(a) Find $\mathbf{Z}_{\text{in}}(s)$.

(b) Scale the elements by $K_m = 10$ and $K_f = 100$. Find $\mathbf{Z}_{\text{in}}(s)$ and ω_0.

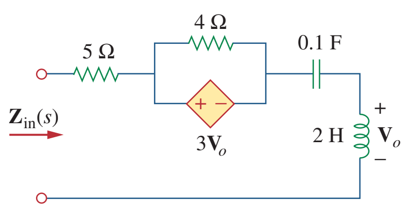

Figure 14.96
For Prob. 14.79.

14.80 (a) For the circuit in Fig. 14.97, draw the new circuit after it has been scaled by $K_m = 200$ and $K_f = 10^4$.

(b) Obtain the Thevenin equivalent impedance at terminals *a-b* of the scaled circuit at $\omega = 10^4$ rad/s.

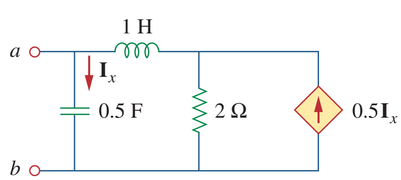

Figure 14.97
For Prob. 14.80.

14.81 The circuit shown in Fig. 14.98 has the impedance

$$Z(s) = \frac{1{,}000(s + 1)}{(s + 1 + j50)(s + 1 - j50)}, \qquad s = j\omega$$

Find:

(a) the values of R, L, C, and G

(b) the element values that will raise the resonant frequency by a factor of 10^3 by frequency scaling

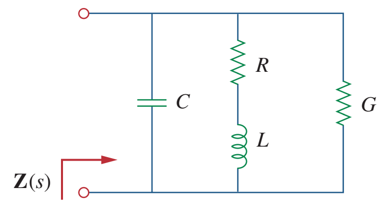

Figure 14.98
For Prob. 14.81.

14.82 Scale the lowpass active filter in Fig. 14.99 so that its corner frequency increases from 1 rad/s to 200 rad/s. Use a 1-μF capacitor.

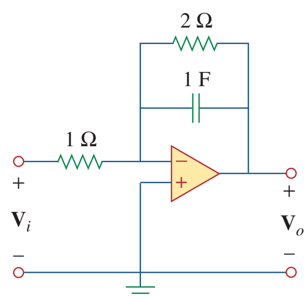

Figure 14.99
For Prob. 14.82.

14.83 The op amp circuit in Fig. 14.100 is to be magnitude-scaled by 100 and frequency-scaled by 10^5. Find the resulting element values.

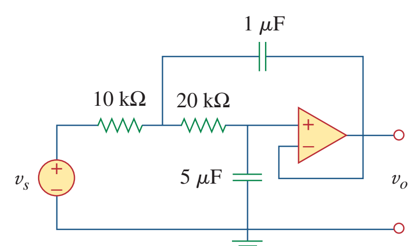

Figure 14.100
For Prob. 14.83.

Section 14.10 Frequency Response Using *PSpice*

14.84 Using *PSpice or MultiSim*, obtain the frequency response of the circuit in Fig. 14.101 on the next page.