Simultaneous Equations

Circuit analysis methods in Chapter 9 require use of simultaneous equations.

To simplify solving simultaneous equations, they are usually set up in standard form. Standard form for two equations with two unknowns is

\[
\begin{align*}
  a_{1,1}x_1 + a_{1,2}x_2 &= b_1 \\
  a_{2,1}x_1 + a_{2,2}x_2 &= b_2
\end{align*}
\]

- **coefficients**
- **variables**
- **constants**
A circuit has the following equations. Set up the equations in standard form.

\[-10 + 270I_A + 1000(I_A - I_B) = 0\]
\[1000(I_B - I_A) + 680I_B + 6 = 0\]

Rearrange so that variables and their coefficients are in order and put constants on the right.

\[1270I_A - 1000I_B = 10\]
\[-1000I_A + 1680I_B = -6\]
Solving Simultaneous Equations

Three methods for solving simultaneous equations are:

- Algebraic substitution
- The determinant method
- Using a calculator
- Addition method
Solve for \( I_A \) using substitution.

\[
1270I_A - 1000I_B = 10
\]
\[
-1000I_A + 1680I_B = -6
\]

Solve for \( I_B \) in the first equation:

\[
I_B = 1.270I_A - 0.010
\]

Substitute for \( I_B \) into the second equation:

\[
-1000I_A + 1680(1.270I_A - 0.010) = -6
\]

Rearrange and solve for \( I_A \).

\[
1134I_A = 10.8 \quad I_A = 9.53 \text{ mA}
\]
If you wanted to find $I_B$ in the previous example, you can substitute the result of $I_A$ back into one of the original equations and solve for $I_B$. Thus,

$$1270I_A - 1000I_B = 10$$
$$1270(9.53 \text{ mA}) - 1000I_B = 10$$

$$I_B = 2.10 \text{ mA}$$
The method of **determinants** is another approach to finding the unknowns. The characteristic determinant is formed from the coefficients of the unknowns.

**Example:**
Write the characteristic determinant for the equations. Calculate its value.

\[
\begin{align*}
1270I_A - 1000I_B &= 10 \\
-1000I_A + 1680I_B &= -6
\end{align*}
\]

**Solution:**

\[
\begin{pmatrix}
1270 & -1000 \\
-1000 & 1680
\end{pmatrix} = 1133600
\]

\[
1270 \cdot 1680 = 2133600 \\
-1000 \cdot -1000 = 1000000
\]

\[
\text{Subtract } 1133600
\]

\[
1270I_A - 1000I_B = 10
\]

\[
-1000I_A + 1680I_B = -6
\]
Solving Simultaneous Equations

To solve for an unknown by determinants, form the determinant for a variable by substituting the constants for the coefficients of the unknown. Divide by the characteristic determinant.

\[
\begin{align*}
\text{Unknown variable} & \quad \text{Constants} \\
x_1 &= \frac{\begin{vmatrix}
    b_1 & a_{12} \\
    b_2 & a_{22}
  \end{vmatrix}}{\begin{vmatrix}
    a_{11} & a_{12} \\
    a_{21} & a_{22}
  \end{vmatrix}} \\
\text{Characteristic determinant} & \quad \text{To solve for } x_2: \\
x_2 &= \frac{\begin{vmatrix}
    a_{11} & b_1 \\
    a_{21} & b_2
  \end{vmatrix}}{\begin{vmatrix}
    a_{11} & a_{12} \\
    a_{21} & a_{22}
  \end{vmatrix}}
\end{align*}
\]

Given:

\[
\begin{align*}
a_{1,1}x_1 + a_{1,2}x_2 &= b_1 \\
a_{2,1}x_1 + a_{2,2}x_2 &= b_2
\end{align*}
\]
Chapter 9

Solving Simultaneous Equations

Example:

Solve the same equations using determinants:

\[
\begin{align*}
1270I_A - 1000I_B &= 10 \\
-1000I_A + 1680I_B &= -6
\end{align*}
\]

Solution:

To solve for \( I_A \), drop the \( I_B \)s

\[
I_A = \frac{\begin{pmatrix} 10 & -1000 \\ -6 & 1680 \end{pmatrix}}{\begin{pmatrix} 1270 & -1000 \\ -1000 & 1680 \end{pmatrix}} = \frac{10 \cdot 1680 - (-6) \cdot (-1000)}{1270 \cdot 1680 - (-1000) \cdot (-1000)} = \frac{16800 - 6000}{10800} = \frac{10800}{1133600} = 9.53 \text{ mA}
\]

To solve for \( I_B \), drop the \( I_A \)s

\[
I_B = \frac{\begin{pmatrix} 1270 & 10 \\ -1000 & -6 \end{pmatrix}}{\begin{pmatrix} 1270 & -1000 \\ -1000 & 1680 \end{pmatrix}} = \frac{1270 \cdot 10 - (-1000) \cdot (-6)}{1270 \cdot 1680 - (-1000) \cdot (-1000)} = \frac{12700 - 6000}{1133600} = \frac{2380}{1133600} = 2.10 \text{ mA}
\]
Solving Simultaneous Equations

Many scientific calculators allow you to enter a set of equations and solve them “automatically”. The **calculator method** will depend on your particular calculator, but you will always write the equations in standard form first and then input the number of equations, the coefficients, and the constants. Pressing the *Solve* key will show the values of the unknowns.

\[
\begin{align*}
  a_{1,1} x_1 + a_{1,2} x_2 &= b_1 \\
  a_{2,1} x_1 + a_{2,2} x_2 &= b_2
\end{align*}
\]
In the loop current method, you can solve for the currents in a circuit using simultaneous equations.

**Steps:**
1. Identify loops (nonredundant) and assign a current in an arbitrary direction *(loop directions must be identical).*
2. Show polarities according to the assigned direction of current in each loop.
3. Apply KVL around each closed loop.
4. Solve the resulting equations for the loop currents.

Loop analysis is developed by applying KVL around loops in the circuit.
Example: Loop current method – Example 1

4. Solve the resulting equations for the loop currents (see following slide).

\[-10 + 0.270I_A + 1.0(I_A - I_B) = 0\]
\[1.0(I_B - I_A) + 0.68I_B + 6.0 = 0\]

Solution:

Assign loops in clockwise direction.
Polarities are assigned as shown. Current entering a resistor is the positive side.

Solve for $I_{R2}$

Notice that the polarity of $R_3$ is based on loop B.
Loop current method – Example 1

**Solution:** Rearranging the loop equations into standard form:

\[
(1.270 I_A) + (-1.0) \frac{-6 + 1.0 I_A}{1.68} = 10
\]

\[
(1.68)(1.270 I_A) + (1.68)(-1.0) \frac{-6 + 1.0 I_A}{1.68} = (1.68)(10)
\]

\[
2.1336 I_A + 6 - 1.0 I_A = 16.8
\]

\[
I_A(2.1336 - 1.0) = 16.8 - 6
\]

\[
I_A(1.133) = 10.8
\]

\[
I_A = \frac{10.8}{1.133} = 9.53 mA
\]

Solve for \( I_B \) in terms of \( I_A \):

\[
E = \frac{8.10}{8.10} \frac{68.160.161336.2}{10)(68.1(270.1)(68.1)(1.0)} = 10
\]

\[
Rearranging the loop equations into standard form:
\]

\[
Rearranging the loop equations into standard form:
\]

\[
Solve for \( I_B \) in terms of \( I_A \):
\]

\[
I_B = \frac{-6.0 + 1.0 I_A}{1.68}
\]

Substitute \( I_B \) equation into first equation, solve for \( I_A \).
Loop current method – Example 1

Solution: (Continued) Next, solve for $I_B$ and $I_{R2}$:

\[
1.270I_A - 1.0I_B = 10
\]
\[-1.0I_A + 1.68I_B = -6.0
\]

$I_A = 9.53 \text{ mA}$

$I_B = 2.10 \text{ mA}$

If $I_{R2}$ is positive ($I_A$ direction), then current direction is $\uparrow$

If $I_{R2}$ is negative ($I_B$ direction) then current direction is $\downarrow$

Next, solve for $I_B$ and $I_{R2}$:

\[
I_1 = I_{R1} = I_A = 9.53 \text{ mA}
\]
\[
I_3 = I_{R3} = I_B = 2.10 \text{ mA}
\]
\[
I_2 = I_{R2} = I_A - I_B = 7.43 \text{ mA}
\]
Solve for all voltages and currents
1. Assign a current in each nonredundant loop in an arbitrary direction (all loops in same direction).

**Counterclockwise direction of loops.**
2. Show polarities according to the assigned direction of current in each loop.

Polarities are assigned as shown. Current entering a resistor is the negative side.
3. Apply KVL around each closed loop. Resistors are entered in kΩ in this example.

Loop 1

\[1.47kI_a + 1k(I_a - I_b) = 12\]
\[2.47kI_a - 1kI_b = 12\]

Loop 2

\[1.8kI_b + 1k(I_b - I_a) = 0\]
\[2.8kI_b - 1kI_a = 0\]
4. Solve the resulting equations for the loop currents (see following slides).

**Loop 1**

\[ 2.47kI_a - 1kI_b = 12 \]

**Loop 2**

\[ 2.8kI_b - 1kI_a = 0 \]
Substitution Technique:

Loop 1:

\[ 2.47kI_a - 1.0kI_b = 12 \]

Loop 2:

\[ -1.00kI_a - 2.8kI_b = 0 \]

Solve Loop 2 in terms of \( I_a \):

\[ 1kI_a = 2.8kI_b \]

\[ I_a = \frac{2.8kI_b}{1k} \Rightarrow 2.8I_b \]
Sub $I_a = 2.8I_b$ solution into Loop 1:

$$2.47kl_a - 1kI_b = 12V$$

$$(2.47k)(2.8I_b) - 1kI_b = 12$$

$$6.92kI_b - 1kI_b = 12$$

$$5.92kI_b = 12$$

$$I_b = \frac{12}{5.92k}$$

$$I_b = 2.03mA$$
Loop current method – Example 2

$I_B$ can now be substituted into loop 1:

\[ 2.47kI_A - 1kI_B = 12 \]

\[ 2.47kI_A - (1k)(2.03mA) = 12 \]

\[ 2.47kI_A - 2.03 = 12 \]

\[ 2.47kI_A = 14.03 \]

\[ I_A = \frac{14.03}{2.47k} \]

\[ I_A = 5.68mA \]
Apply Ohm’s law using appropriate $I_a$ and $I_b$ current values: $E=IR$

\[
VR1 = I_aR1 \Rightarrow (5.68mA)(470\Omega) = 2.67V
\]
\[
VR2 = (I_a - I_b)R2 \Rightarrow (5.68mA - 2.03mA)(1k\Omega) = 3.65V
\]
\[
VR3 = I_bR3 \Rightarrow (2.03mA)(470\Omega) = 0.954V
\]
\[
VR4 = I_bR4 \Rightarrow (2.03mA)(330\Omega) = 0.67V
\]
\[
VR5 = I_aR5 \Rightarrow (5.68mA)(1k\Omega) = 5.68V
\]
\[
VR6 = I_bR6 \Rightarrow (2.03mA)(1k\Omega) = 2.03V
\]
Note that the current through R2 is in the direction of current $I_a$ (it is the larger of the two currents). Correct the polarity for R2 to indicate the proper current flow in the circuit. $I_{R2}$ flows upward.
Check your work by substituting the calculated voltage drops into the original KVL equations for Loop 1 and 2 or into KVL equations expressed as voltage drops and sources.

**Loop 1**

\[ 2.47k(5.68mA) - 1k(2.03mA) = 12 \]

**Loop 2**

\[ 2.8k(2.03mA) - 1k(5.68mA) = 0 \]
Use KVL equations to verify
Chapter 9

Loop current method – Example 2

Use the Addition technique to solve for Loop currents

Addition Technique:

Loop 1: \(2.47kA - 1.0kI_b = 12\)

Loop 2: \(1.00kI_a - 2.8kI_b = 0\)

Eliminate \(I_b\) in both equations by multiplying Loop 1 by \((2.8k)\) and Loop 2 by \((-1k)\):

\[
6.92kI_a - 2.8kI_b = 33.6k \\
- 1.00kI_a + 2.8kI_b = 0 \\
5.92kI_a = 33.6k \\
I_a = \frac{33.6k}{5.92M} \\
I_a = 5.68mA
\]
Use the Addition technique to solve for Loop currents

Substitute the value for $I_a$ into either equation and solve for $I_b$:

**Loop 1:**

$$2.47 kI_a - 1.0kI_b = 12$$

$$2.47 k(5.68mA) - 1.0kI_b = 12$$

$$14.03 - 1.0kI_b = 12$$

$$-1.0kI_b = -2.03$$

$$I_b = \frac{-2.03}{-1k}$$

$$I_b = 2.03mA$$
Use the Determinates method to solve for Loop currents

**Determinates Method:**

Loop 1: \[ 2.47kIa - 1.0kIb = 12 \]

Loop 2: \[ 1.00kIa - 2.8kIb = 0 \]

\[ \begin{vmatrix} 2.47k & -1.0k \\ 1.00k & -2.8k \end{vmatrix} = (2.47k)(-2.8k) - (1.00k)(-1.0k) = -6.92M + 1.00M = -5.92M \]

Determinate:

\[ Ia = \begin{vmatrix} 12 & -1.0k \\ 0 & -2.8k \end{vmatrix} = (12)(-2.8k) - (0)(-1.0k) = -33.6k - 5.92M = 5.68mA \]

\[ Ib = \begin{vmatrix} 2.47k & 12 \\ 1.00k & 0 \end{vmatrix} = (2.47k)(0) - (1.00k)(12) = -12k - 5.92M = 2.03mA \]
The loop current method can be applied to more complicated circuits, such as the Wheatstone bridge. The steps are the same as shown previously.

The advantage to the loop method for the bridge is that it has only 3 unknowns.
Example: Write the loop current equation in standard form for Loop A in the Wheatstone bridge:

\[-15 + 0.68(I_A - I_B) + 0.68(I_A - I_C) = 0\]

\[-15 + 0.68I_A - 0.68I_B + 0.68I_A - 0.68I_C = 0\]

\[1.36I_A - 0.68I_B - 0.68I_C = 15\]

Note: Resistance in kΩ
Example: Write the loop current equation in standard form for Loop B in the Wheatstone bridge:

\[(0.68 + 0.68 + 0.56)I_B - 0.68I_A - 0.56I_C = 0\]

\[0.68(I_B - I_A) + 1.24I_B - 0.56I_C = 0\]

\[0.68I_B - 0.68I_A + 1.24I_B - 0.56I_C = 0\]

\[1.92I_B - 0.68I_A - 0.56I_C = 0\]

Note: Resistance in kΩ
Example: Write the loop current equation in standard form for Loop C in the Wheatstone bridge:
\[(0.68 + 1.0 + 0.56)I_C - 0.68I_A - 0.56I_B = 0\]
\[0.68(I_C - I_A) + 1.56I_C - 0.56I_B = 0\]
\[0.68I_C - 0.68I_A + 1.56I_C - 0.56I_B = 0\]
\[2.24I_C - 0.68I_A - 0.56I_B = 0\]

Note: Resistance in kΩ
In the **node voltage method**, you can solve for the unknown voltages in a circuit using KCL.

**Steps:**
1. Determine the number of nodes. *(A node is the junction of two or more components.)*
2. Select one node as a reference. Assign voltage designations to each unknown node.
3. Assign currents into and out of each node except the reference node.
4. Apply KCL at each node where currents are assigned.
5. Express the current equations in terms of the voltages and solve for the unknown voltages using Ohm’s law.
Node voltage method – Example 1

Solve for VA using the node voltage method.

5. Write KCL in terms of the voltages.

\[ I_1 = \frac{V_{S1} - V_A}{R_1} \quad I_2 = \frac{V_A}{R_2} \quad I_3 = \frac{V_{S2} - V_A}{R_3} \]

\[ I_1 + I_3 = I_2 \]
Solution: Node voltage method – Example 1

\[ \frac{V_{S1} - V_A}{R_1} + \frac{V_{S2} - V_A}{R_3} = \frac{V_A}{R_2} \]

\[ \begin{align*}
10 - V_A & = 0.27 \\
6.0 - V_A & = 0.68 \\
\end{align*} \]

\[ 0.68(10 - V_A) + 0.27(6.0 - V_A) = 0.183V_A \]

\[ V_A = 7.45 \text{ V} \]

(Continued)

Multiply both sides by 0.183

\[ \begin{align*}
6.8 - 0.68V_A & + 1.62 - 0.27V_A = 0.183V_A \\
8.42 + V_A(-0.95) & = 0.183V_A \\
8.42 - V_A(0.95) & = 0.183V_A \\
8.42 = V_A(0.95) + V_A(0.183) & \\
V_A(1.13) & = 8.42 \\
V_A = \frac{8.42}{1.13} & = 7.45V
\end{align*} \]
Steps of Nodal Analysis

(Short version)

1. Choose a reference node.

2. Assign node voltages to the other unknown nodes. Write KCL equations for unknown nodes.

3. Express currents in terms of node voltages. Substitute into KCL equations.

4. Solve the resulting system of linear equations.
Node voltage method – Example 2

Reference Node

3 mA

$I_1$

500Ω  500Ω

500Ω

1kΩ
Steps of Nodal Analysis
(short version)

1. Choose a reference node.

2. Assign node voltages to the other unknown nodes. Write KCL equations for unknown nodes.

3. Express currents in terms of node voltages. Substitute into KCL equations.

4. Solve the resulting system of linear equations.
Node Voltages

$V_1$ and $V_2$ are unknowns for which we solve using KCL.
**Steps of Nodal Analysis**  
*(short version)*

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Choose a reference node.</td>
</tr>
<tr>
<td>2.</td>
<td>Assign node voltages to the other unknown nodes. Write KCL equations for unknown nodes.</td>
</tr>
<tr>
<td>3.</td>
<td>Express currents in terms of node voltages. Substitute into KCL equations.</td>
</tr>
<tr>
<td>4.</td>
<td>Solve the resulting system of linear equations.</td>
</tr>
</tbody>
</table>
Node voltage method – Example 2

KCL at Node 1

\[ V_1 - V_2 = \frac{500 \Omega}{500 \Omega} \]

\[ 3 \text{ mA} = \frac{V_1 - V_2}{500 \Omega} + \frac{V_1}{500 \Omega} \]
KCL at Node 2

\[
\frac{V_1 - V_2}{500\Omega} = \frac{V_2}{1k\Omega} + \frac{V_2}{500\Omega}
\]
### Steps of Nodal Analysis
*(short version)*

1. Choose a reference node.
2. Assign node voltages to the other unknown nodes. Write KCL equations for unknown nodes.
3. Express currents in terms of node voltages. Substitute into KCL equations.
4. Solve the resulting system of linear equations.
Node voltage method – Example 2

System of Equations

| Node 1: | \[
\frac{V_1 - V_2}{500\Omega} + \frac{V_1}{500\Omega} = 3mA
\] |
| Node 2: | \[
\frac{V_2}{500\Omega} + \frac{V_2}{1k\Omega} = \frac{V_1 - V_2}{500\Omega}
\] |
## System of Equations

### Node 1:

\[
\frac{V_1 - V_2}{500 \Omega} + \frac{V_1}{500 \Omega} = 3mA
\]

\[
(500) \left( \frac{V_1 - V_2}{500 \Omega} \right) + (500) \left( \frac{V_1}{500 \Omega} \right) = (500)(3mA)
\]

\[
V_1 - V_2 + V_1 = 1.5
\]

\[
2V_1 - V_2 = 1.5
\]

\[
2V_1 = 1.5 + V_2
\]

\[
V_1 = \frac{1.5 + V_2}{2}
\]
Chapter 9

Node voltage method – Example 2

System of Equations

- **Node 2:**

  \[
  \frac{V_2}{500\Omega} + \frac{V_2}{1k\Omega} = \frac{V_1 - V_2}{500\Omega}
  \]

  \[
  (500) \left( \frac{V_2}{500\Omega} \right) + (500) \left( \frac{V_2}{1k\Omega} \right) = (500) \left( \frac{V_1 - V_2}{500\Omega} \right)
  \]

  \[
  V_2 + (0.5)V_2 = V_1 - V_2
  \]

  \[
  V_2 + (0.5V_2) + V_2 = V_1
  \]

  \[
  (2.5)V_2 = V_1
  \]

  \[
  V_2 = \frac{V_1}{2.5}
  \]
## Chapter 9

### System of Equations

- **Solve for** $V_1$ **by substituting** $V_2 = \frac{V_1}{2.5}$ **into**

  \[
  V_1 = \frac{1.5 + V_2}{2}
  \]

\[
V_1 = \frac{1.5 + \frac{V_1}{2.5}}{2}
\]

\[
2V_1 = 1.5 + \frac{V_1}{2.5}
\]

\[
10V_1 = 7.5 + 2V_1
\]

\[
8V_1 = 7.5
\]

\[
V_1 = \frac{7.5}{8} = 0.9375V
\]

- **Multiply both sides by 5**
Substitute $V_1$ into reduced Node 2 equation to solve for $V_2$:

$$V_2 = \frac{V_1}{2.5}$$

$$V_2 = \frac{0.9375}{2.5} = 0.375V$$
Node Voltages

Node voltage method – Example 2

$V_1 = 0.9375\,v$
$V_2 = 0.375\,v$

$V_1$ and $V_2$ are unknowns for which we solve using KCL.
<table>
<thead>
<tr>
<th>Key Terms</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Branch</strong></td>
<td>One current path that connects two nodes.</td>
</tr>
<tr>
<td><strong>Determinant</strong></td>
<td>The solution of a matrix consisting of an array of coefficients and constants for a set of simultaneous equations.</td>
</tr>
<tr>
<td><strong>Loop</strong></td>
<td>A closed current path in a circuit.</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td>An array of numbers.</td>
</tr>
<tr>
<td><strong>Node</strong></td>
<td>The junction of two or more components.</td>
</tr>
<tr>
<td><strong>Simultaneous equations</strong></td>
<td>A set of $n$ equations containing $n$ unknowns, where $n$ is a number with a value of 2 or more.</td>
</tr>
</tbody>
</table>
1. In a set of simultaneous equations, the coefficient that is written $a_{1,2}$ appears in
   a. the first equation
   b. the second equation
   c. both of the above
   d. none of the above
1. In a set of simultaneous equations, the coefficient that is written $a_{1,2}$ appears in
   a. the first equation
   b. the second equation
   c. both of the above
   d. none of the above
2. In standard form, the constants for a set of simultaneous equations are written
   a. in front of the first variable
   b. in front of the second variable
   c. on the right side of the equation
   d. all of the above
2. In standard form, the constants for a set of simultaneous equations are written
   a. in front of the first variable
   b. in front of the second variable
   c. on the right side of the equation
   d. all of the above
3. To solve simultaneous equations, the minimum number of independent equations must be at least

a. two

b. three

c. four

d. equal to the number of unknowns
3. To solve simultaneous equations, the minimum number of independent equations must be at least
   a. two
   b. three
   c. four
   d. equal to the number of unknowns
4. In the equation \( a_{1,1}x_1 + a_{1,2}x_2 = b_1 \), the quantity \( b_1 \) represents

   a. a constant

   b. a coefficient

   c. a variable

   d. none of the above
4. In the equation $a_{1,1}x_1 + a_{1,2}x_2 = b_1$, the quantity $b_1$ represents

- a. a constant
- b. a coefficient
- c. a variable
- d. none of the above
5. The value of the determinant \[
\begin{pmatrix}
3 & 5 \\
2 & 8 \\
\end{pmatrix}
\] is

a. 4
b. 14
c. 24
d. 34
5. The value of the determinant \[
\begin{pmatrix}
3 & 5 \\
2 & 8
\end{pmatrix}
\] is

- a. 4
- b. 14
- c. 24
- d. 34

\[
3 \cdot 8 = 24 \\
5 \cdot 2 = 10 \\
24 - 10 = 14
\]
6. The characteristic determinant for a set of simultaneous equations is formed using
   a. only constants from the equations
   b. only coefficients from the equations
   c. both constants and coefficients from the equations
   d. none of the above
6. The characteristic determinant for a set of simultaneous equations is formed using

a. only constants from the equations
b. only coefficients from the equations
c. both constants and coefficients from the equations
d. none of the above
7. A negative result for a current in the branch method means
   a. there is an open path
   b. there is a short circuit
   c. the result is incorrect
   d. the current is opposite to the assumed direction
7. A negative result for a current in the branch method means

   a. there is an open path
   b. there is a short circuit
   c. the result is incorrect
   d. the current is opposite to the assumed direction
8. To solve a circuit using the loop method, the equations are first written for each loop by applying
   a. KCL
   b. KVL
   c. Ohm’s law
   d. Thevenin’s theorem
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   a. KCL
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9. A Wheatstone bridge can be solved using loop equations. The minimum number of nonredundant loop equations required is

a. one
b. two
c. three
d. four
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   a. one
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10. In the node voltage method, the equations are developed by first applying
   a. KCL
   b. KVL
   c. Ohm’s law
   d. Thevenin’s theorem
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