Lecture 11

- Magnetically Coupled Circuits

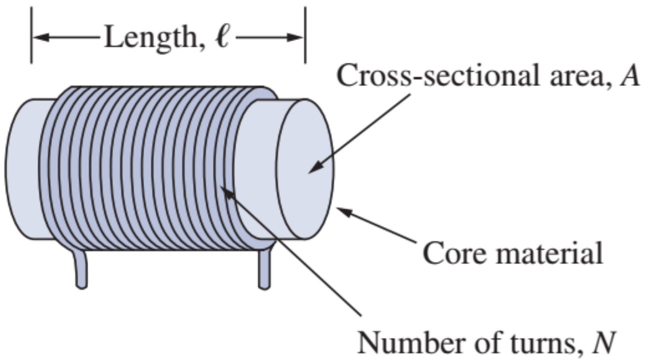
Outline

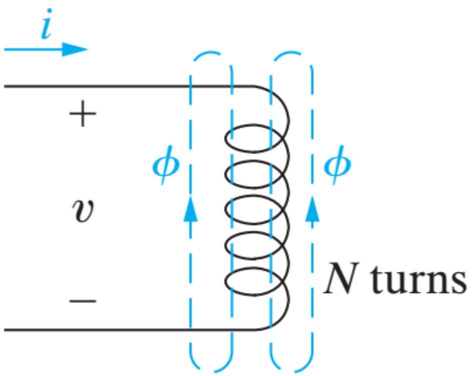
- Mutual inductance
- Transformers

Recall: Self Inductance

- Self inductance:

reaction of the inductor to the change in current ***through itself***.

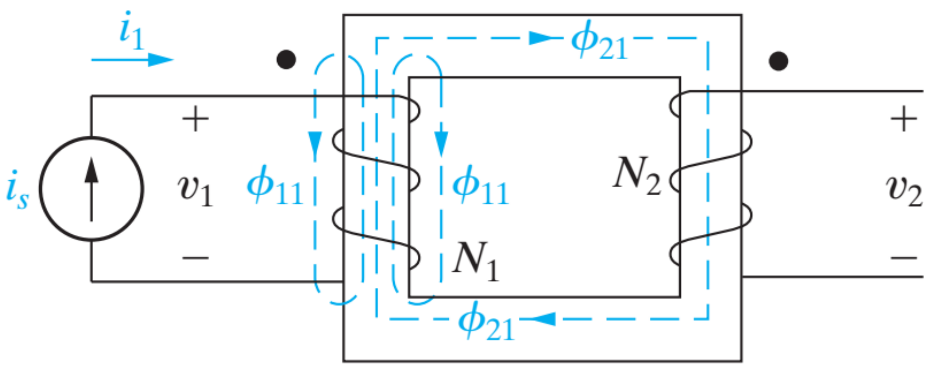




$$v = L\frac{di}{dt}$$

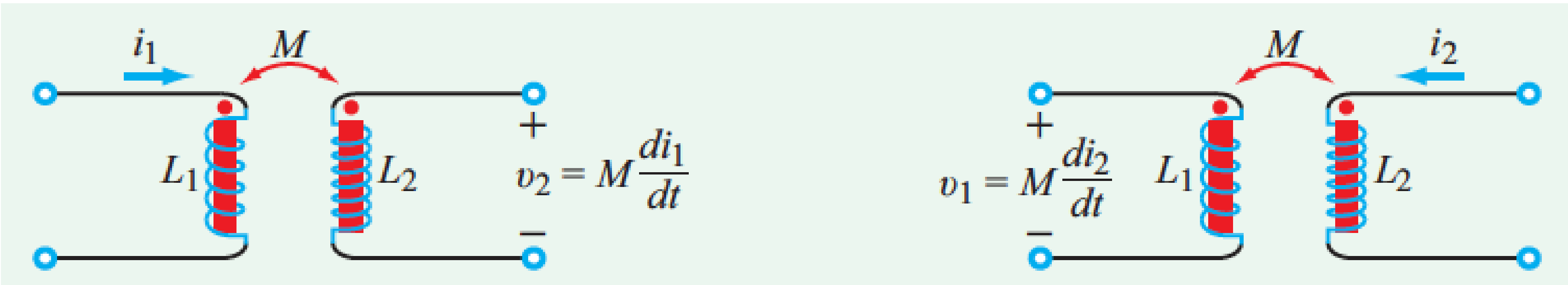
Mutual Inductance

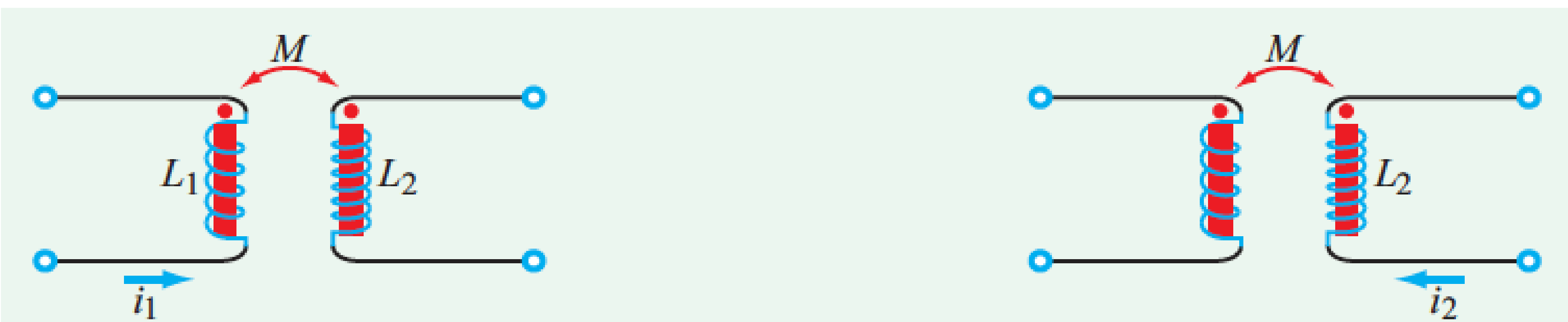
- Mutual inductance: reaction of one inductor to the change in current ***through another inductor***.



$$
\begin{aligned}
v_2 &= \frac{d(N_2\phi_{21})}{dt} = N_2\frac{d}{dt}(\mathcal{P}_{21}N_1 i_1) \\
&= N_2 N_1 \mathcal{P}_{21}\frac{di_1}{dt} \\
&\boxed{= M_{21}\frac{di_1}{dt}}
\end{aligned}
$$

Dot Convention: Defines Directions of Windings





If a current enters the dotted terminal of one coil, the reference polarity of mutual voltage in the 2nd coil is the positive at the dotted terminal, negative at the un-dotted terminal.

[Source: Berkeley]

Magnetically Coupled Circuits

- L_1, L_2: self-inductances
- M: mutual inductance
- Dots: indicating polarity of mutually induced voltages.

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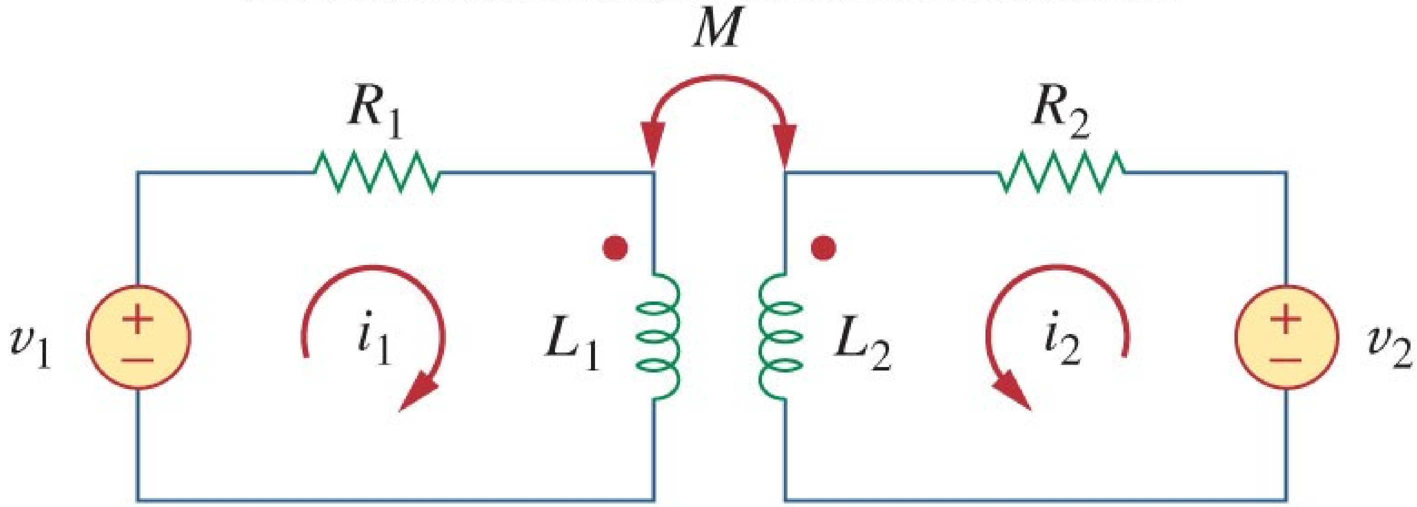
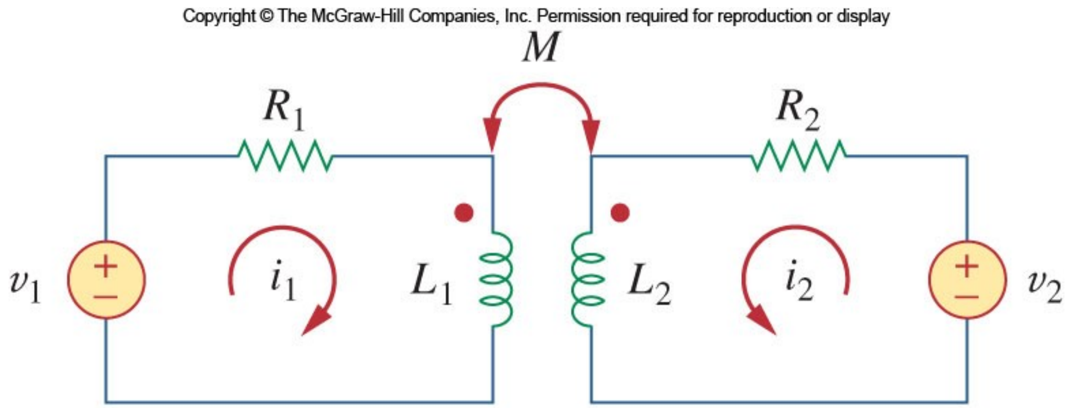
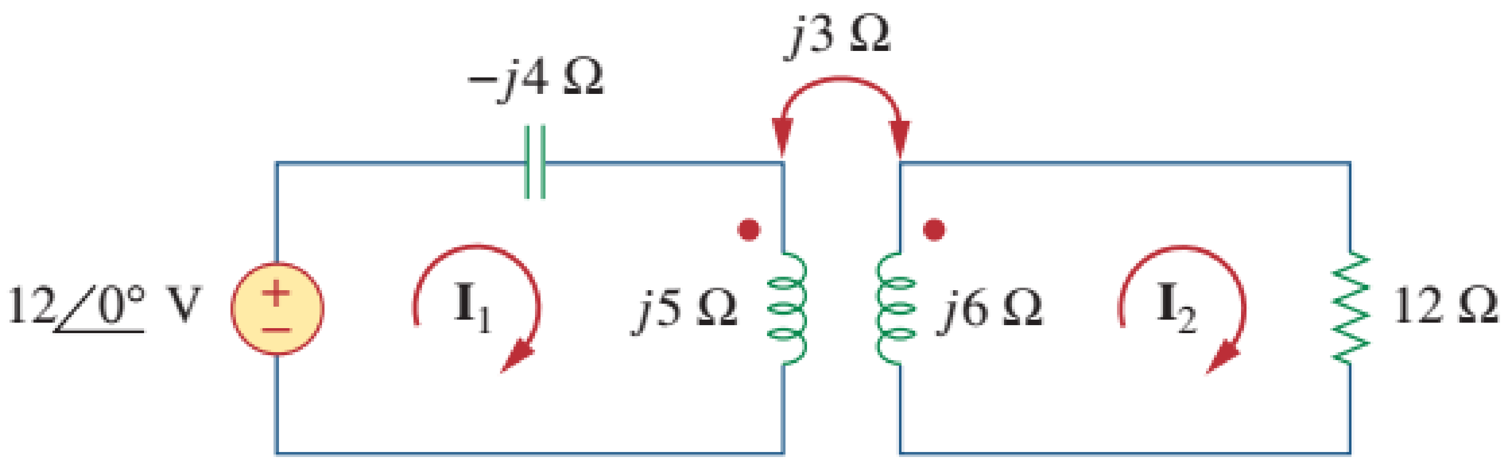


Analysis

- Find i_1 and i_2.
  - In time domain
  - In phasor domain

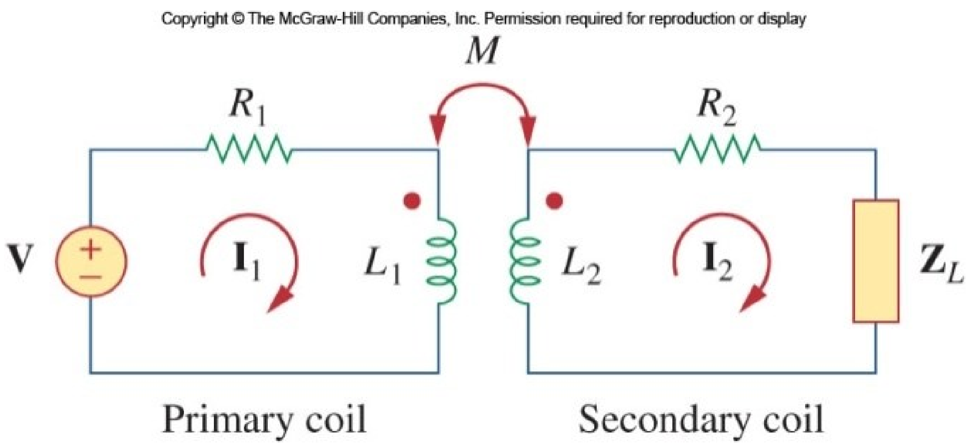


- Calculate the phasor currents $\mathbf{I}_1$, **and** $\mathbf{I}_2$
- Calculate the phasor voltages $\mathbf{V}_1$, **and** $\mathbf{V}_2$ **across the inductors**



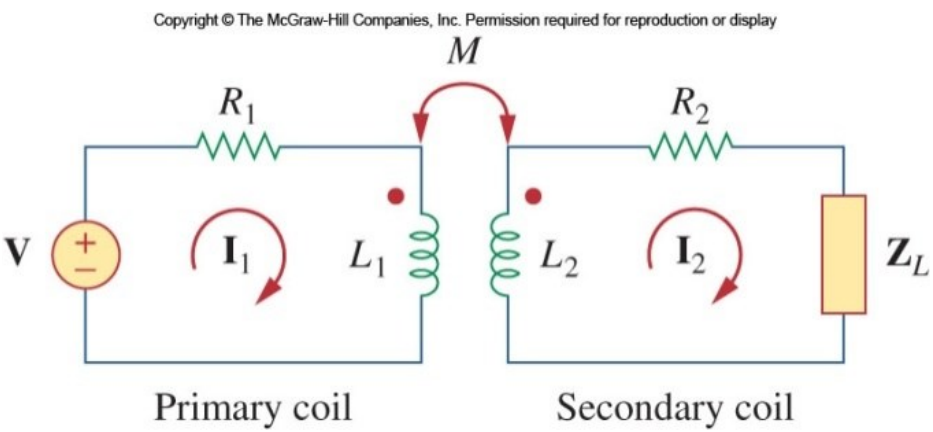
Transformers

- A transformer is a magnetic device that takes advantage of mutual inductance.



Transformer Impedance

- An important parameter to know for a transformer is how the input impedance Z_{in} is seen from the source.

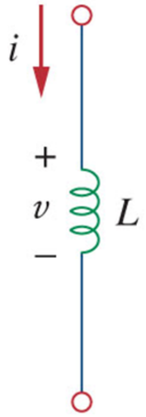


$$\mathbf{Z}_{\text{in}} = \frac{\mathbf{V}}{\mathbf{I}_1} = R_1 + j\omega L_1 + \frac{\omega^2 M^2}{R_2 + j\omega L_2 + \mathbf{Z}_L}$$

Reflected impedance from secondary to primary

Energy in a Coupled Circuit

- The energy stored in an inductor is



- For coupled inductors, the total energy stored is

$$w = \frac{1}{2}L_1 i_1^{\ 2} + \frac{1}{2}L_2 i_2^{\ 2} \pm M i_1 i_2$$

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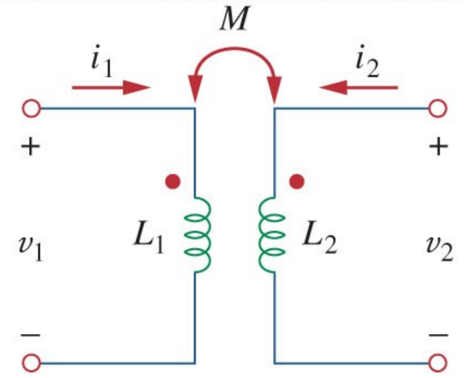

  - The positive sign is selected when the currents both enter or leave the dotted terminals.

Coupling Coefficient *k*

- The system cannot have negative energy

$$\frac{1}{2}L_1 i_1^{\ 2}+\frac{1}{2}L_2 i_2^{\ 2}-M i_1 i_2 \geq 0 \Rightarrow \boxed{M \leq \sqrt{L_1 L_2}}$$

- Define a parameter describes how closely M approaches upper limit.

$$\boxed{k=\frac{M}{\sqrt{L_1 L_2}}}$$

  - Coupling coefficient, $0 \leq k \leq 1$.

Ideal Transformers

- The ideal transformer has:
  - Coils with very large reactance

    $(L_1, L_2, M \rightarrow \infty)$
  - Coupling coefficient k=1.
  - Primary and secondary coils are lossless, $R_1 = R_2 = 0$.

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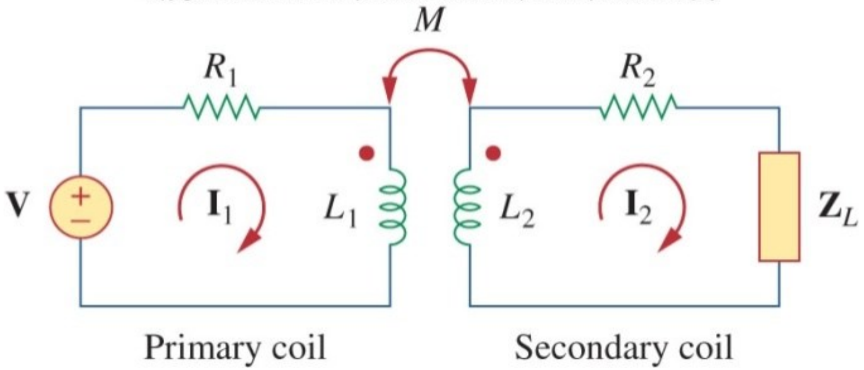
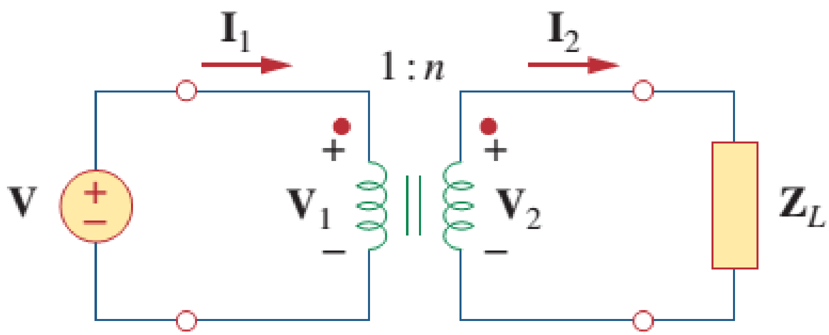


Ideal Transformers

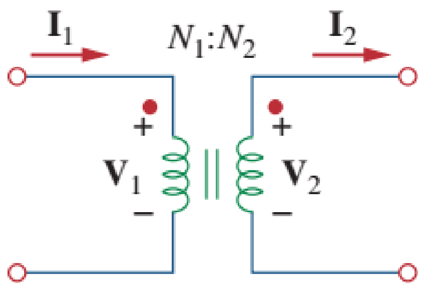


- The voltage is related as:

$$\frac{\mathbf{V_2}}{\mathbf{V_1}} = \frac{N_2}{N_1} = n$$

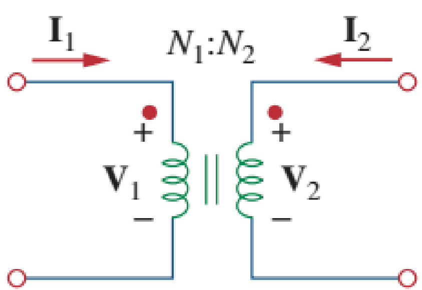
- The current is related as:

1. If $\mathbf{V}_1$ and $\mathbf{V}_2$ are *both* positive or both negative at the dotted terminals, use $+n$ in Eq. (13.52). Otherwise, use $-n$.
2. If $\mathbf{I}_1$ and $\mathbf{I}_2$ *both* enter into or both leave the dotted terminals, use $-n$ in Eq. (13.55). Otherwise, use $+n$.



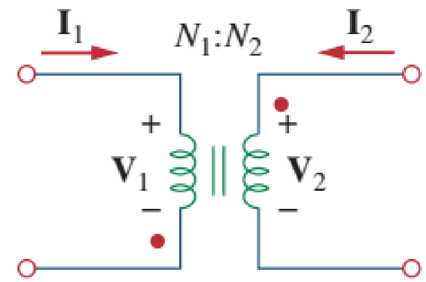
$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{N_2}{N_1} \qquad \frac{\mathbf{I}_2}{\mathbf{I}_1} = \frac{N_1}{N_2}$$

(a)



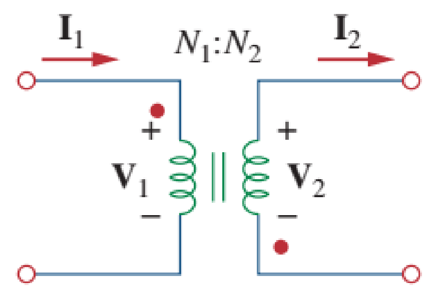
$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{N_2}{N_1} \qquad \frac{\mathbf{I}_2}{\mathbf{I}_1} = -\frac{N_1}{N_2}$$

(b)



$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = -\frac{N_2}{N_1} \qquad \frac{\mathbf{I}_2}{\mathbf{I}_1} = \frac{N_1}{N_2}$$

(c)

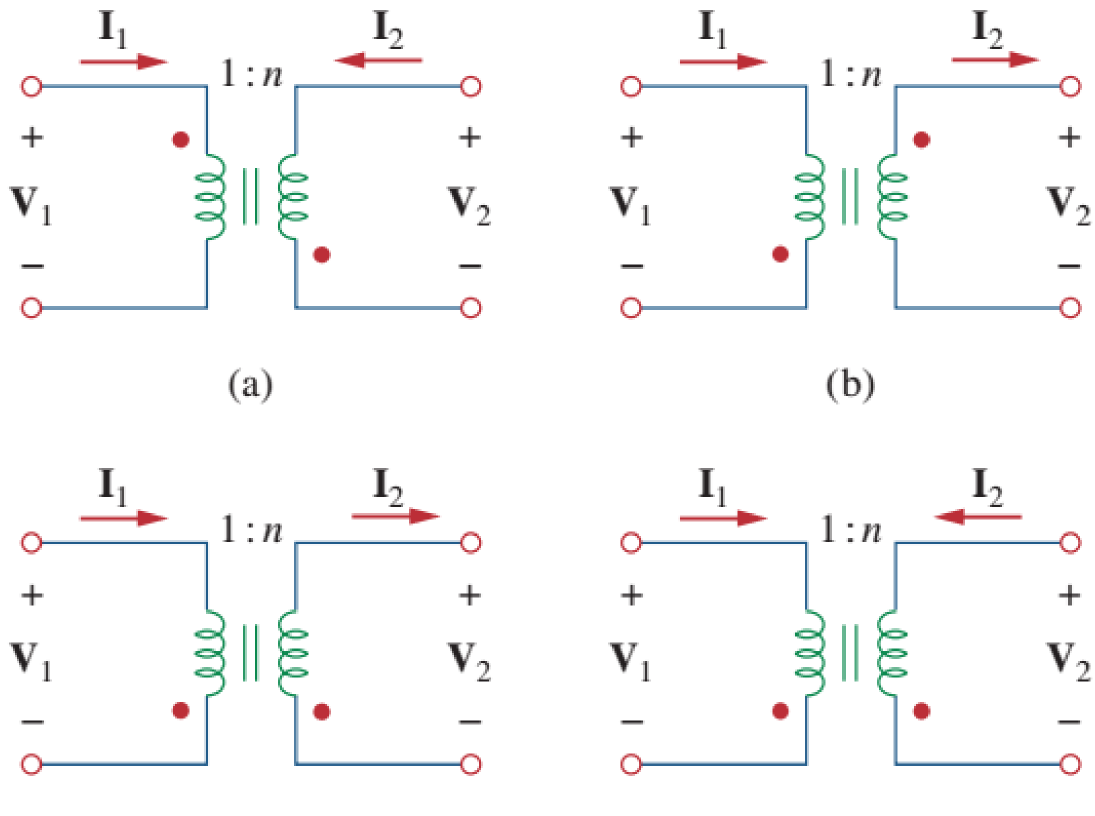


$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = -\frac{N_2}{N_1} \qquad \frac{\mathbf{I}_2}{\mathbf{I}_1} = -\frac{N_1}{N_2}$$

(d)

Practice

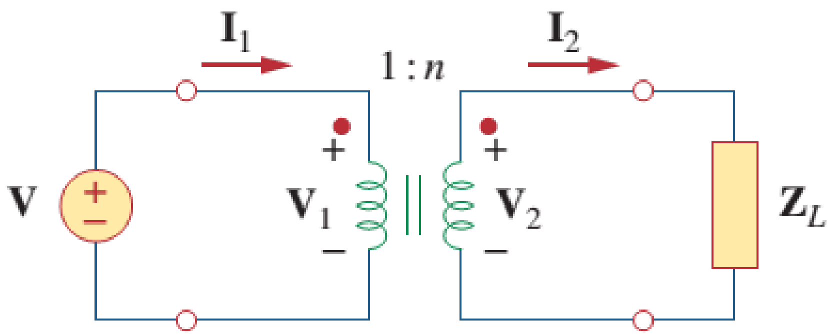
13.36 As done in Fig. 13.32, obtain the relationships between terminal voltages and currents for each of the ideal transformers in Fig. 13.105.



(a) (b) (c) (d)

Ideal Transformers

$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{N_2}{N_1} = n$$

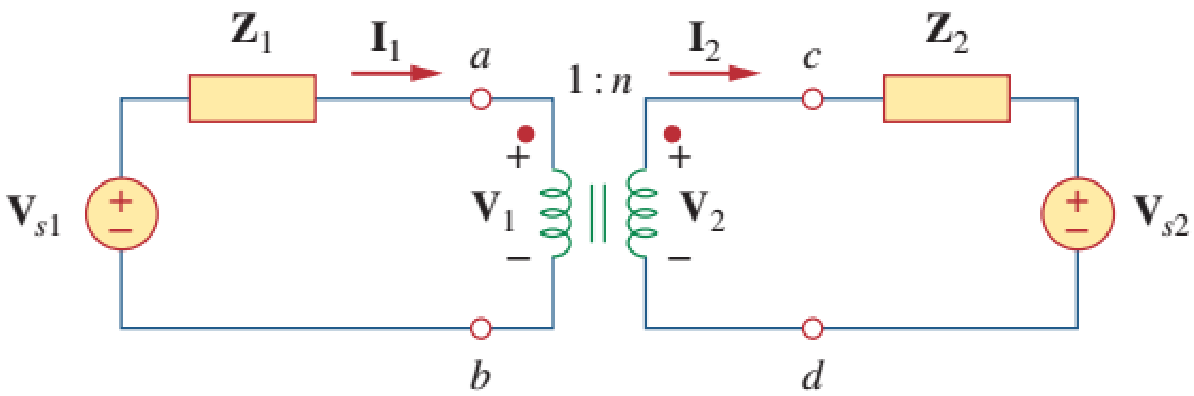


- Reflected impedance

$$\mathbf{Z}_{\text{in}} = \frac{\mathbf{V}_1}{\mathbf{I}_1} =$$

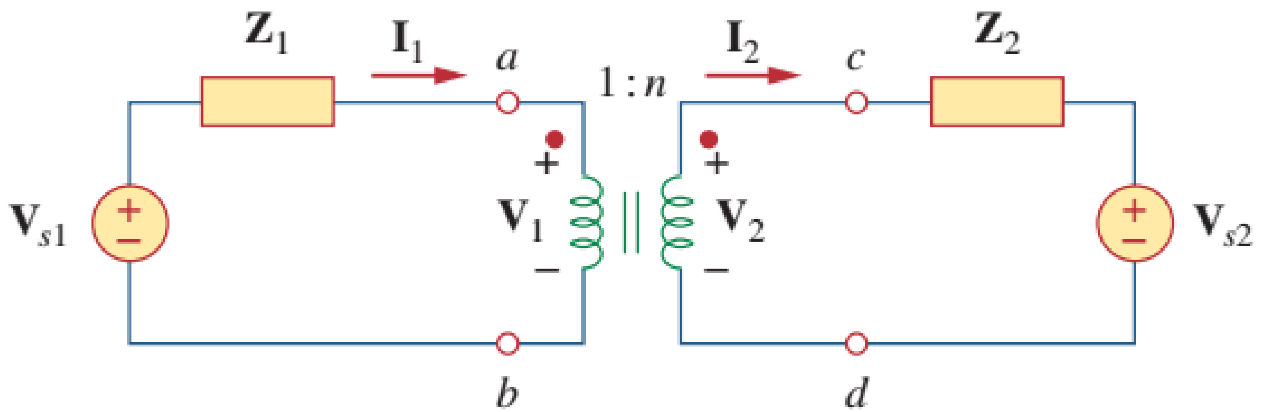
Ideal Transformers

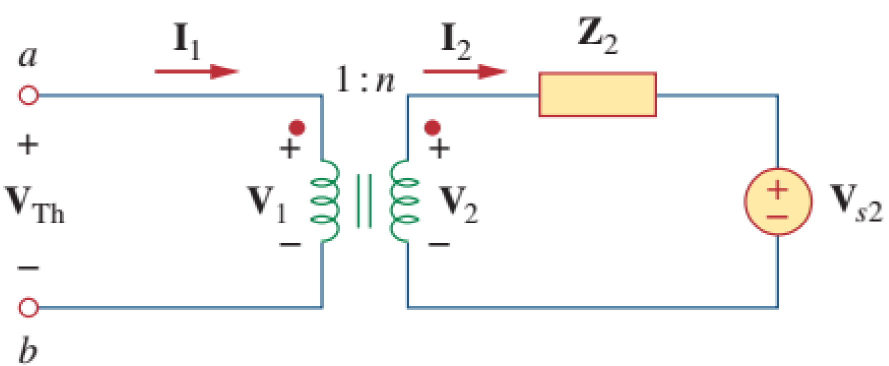
$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{N_2}{N_1} = n$$



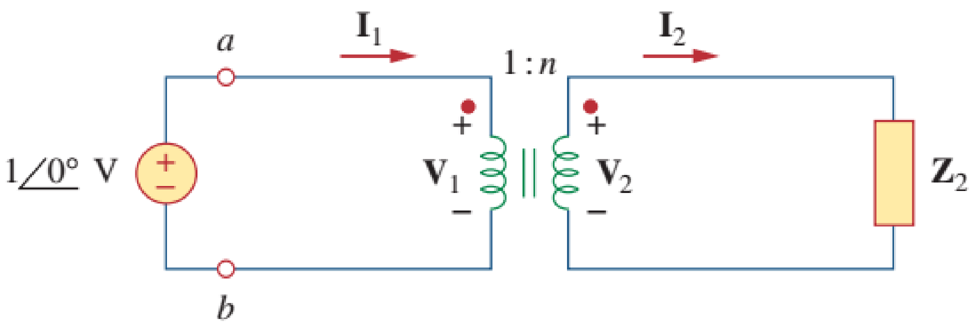
Ideal Transformers

- Reflected impedance and source

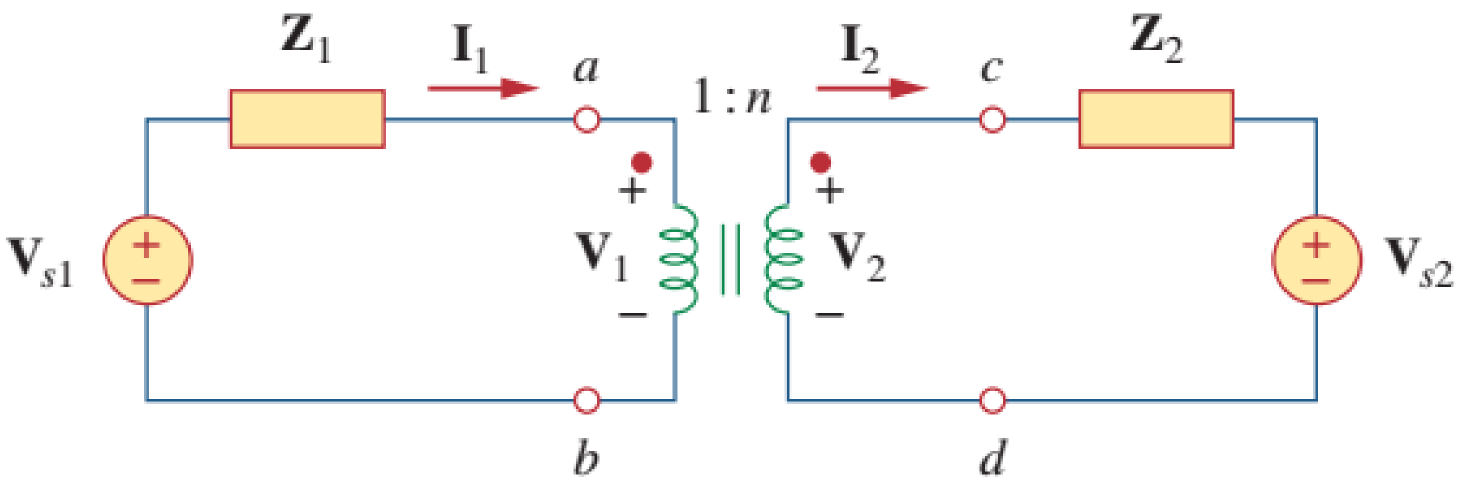


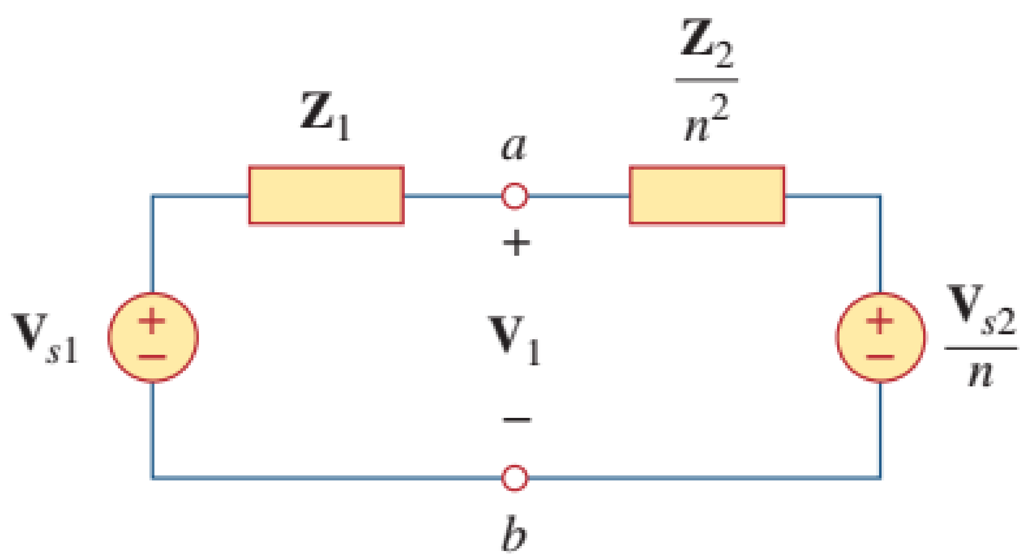


(a)



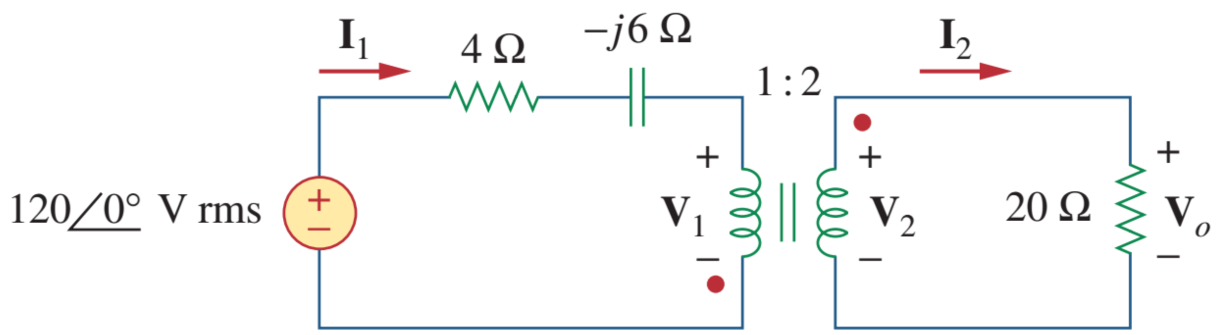
(b)

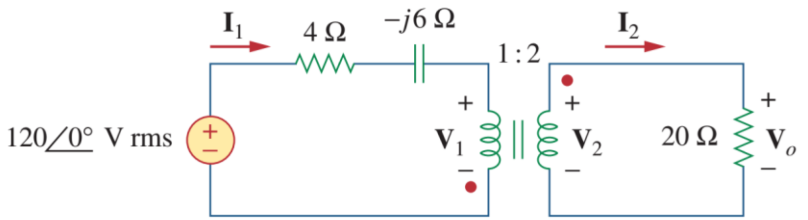

Z1
I1
a
1 : n
I2
c
Z2
Vs1
+
−
V1
V2
Vs2
b
d


Z2/n2
Z1
a
+
Vs1
V1
Vs2/n
−
b

Example

For the ideal transformer circuit of Fig. 13.37, find: (a) the source current $\mathbf{I}_1$, (b) the output voltage $\mathbf{V}_o$, and (c) the complex power supplied by the source.





Solution:

(a) The 20-Ω impedance can be reflected to the primary side and we get

$$\mathbf{Z}_R = \frac{20}{n^2} = \frac{20}{4} = 5\ \Omega$$

Thus,

$$\mathbf{Z}_{\text{in}} = 4 - j6 + \mathbf{Z}_R = 9 - j6 = 10.82\angle -33.69^\circ\ \Omega$$

$$\mathbf{I}_1 = \frac{120\angle 0^\circ}{\mathbf{Z}_{\text{in}}} = \frac{120\angle 0^\circ}{10.82\angle -33.69^\circ} = 11.09\angle 33.69^\circ\ \text{A}$$

(b) Since both $\mathbf{I}_1$ and $\mathbf{I}_2$ leave the dotted terminals,

$$\mathbf{I}_2 = -\frac{1}{n}\mathbf{I}_1 = -5.545\angle 33.69^\circ\ \text{A}$$

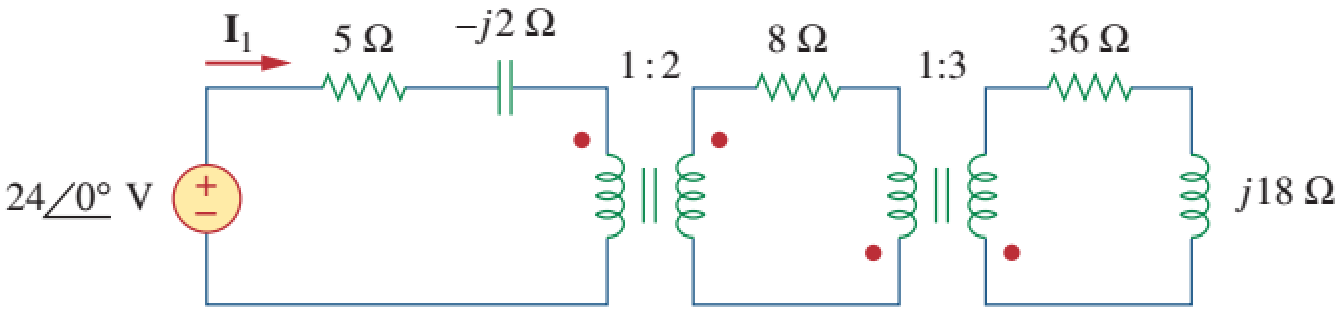
$$\mathbf{V}_o = 20\mathbf{I}_2 = 110.9\angle 213.69^\circ\ \text{V}$$

(c) The complex power supplied is

$$\mathbf{S} = \mathbf{V}_s\mathbf{I}_1^* = (120\angle 0^\circ)(11.09\angle -33.69^\circ) = 1{,}330.8\angle -33.69^\circ\ \text{VA}$$

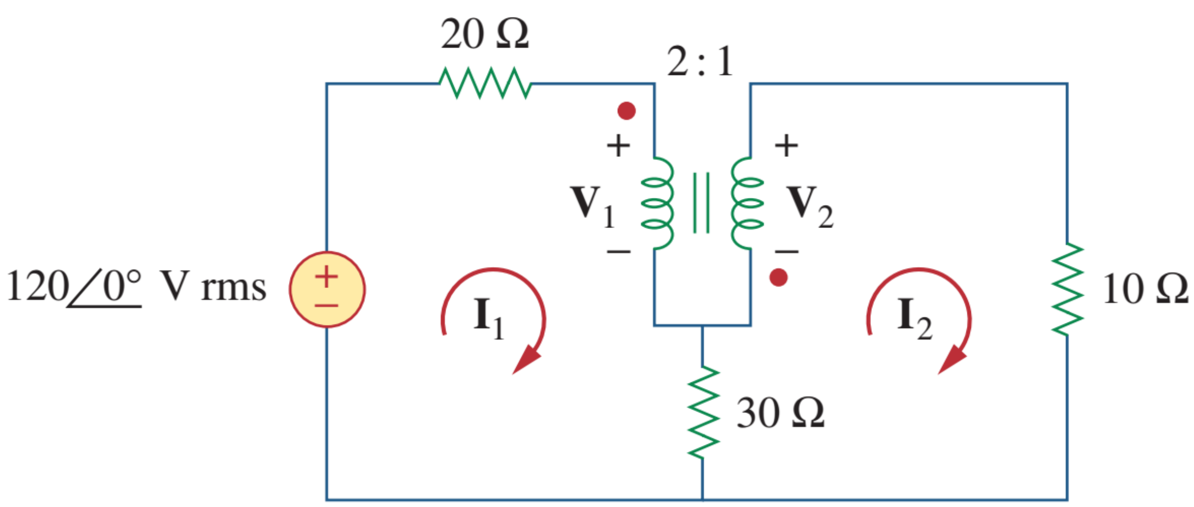
Practice

- Find reflected impedance and $\mathbf{I}_1$



Example

Calculate the power supplied to the 10-Ω resistor in the ideal transformer circuit of Fig. 13.39.



$$-120 + (20 + 30)\mathbf{I}_1 - 30\mathbf{I}_2 + \mathbf{V}_1 = 0$$

or

$$50\mathbf{I}_1 - 30\mathbf{I}_2 + \mathbf{V}_1 = 120 \qquad \textbf{(13.9.1)}$$

For mesh 2,

$$-\mathbf{V}_2 + (10 + 30)\mathbf{I}_2 - 30\mathbf{I}_1 = 0$$

or

$$-30\mathbf{I}_1 + 40\mathbf{I}_2 - \mathbf{V}_2 = 0 \qquad \textbf{(13.9.2)}$$

At the transformer terminals,

$$\mathbf{V}_2 = -\frac{1}{2}\mathbf{V}_1 \qquad \textbf{(13.9.3)}$$

$$\mathbf{I}_2 = -2\mathbf{I}_1 \qquad \textbf{(13.9.4)}$$

(Note that $n = 1/2$.) We now have four equations and four unknowns, but our goal is to get $\mathbf{I}_2$. So we substitute for $\mathbf{V}_1$ and $\mathbf{I}_1$ in terms of $\mathbf{V}_2$ and $\mathbf{I}_2$ in Eqs. (13.9.1) and (13.9.2). Equation (13.9.1) becomes

$$-55\mathbf{I}_2 - 2\mathbf{V}_2 = 120 \qquad \textbf{(13.9.5)}$$

and Eq. (13.9.2) becomes

$$15\mathbf{I}_2 + 40\mathbf{I}_2 - \mathbf{V}_2 = 0 \quad \Rightarrow \quad \mathbf{V}_2 = 55\mathbf{I}_2 \qquad \textbf{(13.9.6)}$$

Substituting Eq. (13.9.6) in Eq. (13.9.5),

$$-165\mathbf{I}_2 = 120 \quad \Rightarrow \quad \mathbf{I}_2 = -\frac{120}{165} = -0.7272 \text{ A}$$

The power absorbed by the 10-Ω resistor is

$$P = (-0.7272)^2(10) = 5.3 \text{ W}$$