Fundamentals of Electric Circuit 2020.5

Chapter 10 Sinusoidal Steady-State Analysis

Chapter 10 Sinusoidal Steady-State Analysis

10.1 Introduction

In Chapter 9, we learned that the forced or steady-state response of circuits to sinusoidal inputs can be obtained by using phasors. We also know that Ohm's and Kirchhoff's laws are applicable to ac circuits.

In this chapter, we want to see how nodal analysis, mesh analysis, Thevenin's theorem, Norton's theorem, superposition, and source transformations are applied in analyzing ac circuits. Since these techniques were already introduced for dc circuits, our major effort here will be to illustrate with examples.

- Analyzing ac circuits usually requires three steps:

1. Transform the circuit to the phasor or frequency domain.
2. Solve the problem using circuit techniques (nodal analysis, mesh analysis, superposition, etc.).
3. Transform the resulting phasor to the time domain.

- Step 1 is not necessary if the problem is specified in the frequency domain.
- In step 2, the analysis is performed in the same manner as dc circuit analysis except that complex numbers are involved.
- Having read Chapter 9, we are adept at handling step 3.

10.2 Nodal analysis

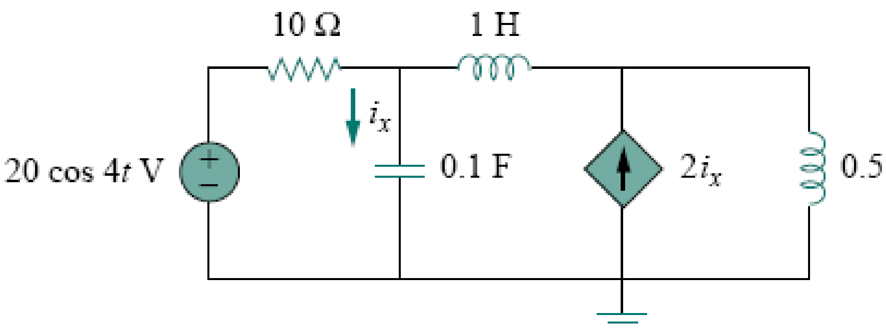
Steps to determine the node voltages:

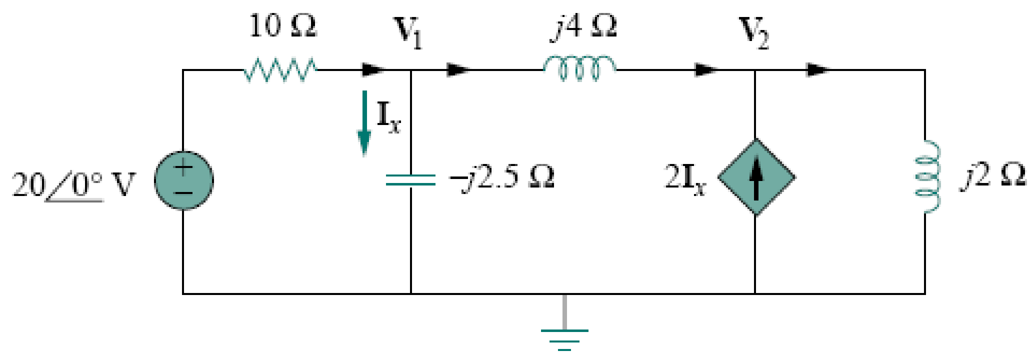
1. Select a node as the reference node.
2. Assign voltages $v_1, v_2, \ldots, v_{n-1}$ to the remaining n-1 nodes. The voltages are referenced with respect to the reference node.
3. Apply KCL to each of the n-1 non-reference nodes. Use Ohm's law to express the branch currents in terms of node voltages.
4. Solve the resulting simultaneous equations to obtain the unknown node voltages.

10.2 Nodal analysis

EXAMPLE 10.1

Find i_x in the circuit of Fig. 10.1 using nodal analysis.





Solution:

We first convert the circuit to the frequency domain:

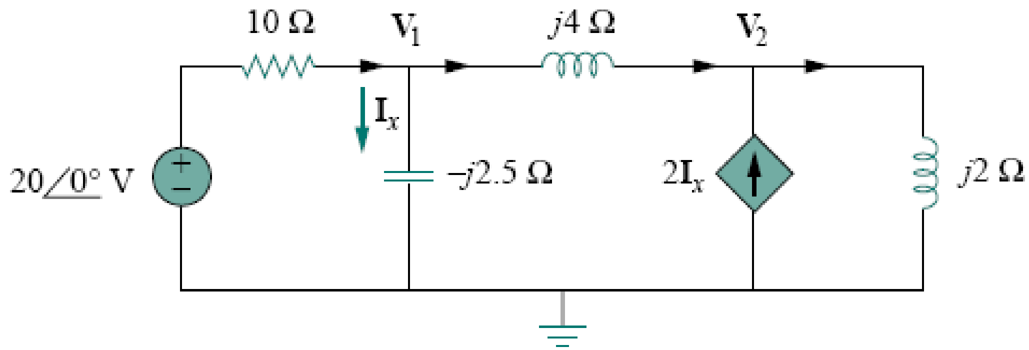
$$20\cos 4t \quad \Longrightarrow \quad 20\angle 0°, \qquad \omega = 4 \text{ rad/s}$$

$$1 \text{ H} \quad \Longrightarrow \quad j\omega L = j4$$

$$0.5 \text{ H} \quad \Longrightarrow \quad j\omega L = j2$$

$$0.1 \text{ F} \quad \Longrightarrow \quad \frac{1}{j\omega C} = -j2.5$$

Thus, the frequency-domain equivalent circuit is as shown in Fig. 10.2.



Applying KCL at node 1,

$$\frac{20 - \mathbf{V}_1}{10} = \frac{\mathbf{V}_1}{-j2.5} + \frac{\mathbf{V}_1 - \mathbf{V}_2}{j4}$$

At node 2,

$$2\mathbf{I}_x + \frac{\mathbf{V}_1 - \mathbf{V}_2}{j4} = \frac{\mathbf{V}_2}{j2}$$

$$\mathbf{I}_x = \mathbf{V}_1/-j2.5. \qquad \frac{2\mathbf{V}_1}{-j2.5} + \frac{\mathbf{V}_1 - \mathbf{V}_2}{j4} = \frac{\mathbf{V}_2}{j2}$$

$$\mathbf{V}_1 = 18.97\angle 18.43° \text{ V}$$

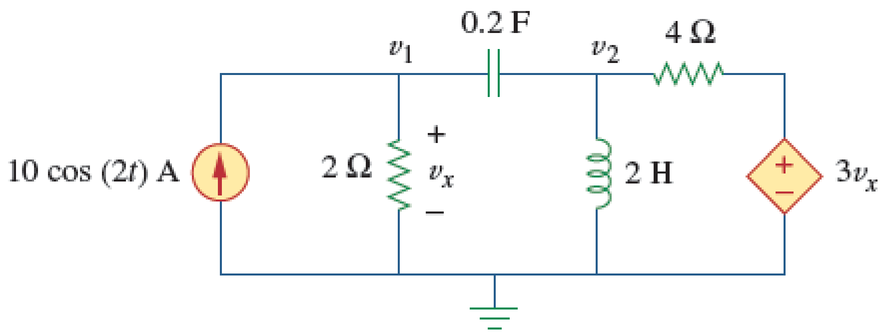
$$\mathbf{V}_2 = 13.91\angle 198.3° \text{ V}$$

The current $\mathbf{I}_x$ is given by $\mathbf{I}_x = \dfrac{\mathbf{V}_1}{-j2.5} = 7.59\angle 108.4° \text{ A}$

Transforming this to the time domain, $i_x = 7.59\cos(4t + 108.4°) \text{ A}$

Practice Problem 10.1

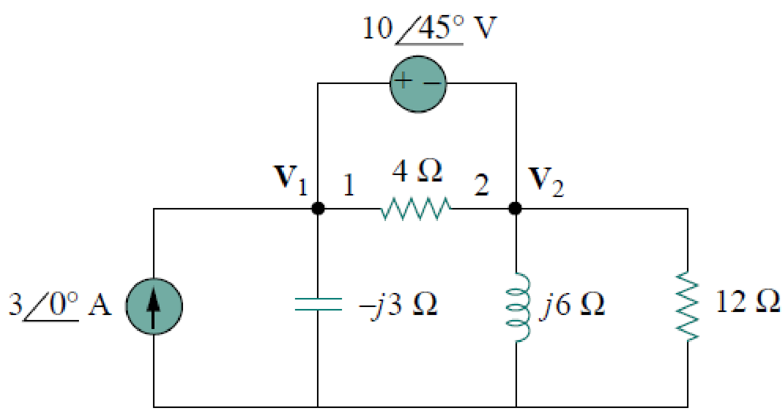
Using nodal analysis, find v_1 and v_2 in the circuit of Fig. 10.3.

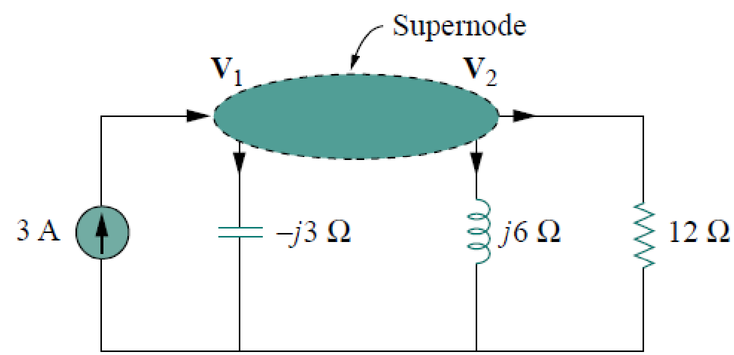


10.2 Nodal analysis

EXAMPLE 10.2

Compute $\mathbf{V}_1$ and $\mathbf{V}_2$ in the circuit of Fig. 10.4.





Solution:

Nodes 1 and 2 form a supernode as shown in Fig. 10.5. Applying KCL at the supernode gives

$$3 = \frac{\mathbf{V}_1}{-j3} + \frac{\mathbf{V}_2}{j6} + \frac{\mathbf{V}_2}{12} \qquad 36 = j4\mathbf{V}_1 + (1 - j2)\mathbf{V}_2$$

But a voltage source is connected between nodes 1 and 2, so that $\mathbf{V}_1 = \mathbf{V}_2 + 10\angle 45^\circ$

$$36 - 40\angle 135^\circ = (1 + j2)\mathbf{V}_2 \qquad \Longrightarrow \qquad \mathbf{V}_2 = 31.41\angle -87.18^\circ \text{ V}$$

$$\mathbf{V}_1 = \mathbf{V}_2 + 10\angle 45^\circ = 25.78\angle -70.48^\circ \text{ V}$$

PRACTICE PROBLEM 10.2

Calculate $\mathbf{V}_1$ and $\mathbf{V}_2$ in the circuit shown in Fig. 10.6.

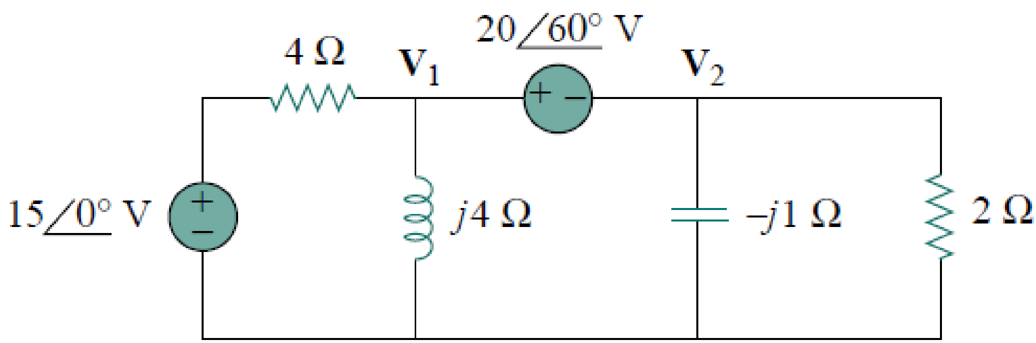


Figure 10.6 For Practice Prob. 10.2.

10.3 Mesh analysis

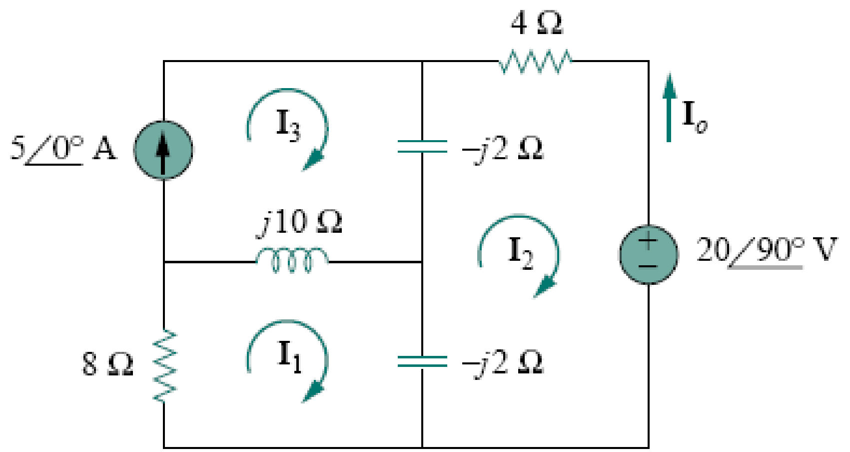
Steps to determine the mesh currents:

- *1.Assign* mesh currents i_1, i_2, ..., i_n to the n meshes.
- *2. Apply* KVL to each of the n meshes. Use Ohm's law to express the voltages in terms of the mesh currents.
- *3. Solve* the resulting n simultaneous equations to get the mesh currents.

10.3 Mesh analysis

EXAMPLE 10.3

Determine current I_o in the circuit using mesh analysis.



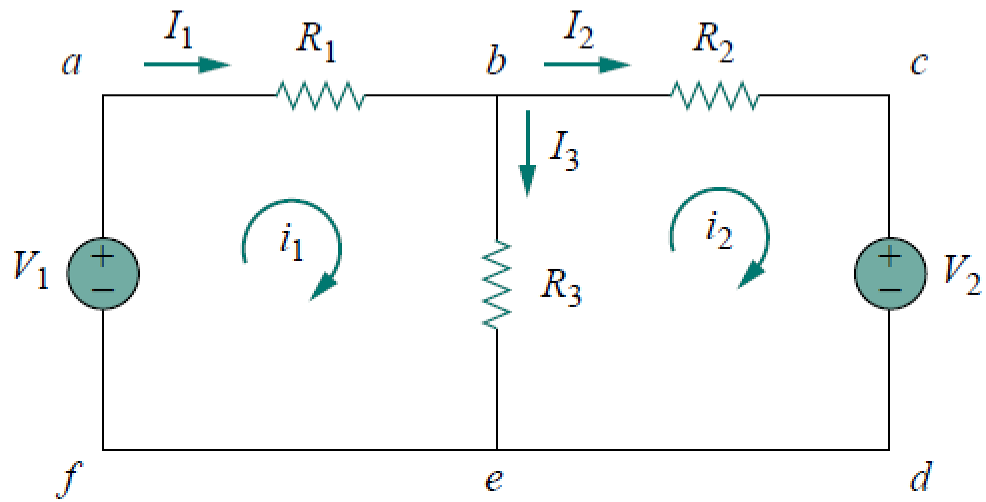
Solution:

Applying KVL to mesh 1, we obtain $(8 + j10 - j2)\mathbf{I}_1 - (-j2)\mathbf{I}_2 - j10\mathbf{I}_3 = 0$

For mesh 2, $(4 - j2 - j2)\mathbf{I}_2 - (-j2)\mathbf{I}_1 - (-j2)\mathbf{I}_3 + 20\angle 90^\circ = 0$

For mesh 3, $\mathbf{I}_3 = 5.$

The desired current is $\mathbf{I}_o = -\mathbf{I}_2 = 6.12\angle 144.78^\circ \text{ A}$



$$-V_1 + R_1 i_1 + R_3(i_1 - i_2) = 0 \qquad \text{or} \qquad (R_1 + R_3)i_1 - R_3 i_2 = V_1$$

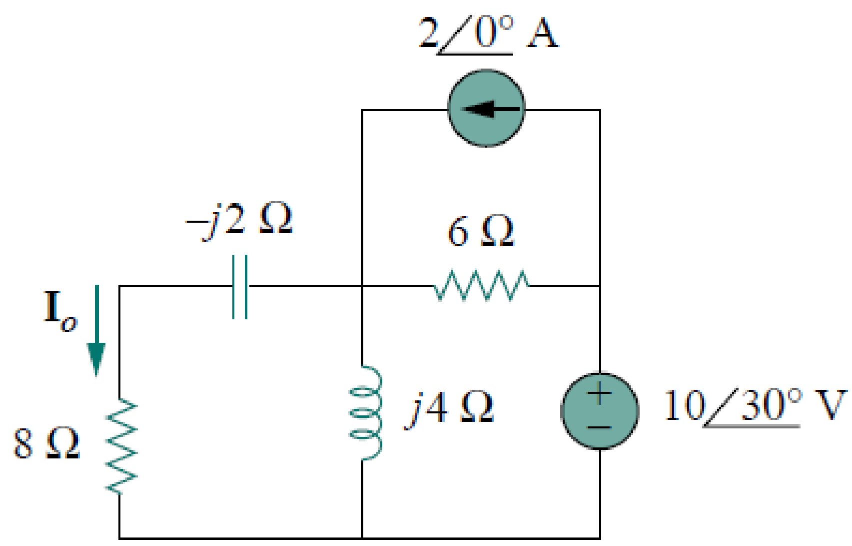
$$R_2 i_2 + V_2 + R_3(i_2 - i_1) = 0 \qquad \text{or} \qquad -R_3 i_1 + (R_2 + R_3)i_2 = -V_2$$

Note in Eq. (3.13) that the coefficient of i_1 is the sum of the resistances in the first mesh, while the coefficient of i_2 is the negative of the resistance common to meshes 1 and 2. Now observe that the same is true in Eq. (3.14). This can serve as a shortcut way of writing the mesh equations.

The shortcut way will not apply if one mesh current is assumed clockwise and the other assumed anticlockwise, although this is permissible.

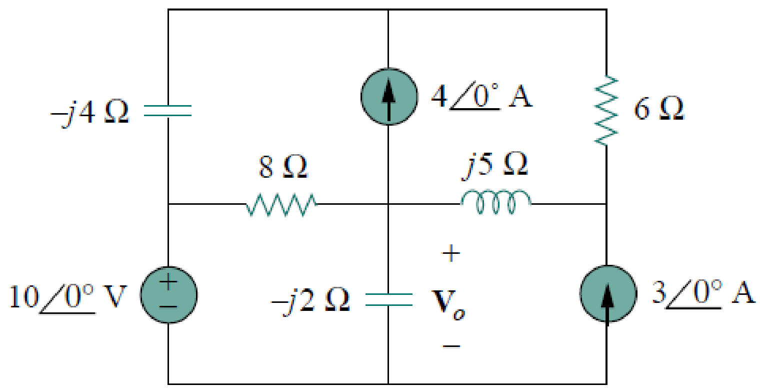
PRACTICE PROBLEM 10.3

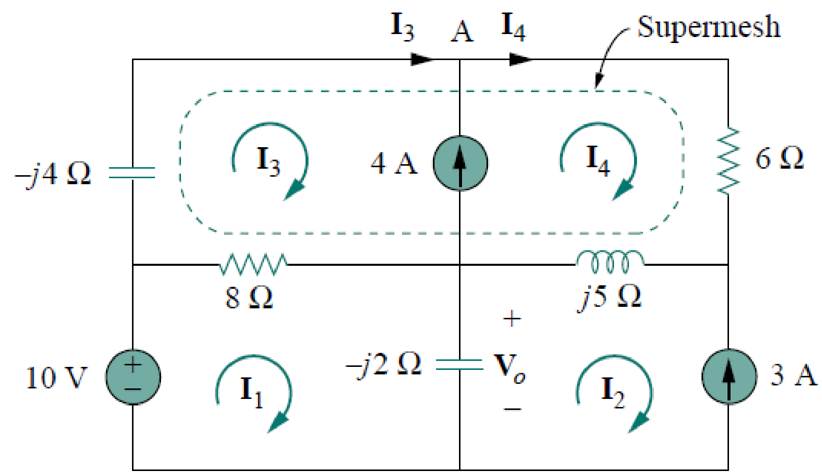
Find $\mathbf{I}_o$ in Fig. 10.8 using mesh analysis.



EXAMPLE 10.4

Solve for $\mathbf{V}_o$ in the circuit in Fig. 10.9 using mesh analysis.





Solution:

As shown in Fig. 10.10, meshes 3 and 4 form a supermesh due to the current source between the meshes. For mesh 1, KVL gives

$$-10 + (8 - j2)\mathbf{I}_1 - (-j2)\mathbf{I}_2 - 8\mathbf{I}_3 = 0$$

For mesh 2, $\mathbf{I}_2 = -3$

For the supermesh, $(8 - j4)\mathbf{I}_3 - 8\mathbf{I}_1 + (6 + j5)\mathbf{I}_4 - j5\mathbf{I}_2 = 0$

Due to the current source between meshes 3 and 4, at node A, $\mathbf{I}_4 = \mathbf{I}_3 + 4$

$$\mathbf{V}_o = -j2(\mathbf{I}_1 - \mathbf{I}_2) = -j2(3.618\angle 274.5° + 3)$$
$$= -7.2134 - j6.568 = 9.756\angle 222.32° \text{ V}$$

Practice Problem 10.4

Calculate current $\mathbf{I}_o$ in the circuit of Fig. 10.11.

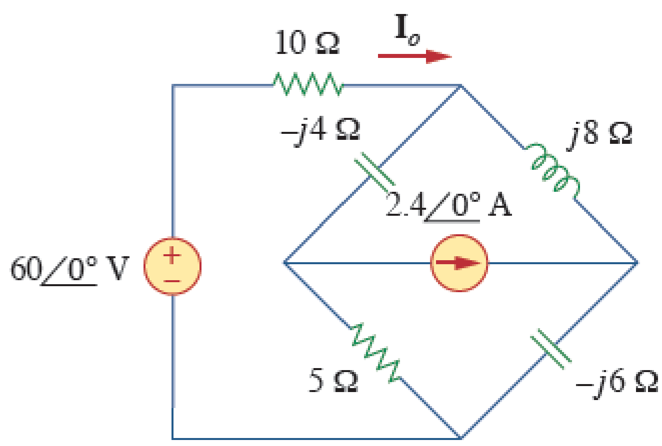


Figure 10.11
For Practice Prob. 10.4.

10.4 Superposition Theorem

- Since ac circuits are linear, the superposition theorem applies to ac circuits the same way it applies to dc circuits.

Steps to apply superposition principle

1. ***Turn off*** all independent sources except one source. Find the output (voltage or current) due to that active source using nodal or mesh analysis.
2. ***Repeat step 1*** for each of the other independent sources.
3. ***Find*** the total contribution by adding ***algebraically*** all the contributions due to the independent sources.

Superposition Theorem

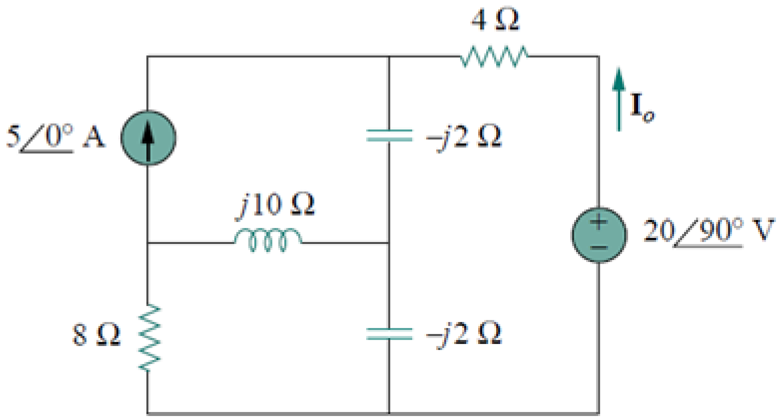
Two things have to be keep in mind:

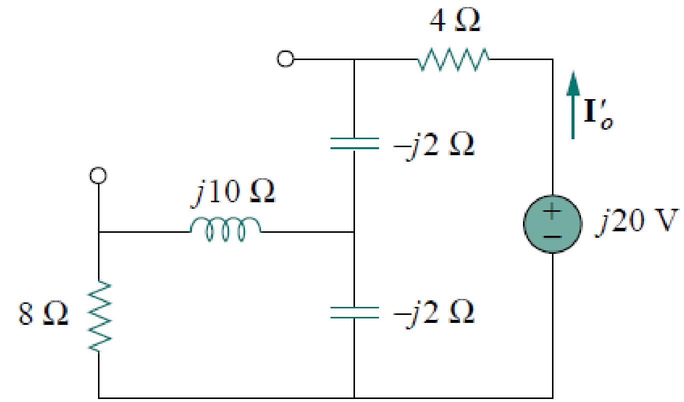
When we say turn off all other independent sources:

- Independent voltage sources are replaced by 0 V (short circuit) and
- Independent current sources are replaced by 0 A (open circuit).
- Dependent sources are left intact because they are controlled by circuit variables.

EXAMPLE 10.5

Use the superposition theorem to find $\mathbf{I}_o$ in the circuit in Fig. 10.7.





(a)

Solution:

Let

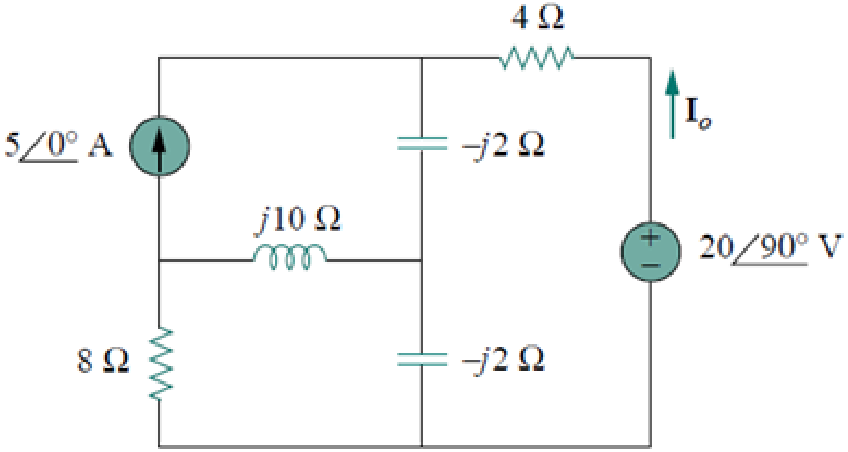
$$\mathbf{I}_o = \mathbf{I}'_o + \mathbf{I}''_o \tag{10.5.1}$$

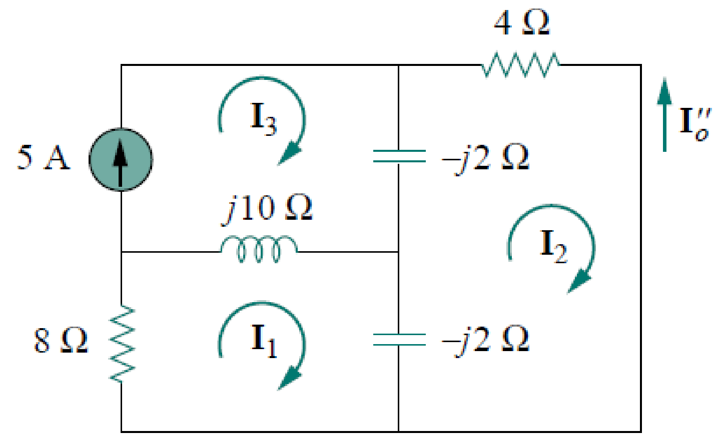
where $\mathbf{I}'_o$ and $\mathbf{I}''_o$ are due to the voltage and current sources, respectively. To find $\mathbf{I}'_o$, consider the circuit in Fig. 10.12(a). If we let $\mathbf{Z}$ be the parallel combination of $-j2$ and $8 + j10$, then

$$\mathbf{Z} = \frac{-j2(8 + j10)}{-2j + 8 + j10} = 0.25 - j2.25$$

and current $\mathbf{I}'_o$ is $\mathbf{I}'_o = \dfrac{j20}{4 - j2 + \mathbf{Z}} = \dfrac{j20}{4.25 - j4.25}$

$$= -2.353 + j2.353$$





(b)

To get $\mathbf{I}_o''$, consider the circuit in Fig. 10.12(b). For mesh 1,

$$(8 + j8)\mathbf{I}_1 - j10\mathbf{I}_3 + j2\mathbf{I}_2 = 0$$

For mesh 2,

$$(4 - j4)\mathbf{I}_2 + j2\mathbf{I}_1 + j2\mathbf{I}_3 = 0$$

For mesh 3,

$$\mathbf{I}_3 = 5$$

$$\mathbf{I}_2 = \frac{90 - j40}{34} = 2.647 - j1.176$$

Current $\mathbf{I}_o''$ is obtained as

$$\mathbf{I}_o'' = -\mathbf{I}_2 = -2.647 + j1.176$$

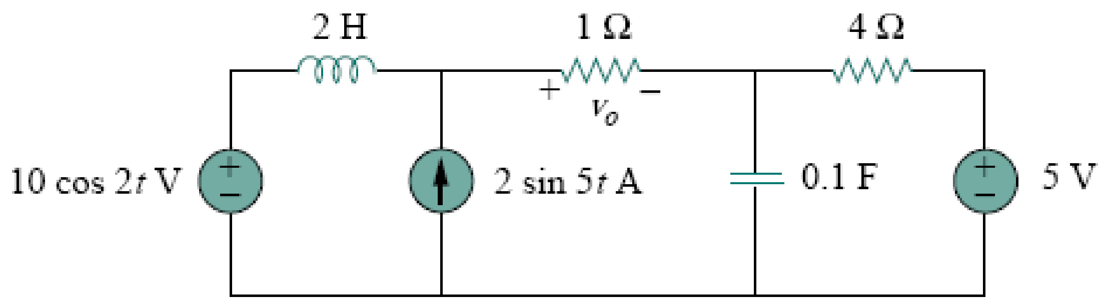
$$\mathbf{I}_o = \mathbf{I}_o' + \mathbf{I}_o'' = -5 + j3.529 = 6.12\underline{/144.78^\circ} \text{ A}$$

10.4 Superposition Theorem

- The theorem becomes important if the circuit has sources operating at *different frequencies*.
- In this case, since the impedances depend on frequency, we must have a different frequency-domain circuit for each frequency.
- The total response must be obtained by adding the individual responses in the time domain.
- When a circuit has sources operating at different frequencies, one must add the responses due to the individual frequencies in the time domain.

EXAMPLE 10.6

Find v_o in the circuit in Fig. 10.13 using the superposition theorem.



Solution:

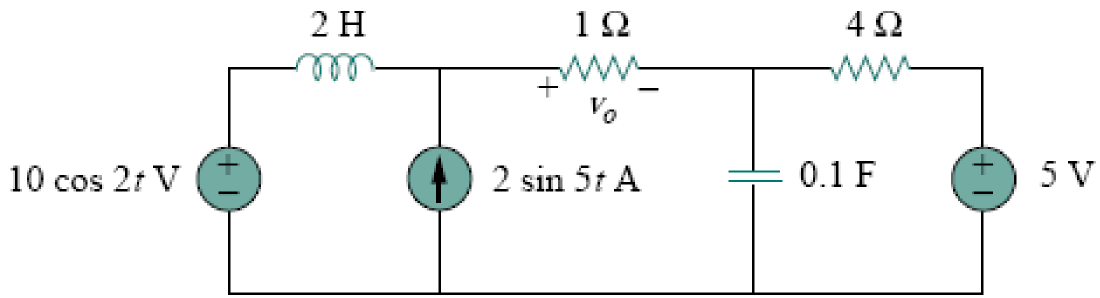
Since the circuit operates at three different frequencies ($\omega = 0$ for the dc voltage source), one way to obtain a solution is to use superposition, which breaks the problem into single-frequency problems. So we let

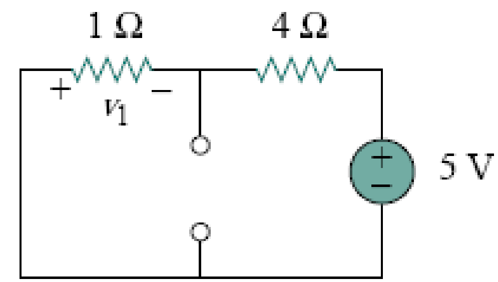
$$v_o = v_1 + v_2 + v_3$$

v_1 is due to the 5-V dc voltage source,

v_2 is due to the 10 cos 2t V voltage source,

v_3 is due to the 2 sin 5t A current source.





v_1 is due to the 5-V dc voltage source,

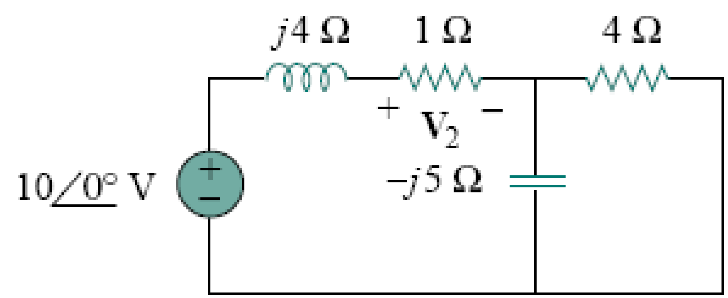
$$-v_1 = \frac{1}{1+4}(5) = 1 \text{ V}$$

v_2 is due to the 10 cos 2*t* V voltage source,

$$10\cos 2t \quad \Longrightarrow \quad 10\angle 0^\circ, \qquad \omega = 2 \text{ rad/s}$$

$$2 \text{ H} \quad \Longrightarrow \quad j\omega L = j4\ \Omega$$

$$0.1 \text{ F} \quad \Longrightarrow \quad \frac{1}{j\omega C} = -j5\ \Omega$$

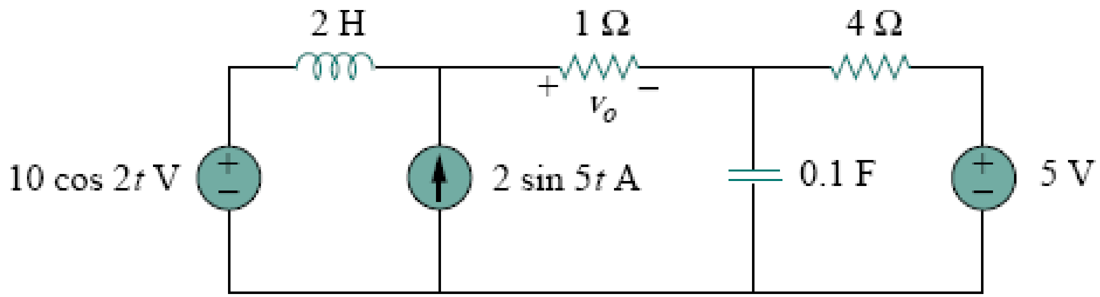


$$\mathbf{Z} = -j5 \parallel 4 = \frac{-j5 \times 4}{4 - j5} = 2.439 - j1.951$$

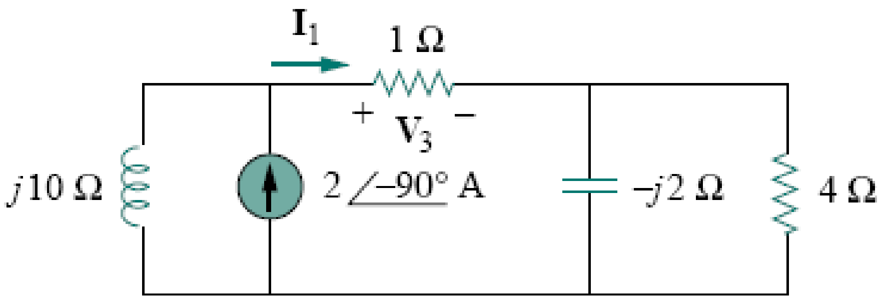
$$\mathbf{V}_2 = \frac{1}{1 + j4 + \mathbf{Z}}(10\angle 0^\circ) = \frac{10}{3.439 + j2.049} = 2.498\angle -30.79^\circ$$

In the time domain,

$$v_2 = 2.498\cos(2t - 30.79^\circ)$$



v_3 is due to the 2 sin 5*t* A current source.



$$2\sin 5t \quad\Longrightarrow\quad 2\angle -90^\circ, \qquad \omega = 5 \text{ rad/s}$$

$$2\text{ H} \quad\Longrightarrow\quad j\omega L = j10\ \Omega$$

$$0.1\text{ F} \quad\Longrightarrow\quad \frac{1}{j\omega C} = -j2\ \Omega$$

$$\mathbf{Z}_1 = -j2 \parallel 4 = \frac{-j2\times 4}{4-j2} = 0.8 - j1.6\ \Omega$$

By current division,

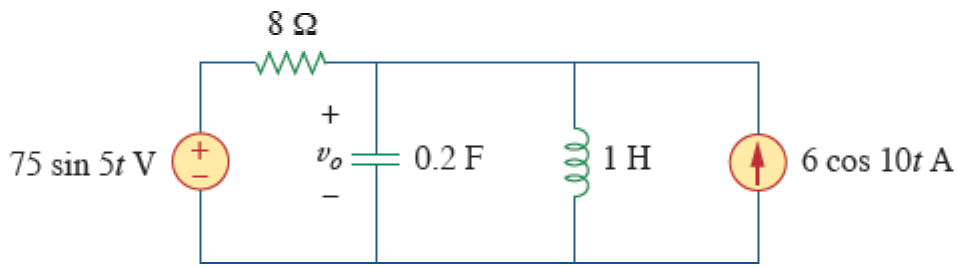
$$\mathbf{I}_1 = \frac{j10}{j10+1+\mathbf{Z}_1}(2\angle -90^\circ)\text{ A} \qquad \mathbf{V}_3 = \mathbf{I}_1 \times 1 = \frac{j10}{1.8+j8.4}(-j2) = 2.328\angle -77.91^\circ\text{ V}$$

In the time domain, $\quad v_3 = 2.33\cos(5t - 80^\circ) = 2.33\sin(5t + 10^\circ)\text{ V}$

$$v_o(t) = -1 + 2.498\cos(2t - 30.79^\circ) + 2.33\sin(5t + 10^\circ)\text{ V}$$

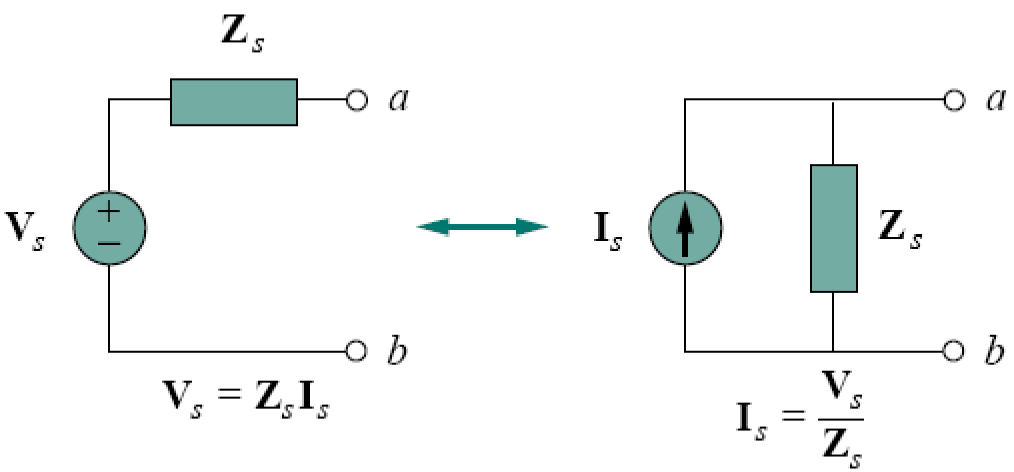
Practice Problem 10.6

Calculate v_o in the circuit of Fig. 10.15 using the superposition theorem.



10.5 Source Transformation

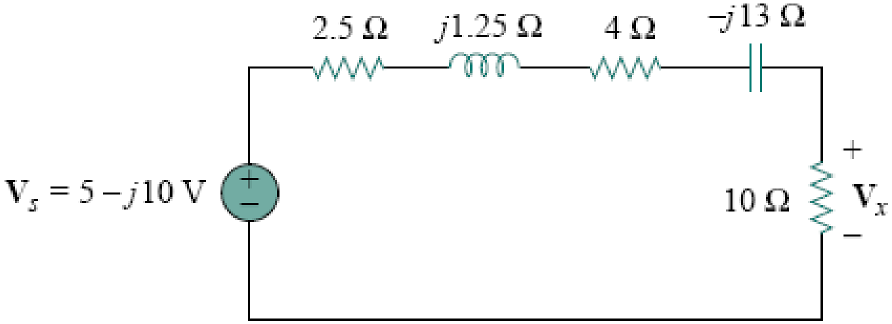
- Source transformation in the frequency domain involves transforming a voltage source in series with an impedance to a current source in parallel with an impedance, or vice versa.

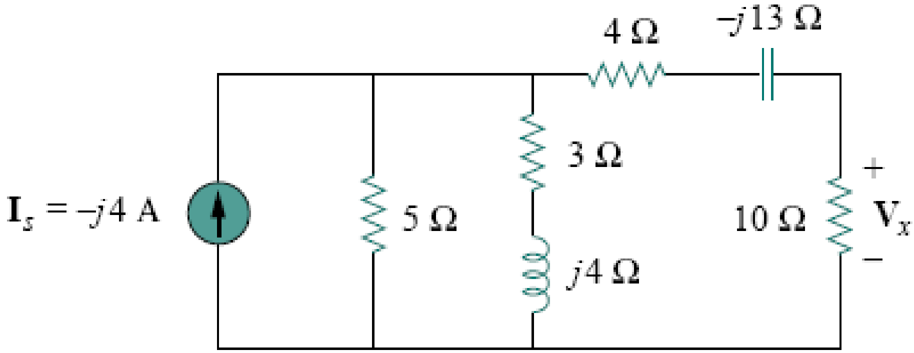


$$\mathbf{V}_s = \mathbf{Z}_s\mathbf{I}_s \quad \Longleftrightarrow \quad \mathbf{I}_s = \frac{\mathbf{V}_s}{\mathbf{Z}_s}$$

EXAMPLE 10.7

Calculate $\mathbf{V}_x$ in the circuit of using the method of source transformation.





Solution:

We transform the voltage source to a current source and obtain the circuit

$$\mathbf{I}_s = \frac{20\angle -90^\circ}{5} = 4\angle -90^\circ = -j4 \text{ A}$$

The parallel combination of 5-Ω resistance and $(3 + j4)$ impedance gives

$$\mathbf{Z}_1 = \frac{5(3 + j4)}{8 + j4} = 2.5 + j1.25\ \Omega$$

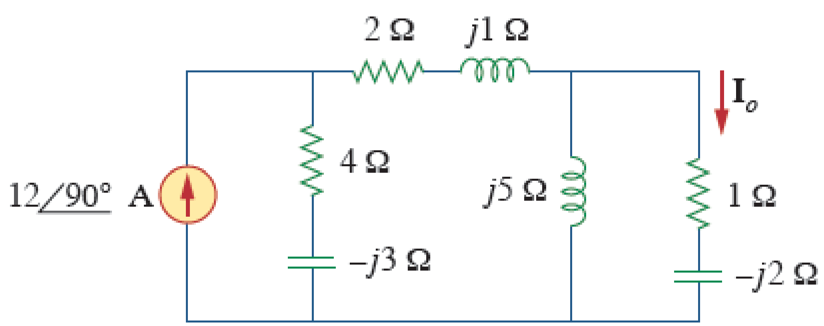
Converting the current source to a voltage source yields the circuit

$$\mathbf{V}_s = \mathbf{I}_s\mathbf{Z}_1 = -j4(2.5 + j1.25) = 5 - j10 \text{ V}$$

$$\mathbf{V}_x = \frac{10}{10 + 2.5 + j1.25 + 4 - j13}(5 - j10) = 5.519\angle -28^\circ \text{ V}$$

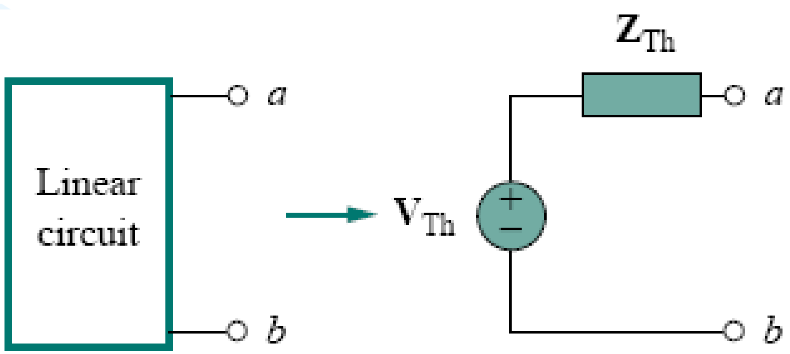
Practice Problem 10.7

Find $\mathbf{I}_o$ in the circuit of Fig. 10.19 using the concept of source transformation.



10.6 Thevenin and Norton equivalent circuits

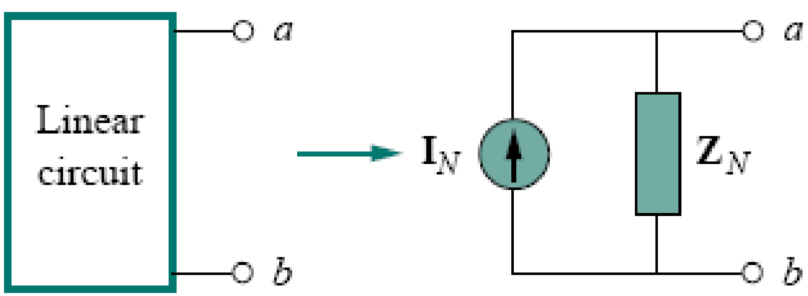
- Thevenin's and Norton's theorems are applied to ac circuits in the same way as they are to dc circuits. The only additional effort arises from the need to manipulate complex numbers.



$$\mathbf{V}_{\mathrm{Th}} = \mathbf{Z}_N \mathbf{I}_N, \qquad \mathbf{Z}_{\mathrm{Th}} = \mathbf{Z}_N$$

$\mathbf{V}_{\mathrm{Th}}$ is the open-circuit voltage

The frequency-domain version of a Thevenin equivalent circuit

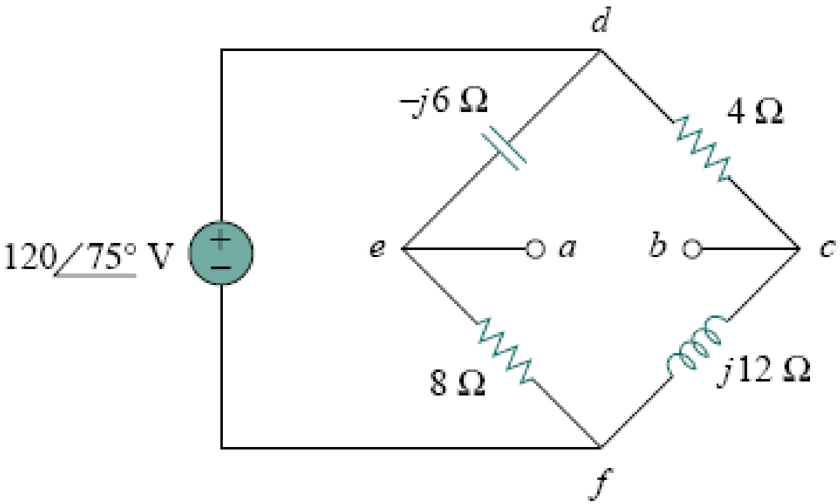


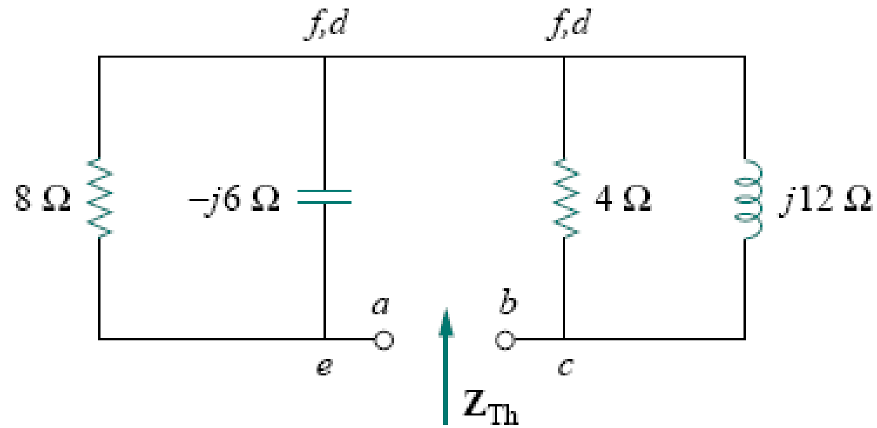
$\mathbf{I}_N$ is the short-circuit current

The frequency-domain version of a Norton equivalent circuit

EXAMPLE 10.8

Obtain the Thevenin equivalent at terminals *a*-*b* of the circuit.





Solution:

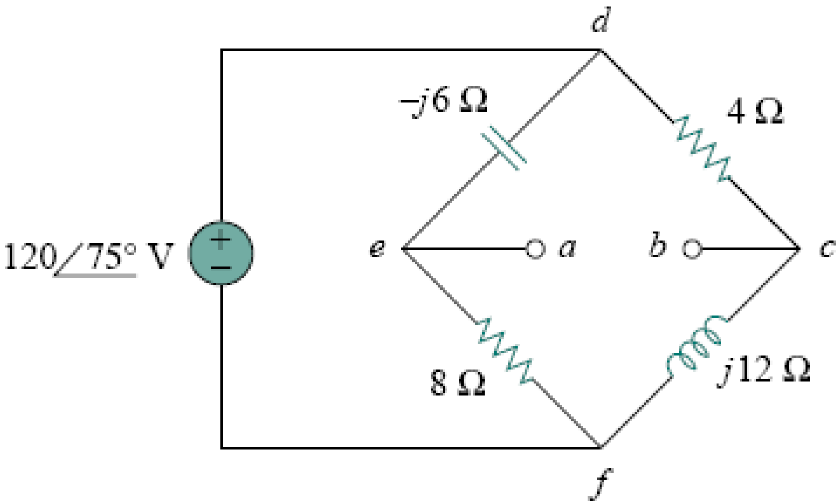
We find $\mathbf{Z}_{\text{Th}}$ by setting the voltage source to zero.

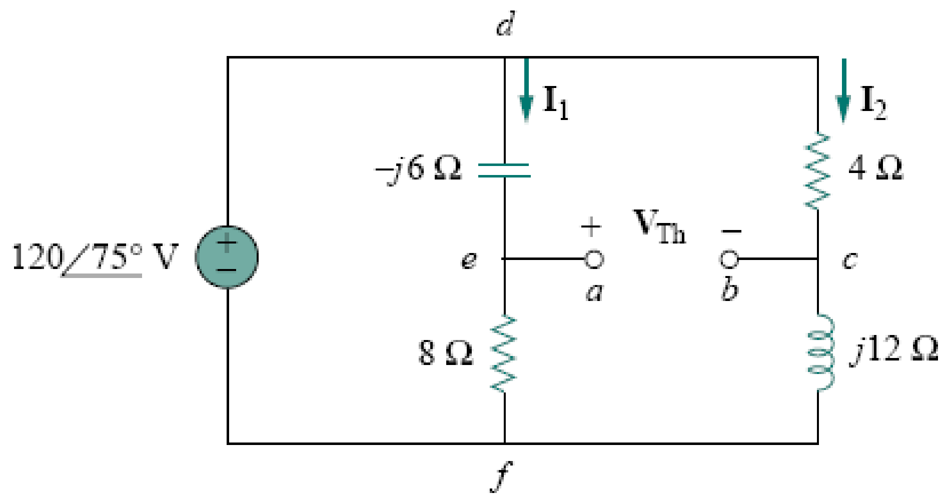
$$\mathbf{Z}_1 = -j6 \parallel 8 = \frac{-j6 \times 8}{8 - j6} = 2.88 - j3.84\ \Omega \qquad \mathbf{Z}_2 = 4 \parallel j12 = \frac{j12 \times 4}{4 + j12} = 3.6 + j1.2\ \Omega$$

$$\mathbf{Z}_{\text{Th}} = \mathbf{Z}_1 + \mathbf{Z}_2 = 6.48 - j2.64\ \Omega$$

EXAMPLE 10.8

Obtain the Thevenin equivalent at terminals *a*-*b* of the circuit.





To find $\mathbf{V}_{Th}$,

$$\mathbf{I}_1 = \frac{120\angle 75^\circ}{8 - j6} \text{ A}, \qquad \mathbf{I}_2 = \frac{120\angle 75^\circ}{4 + j12} \text{ A}$$

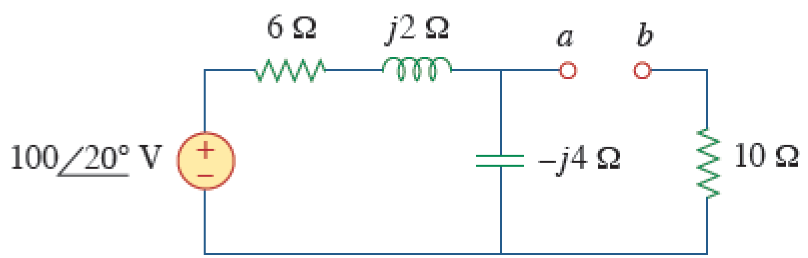
Applying KVL around loop *bcdeab*

$$\mathbf{V}_{Th} - 4\mathbf{I}_2 + (-j6)\mathbf{I}_1 = 0$$

$$\mathbf{V}_{Th} = 4\mathbf{I}_2 + j6\mathbf{I}_1 = 37.95\angle 220.31^\circ \text{ V}$$

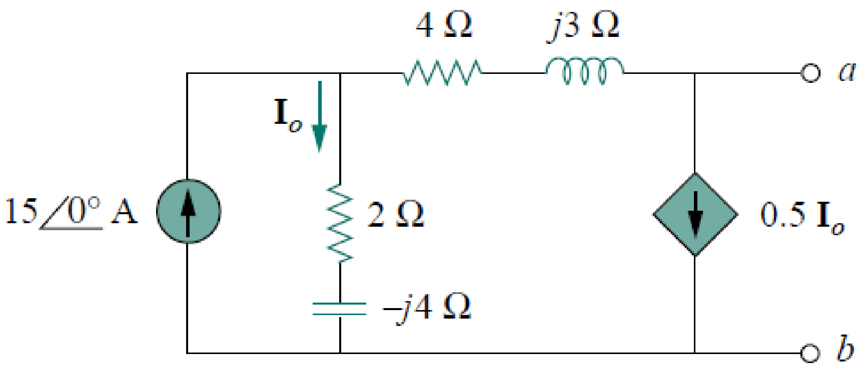
Practice Problem 10.8

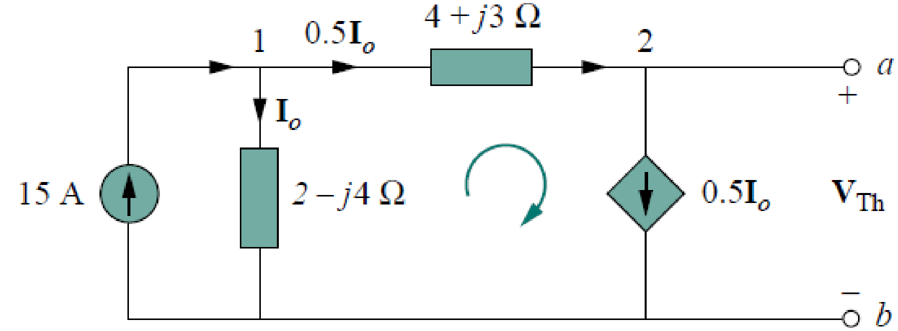
Find the Thevenin equivalent at terminals *a*-*b* of the circuit in Fig. 10.24.



EXAMPLE 10.9

Find the Thevenin equivalent of the circuit in Fig. 10.25 as seen from terminals a-b.





(a)

Solution:

To find $\mathbf{V}_{\text{Th}}$, we apply KCL at node 1 in Fig. 10.26(a).

$$15 = \mathbf{I}_o + 0.5\mathbf{I}_o \qquad \Longrightarrow \qquad \mathbf{I}_o = 10 \text{ A}$$

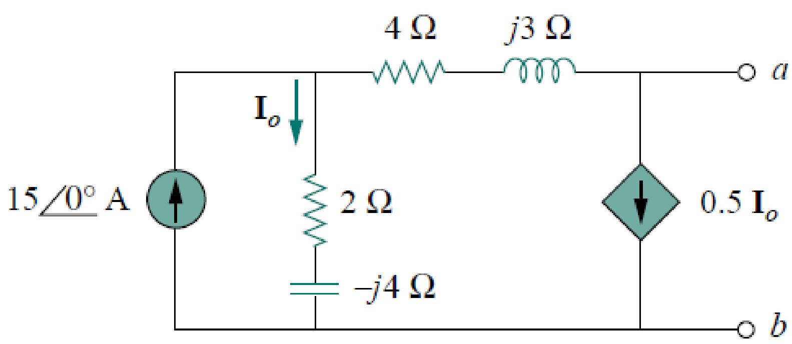
Applying KVL to the loop on the right-hand side in Fig. 10.26(a), we obtain

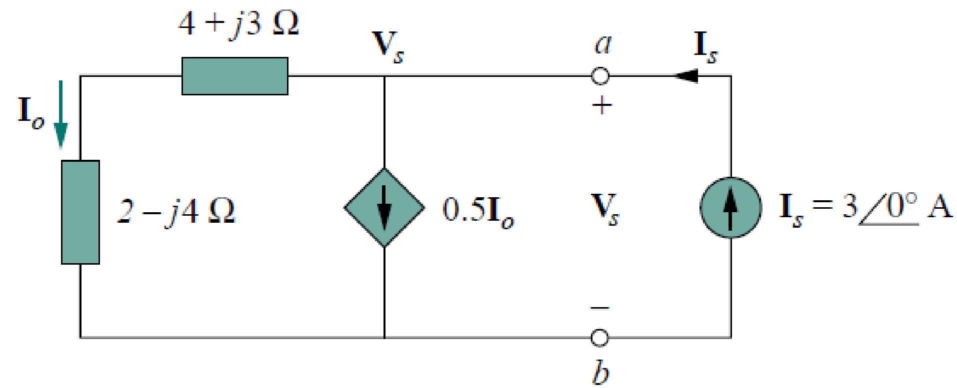
$$-\mathbf{I}_o(2 - j4) + 0.5\mathbf{I}_o(4 + j3) + \mathbf{V}_{\text{Th}} = 0$$

$\mathbf{V}_{\text{Th}} = 10(2 - j4) - 5(4 + j3) = -j55$ Thus, the Thevenin voltage is $\mathbf{V}_{\text{Th}} = 55\underline{/-90^\circ}$ V

EXAMPLE 10.9

Find the Thevenin equivalent of the circuit in Fig. 10.25 as seen from terminals *a*-*b*.





At the node, KCL gives

$$3 = \mathbf{I}_o + 0.5\mathbf{I}_o \quad \Longrightarrow \quad \mathbf{I}_o = 2 \text{ A}$$

Applying KVL to the outer loop in Fig. 10.26(b) gives

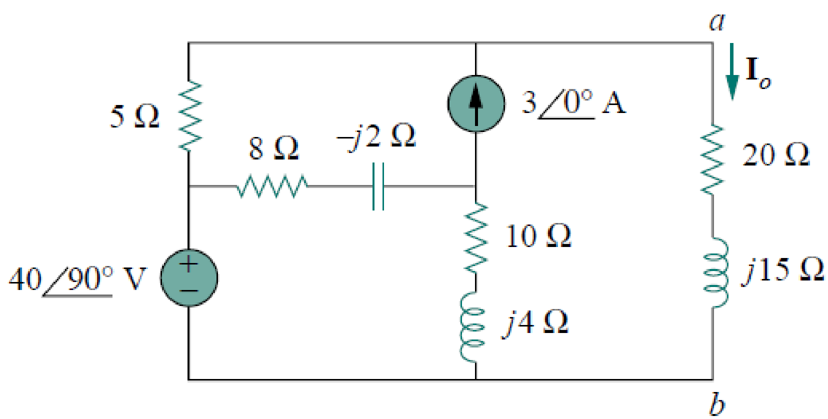
$$\mathbf{V}_s = \mathbf{I}_o(4 + j3 + 2 - j4) = 2(6 - j)$$

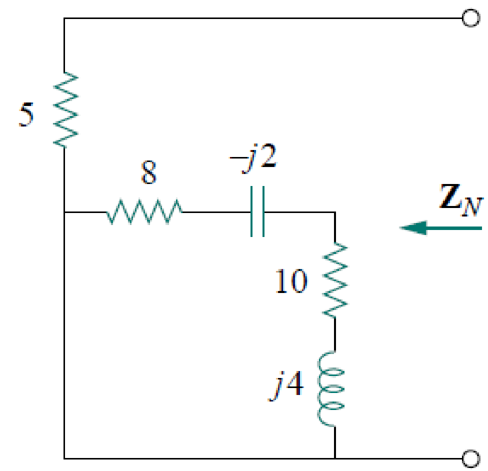
The Thevenin impedance is

$$\mathbf{Z}_{\text{Th}} = \frac{\mathbf{V}_s}{\mathbf{I}_s} = \frac{2(6 - j)}{3} = 4 - j0.6667 \ \Omega$$

EXAMPLE 10.10

Obtain current $\mathbf{I}_o$ in Fig. 10.28 using Norton's theorem.



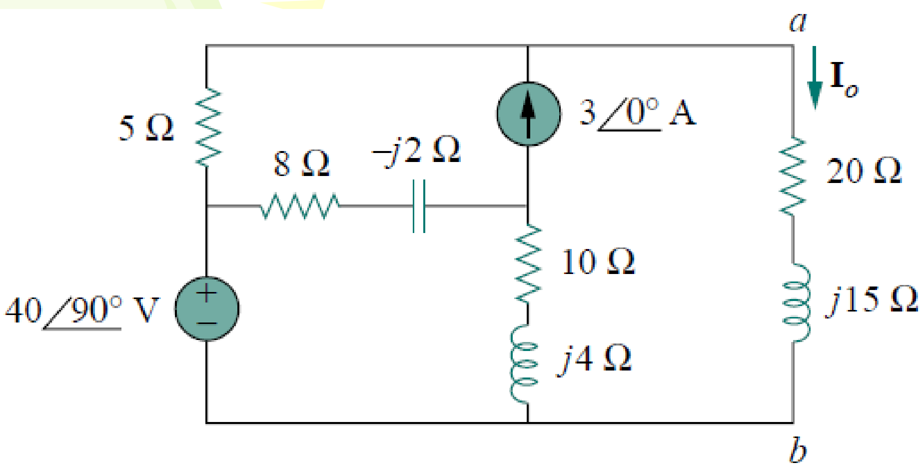


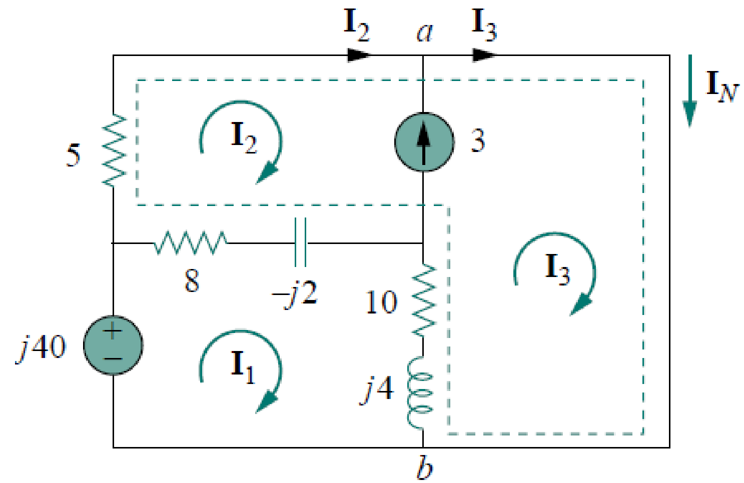
(a)

Solution:

Our first objective is to find the Norton equivalent at terminals a-b. $\mathbf{Z}_N$ is found in the same way as $\mathbf{Z}_{\text{Th}}$. We set the sources to zero as shown in Fig. 10.29(a). As evident from the figure, the $(8 - j2)$ and $(10 + j4)$ impedances are short-circuited, so that

$$\mathbf{Z}_N = 5\ \Omega$$





(b)

To get $\mathbf{I}_N$, we short-circuit terminals a-b as in Fig. 10.29(b) and apply mesh analysis. Notice that meshes 2 and 3 form a supermesh because of the current source linking them. For mesh 1,

$$-j40 + (18 + j2)\mathbf{I}_1 - (8 - j2)\mathbf{I}_2 - (10 + j4)\mathbf{I}_3 = 0$$

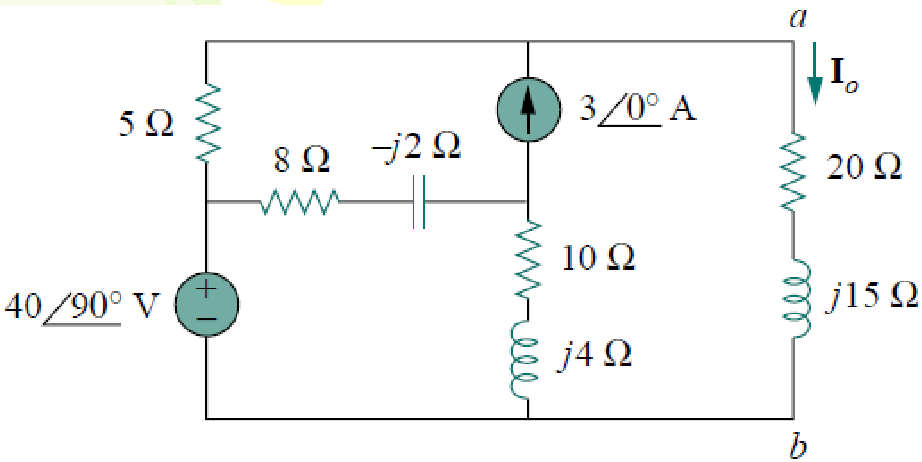
For the supermesh,

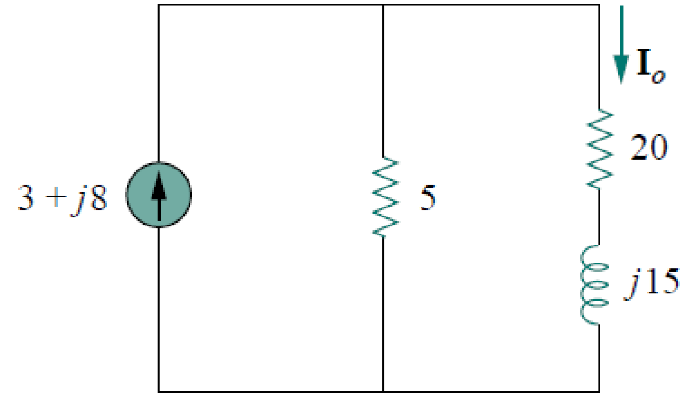
$$(13 - j2)\mathbf{I}_2 + (10 + j4)\mathbf{I}_3 - (18 + j2)\mathbf{I}_1 = 0$$

At node a, due to the current source between meshes 2 and 3,

$$\mathbf{I}_3 = \mathbf{I}_2 + 3$$

The Norton current is $\mathbf{I}_N = \mathbf{I}_3 = (3 + j8)\ \text{A}$





(c)

$$\mathbf{Z}_N = 5\ \Omega \qquad \mathbf{I}_N = \mathbf{I}_3 = (3 + j8)\ \text{A}$$

Figure 10.29(c) shows the Norton equivalent circuit along with the impedance at terminals *a*-*b*. By current division,

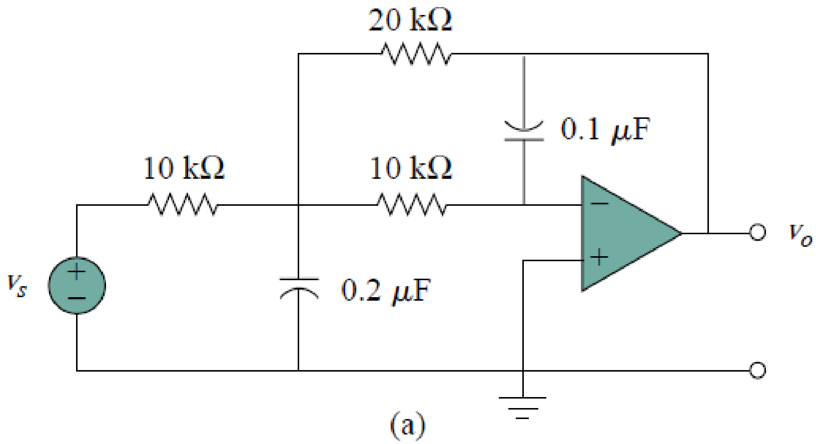
$$\mathbf{I}_o = \frac{5}{5 + 20 + j15}\mathbf{I}_N = \frac{3 + j8}{5 + j3} = 1.465\underline{/38.48^\circ}\ \text{A}$$

10.7 Op Amp circuits

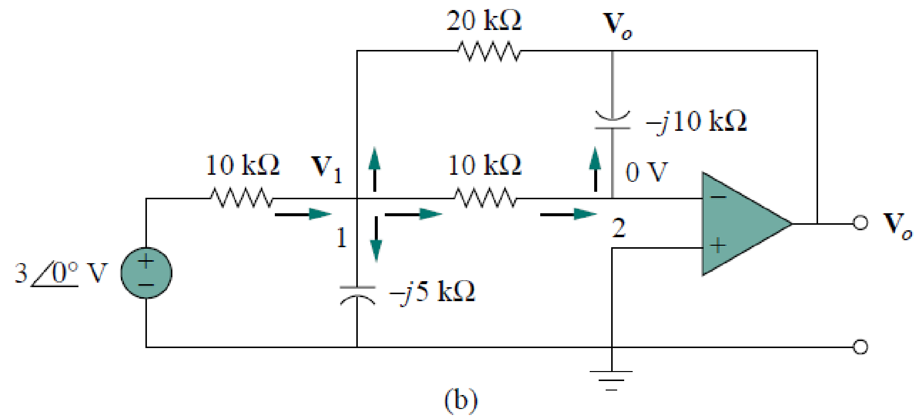
- The three steps stated in Section 10.1 also apply to op amp circuits, as long as the op amp is operating in the linear region. As usual, we will assume ideal op amps. (See Section 5.2.)
- As discussed in Chapter 5, the key to analyzing op amp circuits is to keep two important properties of an ideal op amp in mind:
- 1. No current enters either of its input terminals.
- 2. The voltage across its input terminals is zero.

EXAMPLE 10.11

Determine $v_o(t)$ for the op amp circuit in Fig. 10.31(a) if $v_s = 3\cos 1000t$ V.



(a)



(b)

Solution:

We first transform the circuit to the frequency domain, as shown in Fig. 10.31(b), where $\mathbf{V}_s = 3\angle 0°$, $\omega = 1000$ rad/s. Applying KCL at node 1,

$$\frac{3\angle 0° - \mathbf{V}_1}{10} = \frac{\mathbf{V}_1}{-j5} + \frac{\mathbf{V}_1 - 0}{10} + \frac{\mathbf{V}_1 - \mathbf{V}_o}{20} \qquad 6 = (5 + j4)\mathbf{V}_1 - \mathbf{V}_o$$

At node 2, KCL gives $\dfrac{\mathbf{V}_1 - 0}{10} = \dfrac{0 - \mathbf{V}_o}{-j10}$ $\qquad \mathbf{V}_1 = -j\mathbf{V}_o$

$$\mathbf{V}_o = \frac{6}{3 - j5} = 1.029\angle 59.04° \qquad v_o(t) = 1.029\cos(1000t + 59.04°)\ \text{V}$$

Summary and Review

1. We apply nodal and mesh analysis to ac circuits by applying KCL and KVL to the phasor form of the circuits.

2. In solving for the steady-state response of a circuit that has independent sources with different frequencies, each independent source must be considered separately.

   The most natural approach to analyzing such circuits is to apply the superposition theorem. A separate phasor circuit for each frequency must be solved independently, and the corresponding response should be obtained in the time domain.

   The overall response is the sum of the time-domain responses of all the individual phasor circuits.

3. **The concept of source transformation is also applicable in the frequency domain.**
4. **The Thevenin equivalent of an ac circuit consists of a voltage source V_{Th} in series with the Thevenin impedance Z_{Th}.**
5. **The Norton equivalent of an ac circuit consists of a current source I_N in parallel with the Norton impedance Z_N (= Z_{Th}).**

First time homework:

10.9 Use nodal analysis to find v_o in the circuit of Fig. 10.58.

ML

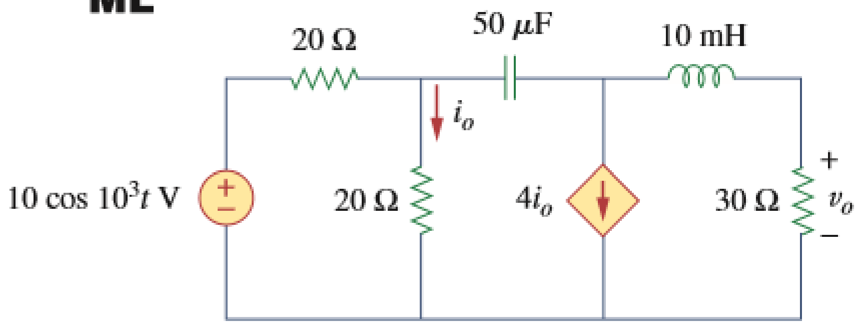


Figure 10.58
For Prob. 10.9.

10.19 Obtain $\mathbf{V}_o$ in Fig. 10.68 using nodal analysis.

ML

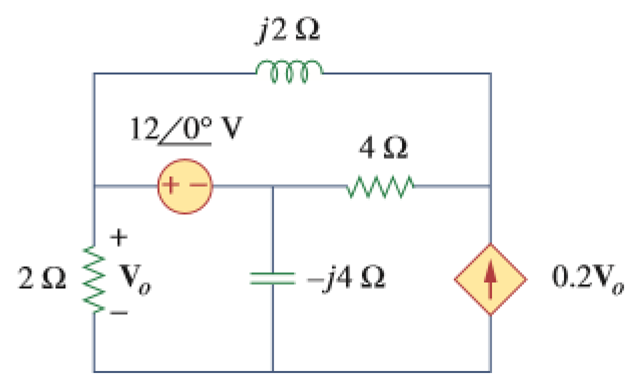


Figure 10.68
For Prob. 10.19.

10.32 Determine $\mathbf{V}_o$ and $\mathbf{I}_o$ in the circuit of Fig. 10.80 using mesh analysis.

ML

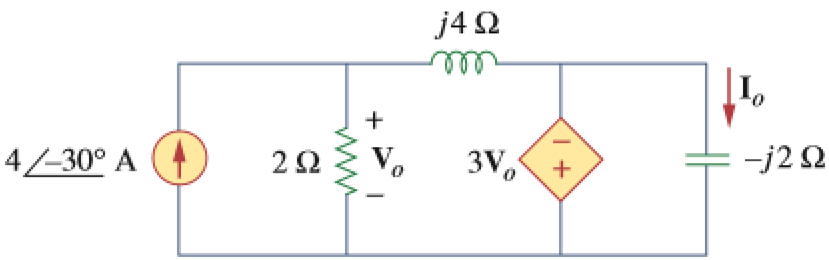


Figure 10.80
For Prob. 10.32.

10.37 Use mesh analysis to find currents $\mathbf{I}_1$, $\mathbf{I}_2$, and $\mathbf{I}_3$ in the circuit of Fig. 10.82.

ML

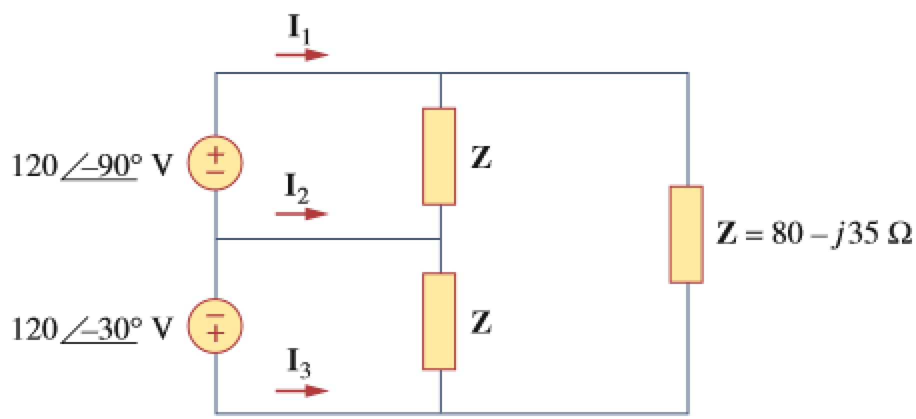


Figure 10.82
For Prob. 10.37.

Second time homework:

10.43 Using the superposition principle, find i_x in the circuit of Fig. 10.88.

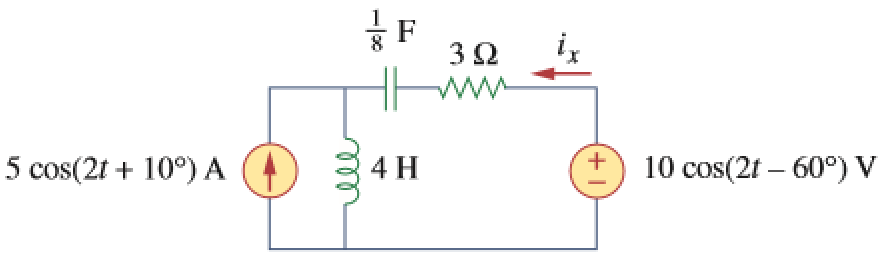


Figure 10.88
For Prob. 10.43.

10.45 Use superposition to find $i(t)$ in the circuit of Fig. 10.90.

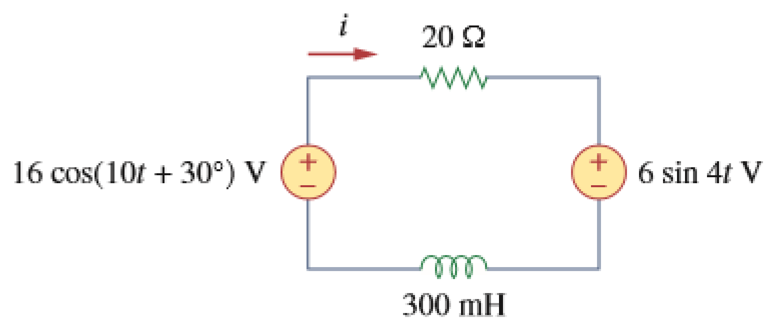


Figure 10.90
For Prob. 10.45.

10.53 Use the concept of source transformation to find $\mathbf{V}_o$ in the circuit of Fig. 10.97.

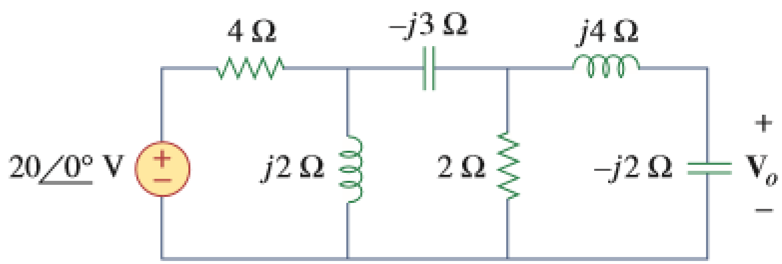
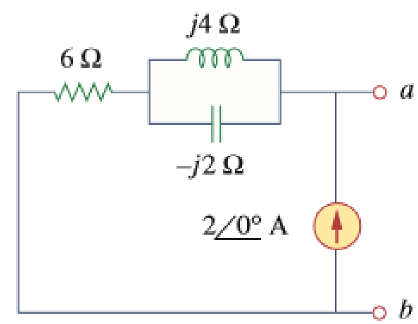
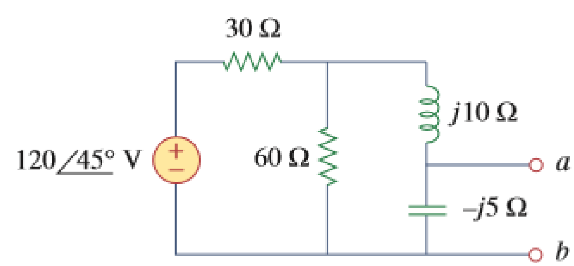


Figure 10.97
For Prob. 10.53.

10.56 For each of the circuits in Fig. 10.99, obtain Thevenin and Norton equivalent circuits at terminals *a*-*b*.



(a)



(b)

Figure 10.99
For Prob. 10.56.

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

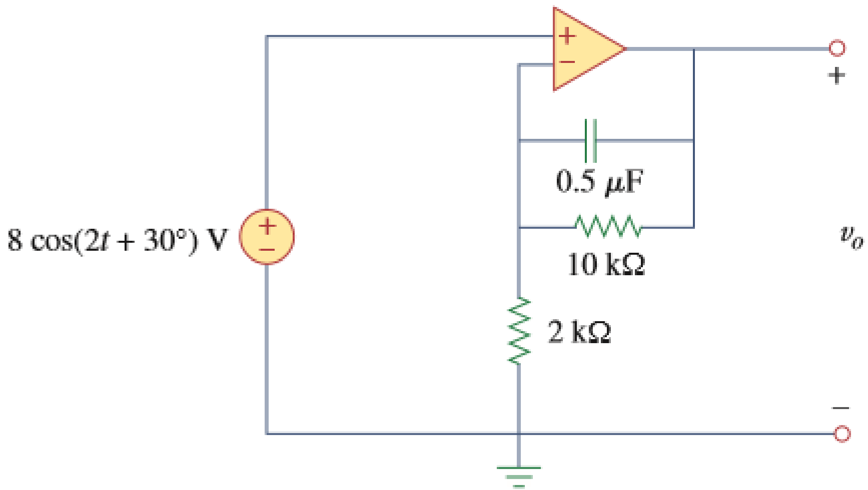


Figure 10.114
For Prob. 10.71.

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 $\omega = 1/R_2C_2$.

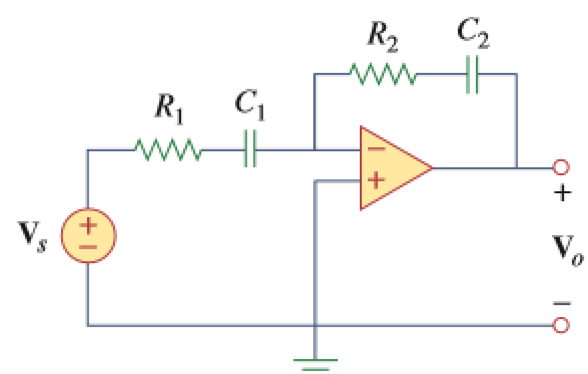


Figure 10.117
For Prob. 10.74.