Circuit Analysis and Design

Academic year 2019/2020 – Semester 1 – Presentation 5

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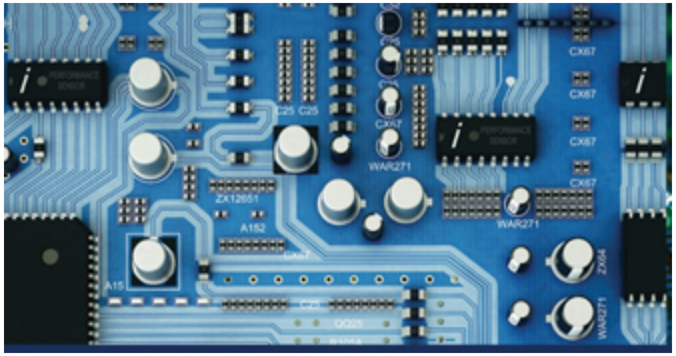
"A good student never steal or cheat"

Agenda



- Introduction
- Nodal analysis
- Supernode
- Summary

Introduction

- In this chapter, systematic approaches to analyze electric circuits are presented. The approaches refer to nodal analysis and mesh analysis. These two analysis methods can be universally applied in solving circuit problems.

- Nodal analysis is a method of finding all unknown node voltages of a circuit. The method is based on Kirchhoff's current law (KCL).

- In a special case, if there is a voltage source connecting two nodes, we can form a supernode by first excluding the voltage source, and then write the sum of currents that are leaving its two node-voltage terminals.

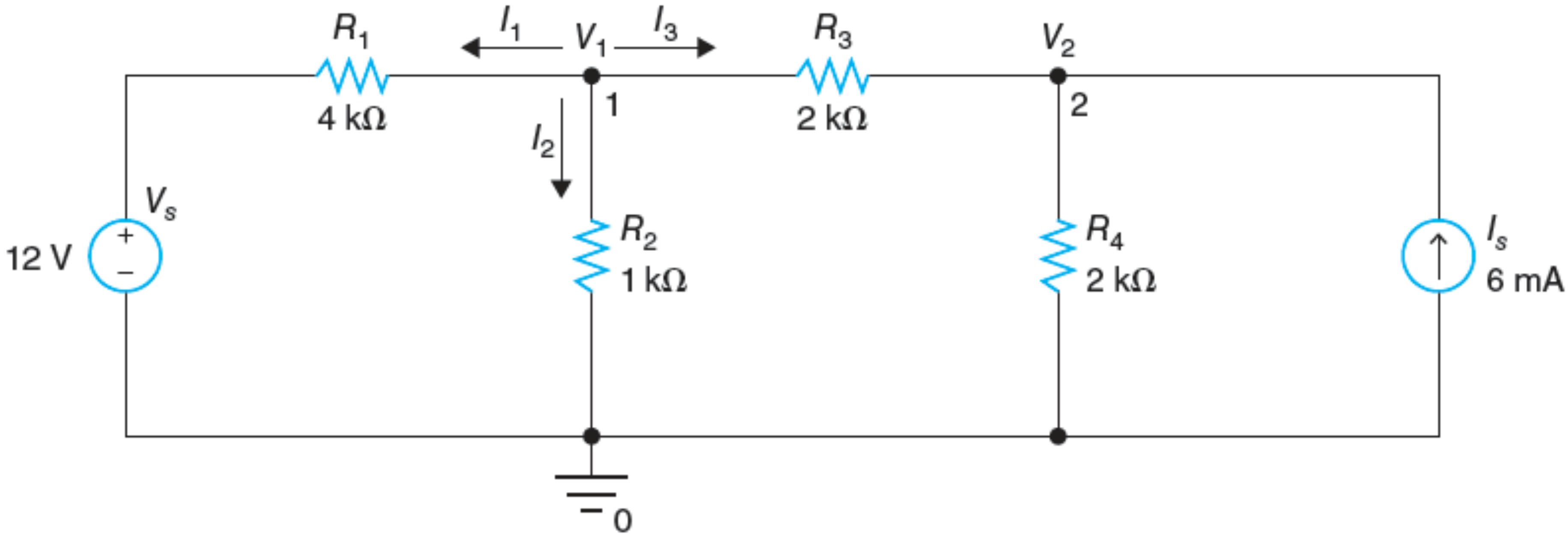
- Mesh analysis is a method of finding all unknown mesh currents of a circuit, and is based on Kirchhoff's voltage law (KVL).

- If there is a current source between two meshes, we can form a supermesh consisting of two meshes.

Nodal Analysis

- Nodal analysis is a method of finding all the unknown node voltages of a circuit.
- The method is based on Kirchhoff's current law (KCL): The sum of the currents leaving a node is zero.
- Nodes can be labeled 1, 2, 3, . . . , or a, b, c, . . . (0 can be used for the reference node), and voltages on these nodes can be labeled V_1, V_2, V_3, . . . , or V_a, V_b, V_c, ...
- The node voltage of a reference node (0 V) and nodes with specified voltage sources to a reference node are known.
- For each node whose voltage is unknown, we can write a node-voltage equation by summing the currents leaving (entering, or some entering and the rest leaving) the node. This is tantamount to writing KCL at each node.
- The currents leaving the node through resistors can be found by applying Ohm's law.
- A solution to the node voltages is obtained by solving the set of node-voltage equations.
- Once all the node voltages are computed, the current in each branch can be found using Ohm's law.

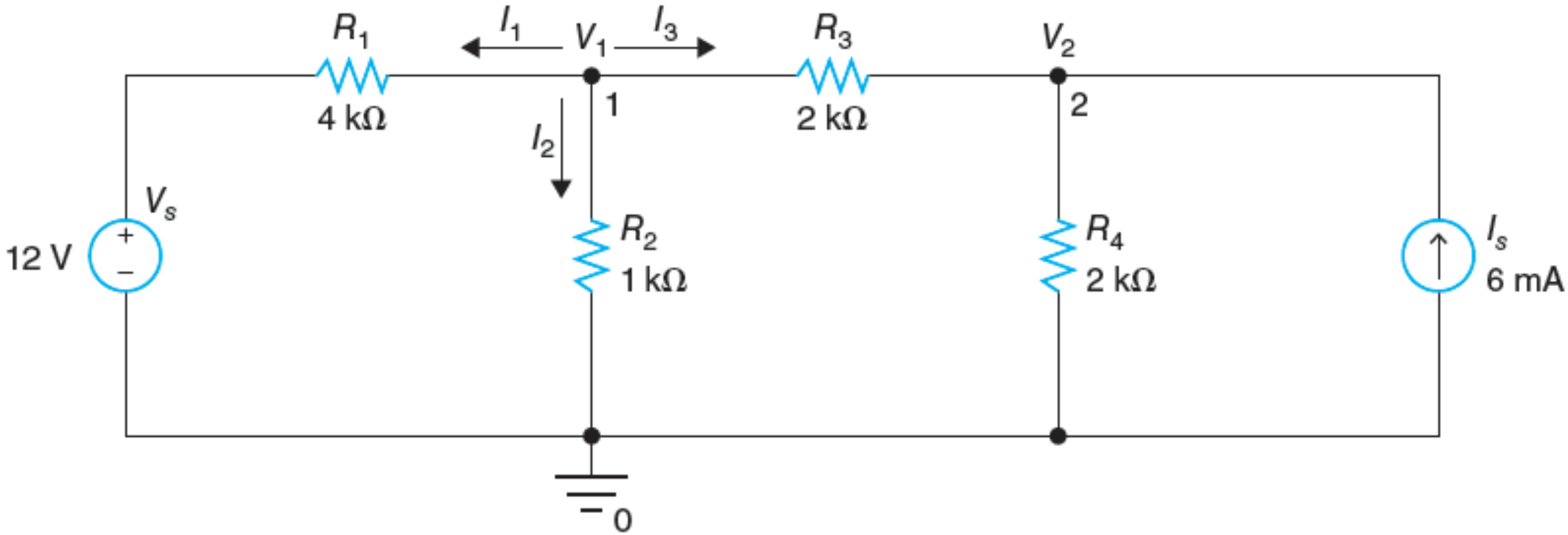
A Circuit with Two Unknown Node Voltages



- In the circuit shown below, the voltage V_1 at node 1 and the voltage V_2 at node 2 are unknown.

- Three branches are connected to node 1. The currents leaving node 1 through these branches are labeled as I_1, I_2, and I_3. According to KCL, the sum of currents leaving node 1 is zero, that is, $I_1 + I_2 + I_3 = 0$. We are trying to find node voltages. We have to represent these three currents as a function of unknown node voltages V_1 and V_2.

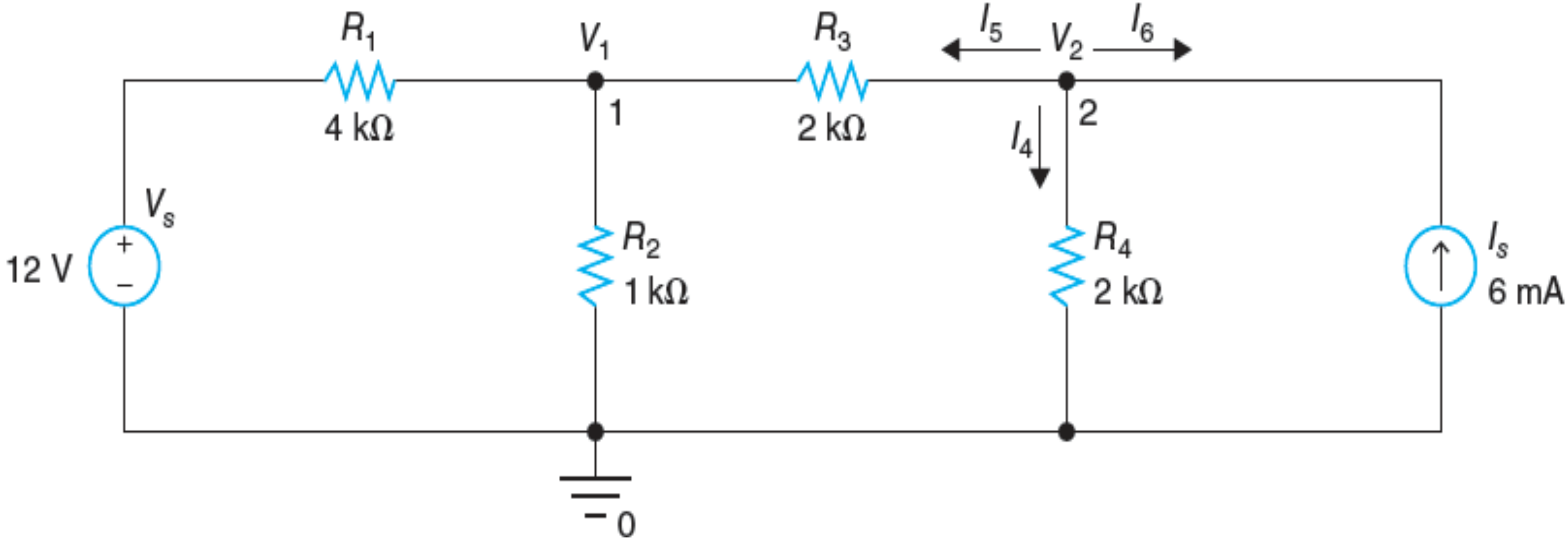
A Circuit with Two Unknown Node Voltages



- The voltage across R_1 from right to left is $V_1 – V_s$. According to Ohm's law, the current I_1 is given by $(V_1 – V_s)/R_1$. The voltage across R_2 from top to bottom is $V_1 – 0$. According to Ohm's law, the current I_2 is given by $(V_1 – 0)/R_2$. The voltage across R_3 from left to right is $V_1 – V_2$. According to Ohm's law, the current I_3 is given by $(V_1 – V_2)/R_3$.

- The equation $I_1 + I_2 + I_3 = 0$ can be written: $$\frac{V_1 - V_s}{R_1} + \frac{V_1}{R_2} + \frac{V_1 - V_2}{R_3} = 0 \qquad (1)$$

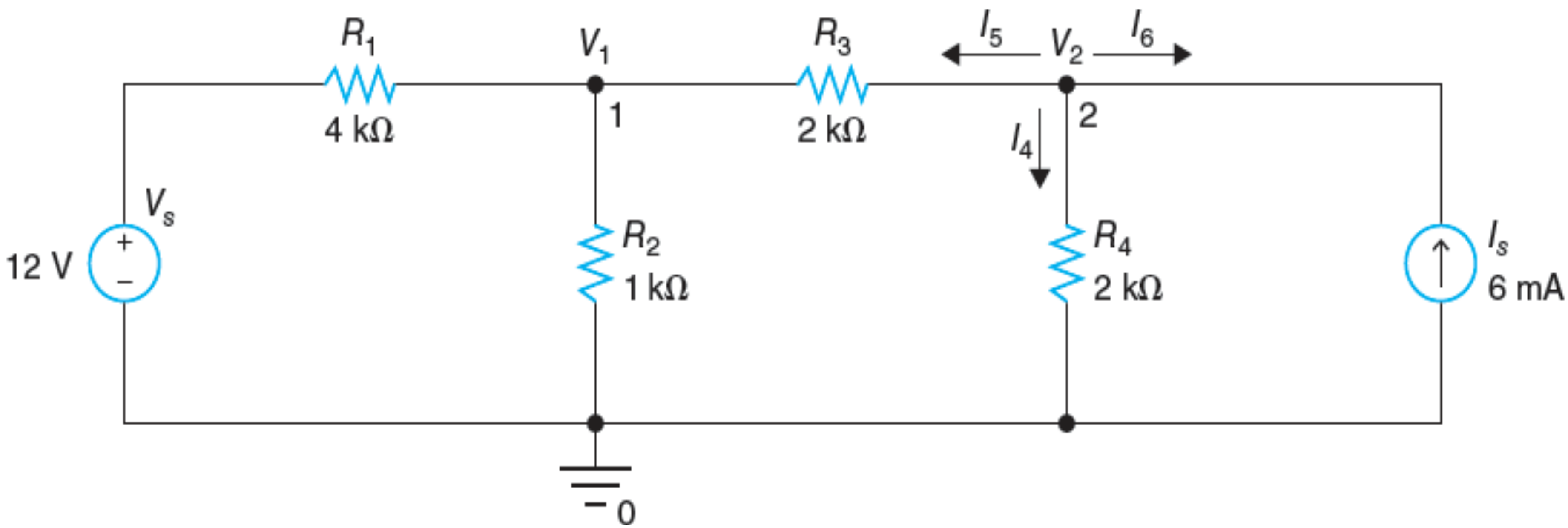
A Circuit with Two Unknown Node Voltages



- Three branches are connected to node 2. The currents leaving node 2 through these branches are labeled as I_4, I_5, and I_6.

- According to KCL, the sum of currents leaving node 2 is zero, that is, $I_4 + I_5 + I_6 = 0$. We are trying to find node voltages. We have to represent these three currents as a function of unknown node voltages V_1 and V_2.

A Circuit with Two Unknown Node Voltages



- The voltage across R_4 from top to bottom is $V_2 – 0$. According to Ohm's law, the current I_4 is given by $(V_2 – 0)/R_4$. The voltage across R_3 from right to left is $V_2 – V_1$. According to Ohm's law, the current I_5 is given by $(V_2 – V_1)/R_3$. Notice that $I_5 = – I_3$. The magnitude of current I_6 is identical to I_s, but flows in the opposite direction. Thus, $I_6 = – I_s$.

- The equation $I_4 + I_5 + I_6 = 0$ can be written as $$\frac{V_2}{R_4} + \frac{V_2 - V_1}{R_3} - I_s = 0 \qquad (2)$$

A Circuit with Two Unknown Node Voltages

$$\frac{V_1 - V_s}{R_1} + \frac{V_1}{R_2} + \frac{V_1 - V_2}{R_3} = 0 \qquad (1) \qquad\qquad \frac{V_2}{R_4} + \frac{V_2 - V_1}{R_3} - I_s = 0 \qquad (2)$$

- Substituting component values to Equations (1), we obtain

$$\frac{V_1 - 12}{4000} + \frac{V_1}{1000} + \frac{V_1 - V_2}{2000} = 0 \qquad (3)$$

- Multiplying by 4000 in every term of Equation (3), we get

  $V_1 - 12 + 4V_1 + 2V_1 - 2V_2 = 0$

  which can be simplified to

  $7V_1 - 2V_2 = 12 \qquad (4)$

A Circuit with Two Unknown Node Voltages

$$\frac{V_1 - V_s}{R_1} + \frac{V_1}{R_2} + \frac{V_1 - V_2}{R_3} = 0 \qquad (1) \qquad\qquad \frac{V_2}{R_4} + \frac{V_2 - V_1}{R_3} - I_s = 0 \qquad (2)$$

- Substituting component values to Equation (2), we obtain

$$\frac{V_2}{2000} + \frac{V_2 - V_1}{2000} - 0.006 = 0 \qquad (5)$$

- Multiplying by 2000 in every term of Equation (5), we get

$V_2 + V_2 – V_1 – 12 = 0$

which can be rewritten as

$$- V_1 + 2V_2 = 12 \qquad (6)$$

A Circuit with Two Unknown Node Voltages

- Solving Equation (6) for V_1, we obtain
  $V_1 = 2V_2 - 12 \quad (7)$

- Substituting Equation (7) into Equation (4), we get
  $7(2V_2 - 12) - 2V_2 = 12 \Rightarrow$
  $12V_2 = 96$

- Thus,
  $V_2 = 8$ V

- From Equation (7), we obtain
  $V_1 = 4$ V

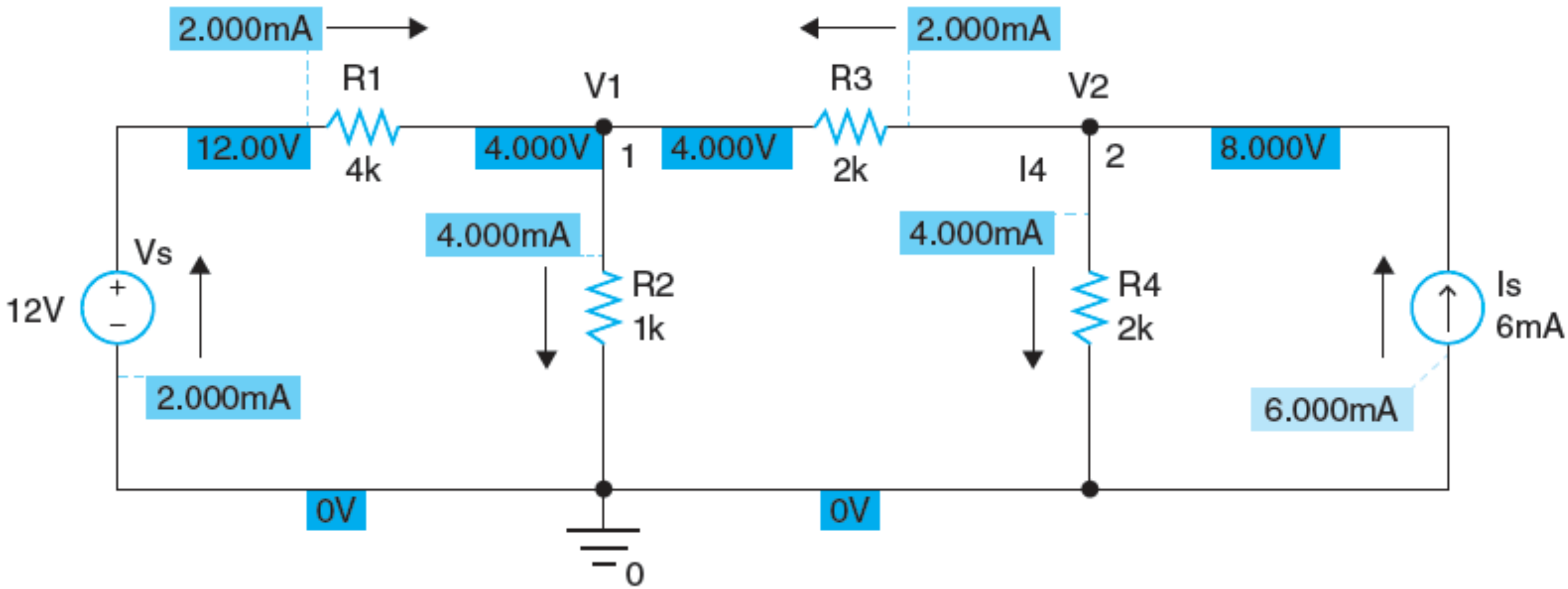
A Circuit with Two Unknown Node Voltages (Continued)

- $7V_1 - 2V_2 = 12 \quad (4)$
- $-V_1 + 2V_2 = 12 \quad (6)$

- Equations (4) and (6) can be put into matrix form as

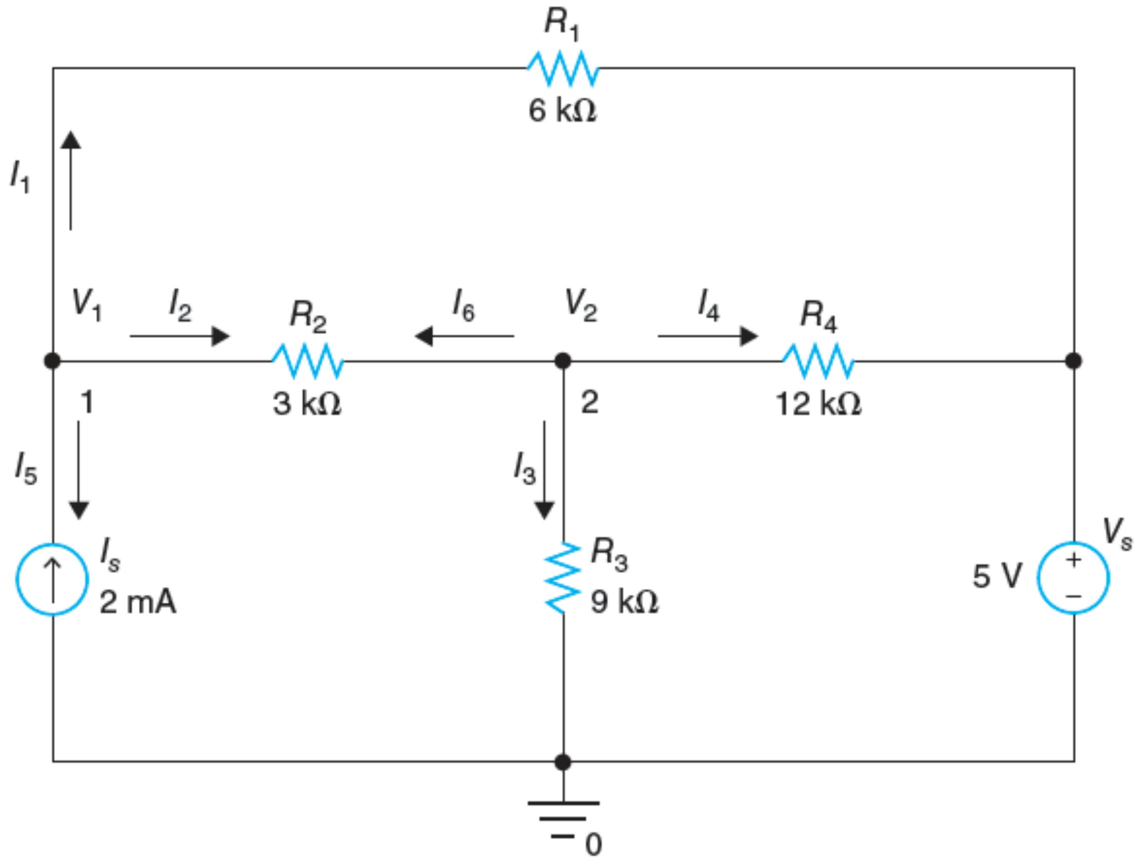
$$\begin{bmatrix} 7 & -2 \\ -1 & 2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 12 \\ 12 \end{bmatrix} \qquad (8)$$

A Circuit with Two Unknown Node Voltages



- The currents I_1, I_2, I_3, I_4, I_5, and I_6 can be calculated from V_1 = 4 V and V_2 = 8 V.
- $I_1 = (V_1 - V_s)/R_1 = (4 - 12)/4000$ A = - 0.002 A= - 2 mA
- $I_2 = (V_1 - 0)/R_2 = (4 - 0)/1000$ A = 0.004 A= 4 mA
- $I_4 = (V_2 - 0)/R_4 = (8 - 0)/2000$ A = 0.004 A= 4 mA
- $I_5 = (V_2 - V_1)/R_3 = (8 - 4)/2000$ A = 0.002 A= 2 mA
- $I_6 = - I_s$ = - 0.006 A= - 6 mA
- The actual positive direction of current is shown in the PSpice simulation here:
- In PSpice, the label of current is connected to the terminal of the part where current enters the part.

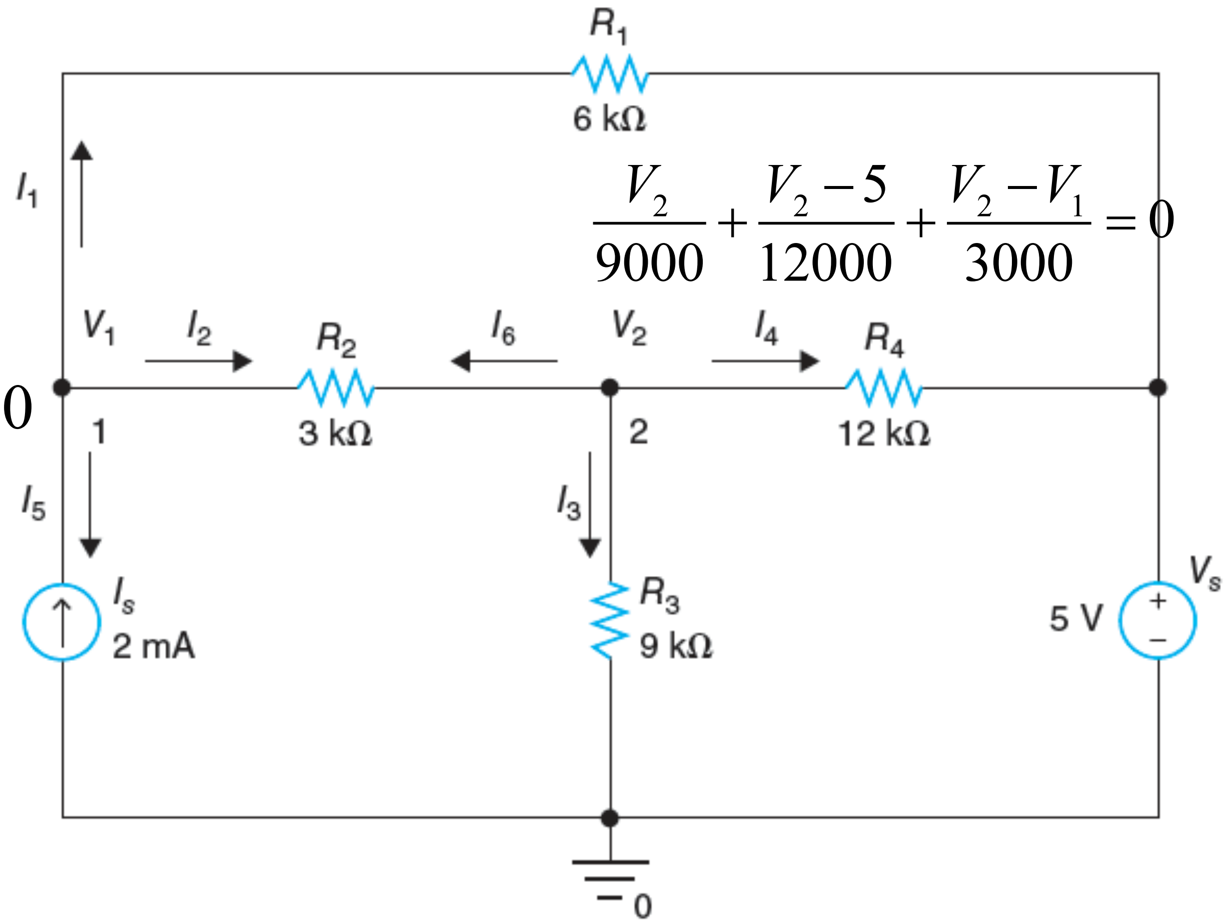
EXAMPLE 3.1



- Find V_1 and V_2 at node 1,
- $I_1 + I_2 + I_5 = 0 \Rightarrow$ $$\frac{V_1 - 5}{6000} + \frac{V_1 - V_2}{3000} - 2\times 10^3 = 0$$
- Multiply by 6000: $V_1 - 5 + 2V_1 - 2V_2 - 12 = 0 \Rightarrow$
- $3V_1 - 2V_2 = 17$ (1)
- At node 2, $I_3 + I_4 + I_6 = 0 \Rightarrow$ $$\frac{V_2}{9000} + \frac{V_2 - 5}{12000} + \frac{V_2 - V_1}{3000} = 0$$

EXAMPLE 3.1

$$\frac{V_1 - 5}{6000} + \frac{V_1 - V_2}{3000} - 2\times 10^{3} = 0$$



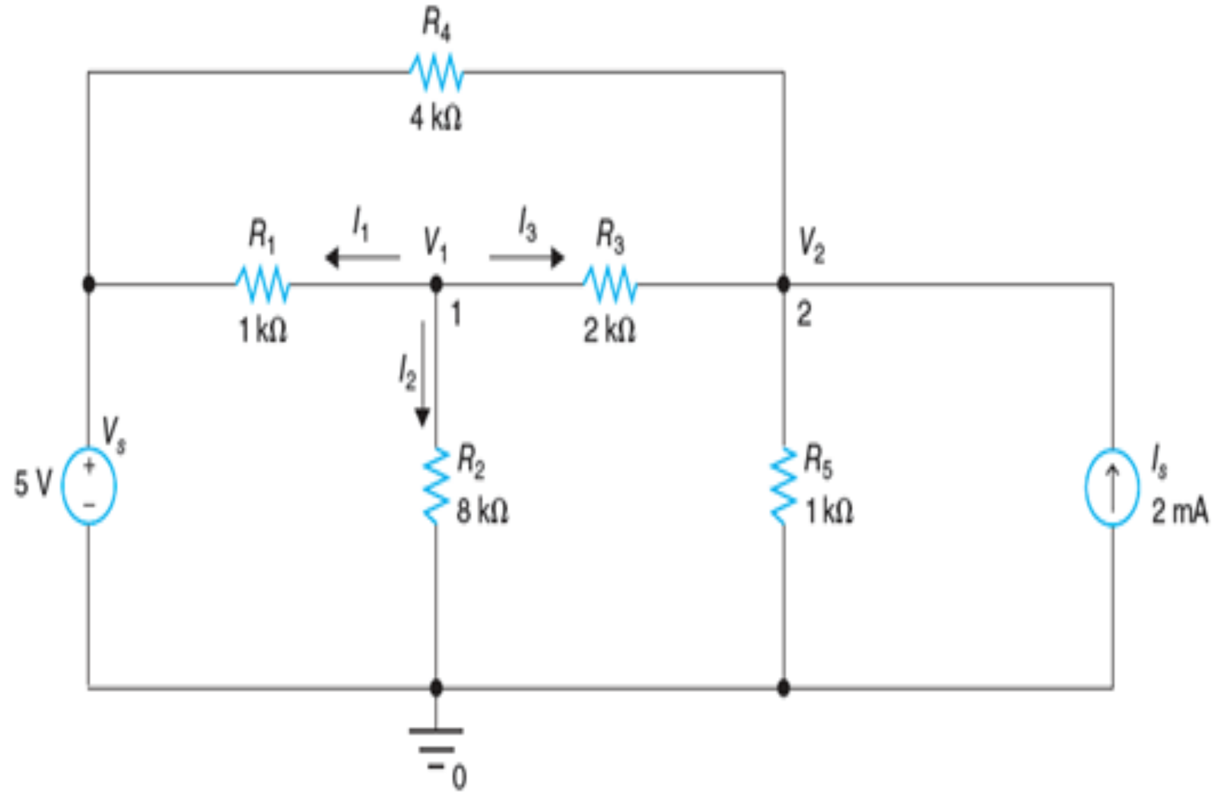
$$\frac{V_2}{9000} + \frac{V_2 - 5}{12000} + \frac{V_2 - V_1}{3000} = 0$$

- Multiply by 36000: $4V_2 + 3V_2 - 15 + 12V_2 - 12V_1 = 0 \Rightarrow -12V_1 + 19V_2 = 15$ (2)
- Multiply Equation $3V_1 - 2V_2 = 17$ by 4: $12V_1 - 8V_2 = 68$ (3)

- Add Equations (2) and (3): $11V_2 = 83$ ➔ $\mathbf{V_2} = 83/11$ **= 7.5455 V**

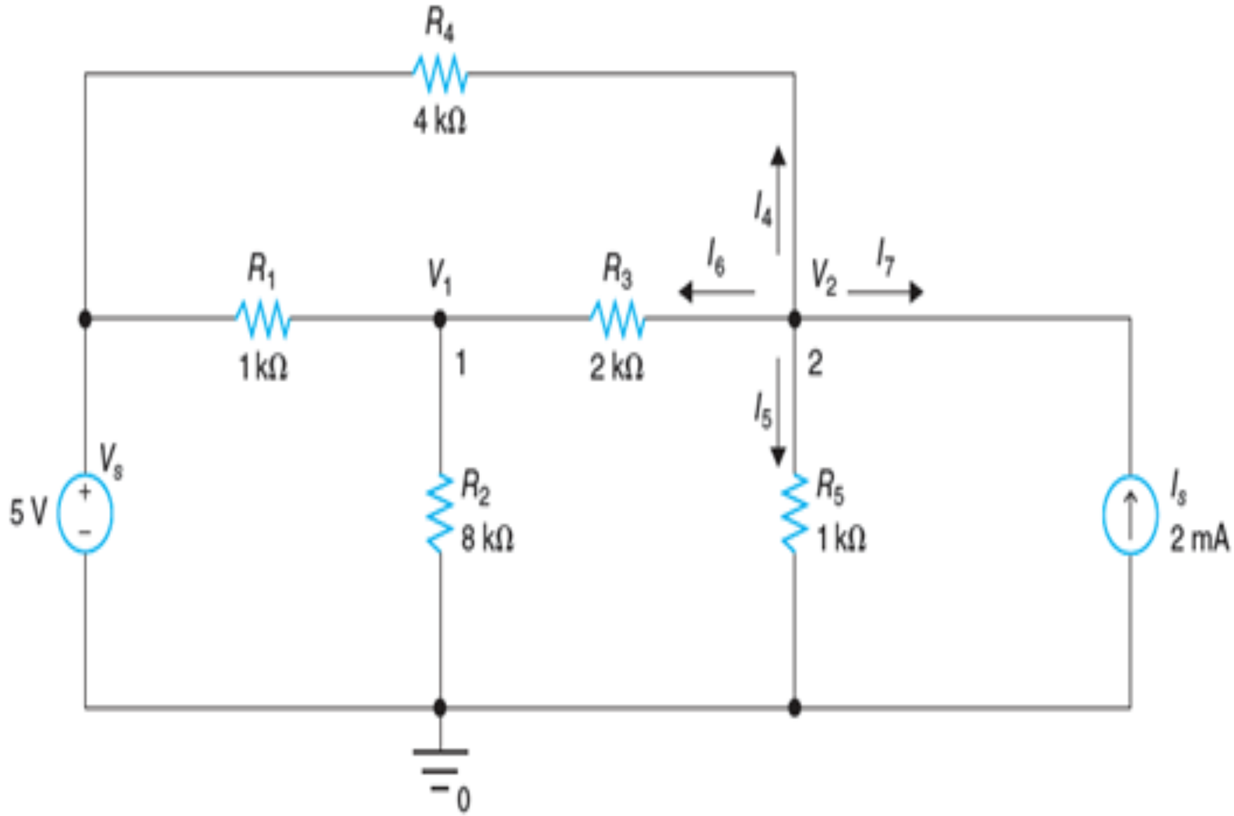
- From Equation (1): $\mathbf{V_1} = (2V_2 + 17)/3 =$ **10.6970 V**

EXAMPLE 3.2



- Find V_1 and V_2
- At node 1, $I_1 + I_2 + I_3 = 0 \Rightarrow$ $\dfrac{V_1 - 5}{1000} + \dfrac{V_1}{8000} + \dfrac{V_1 - V_2}{2000} = 0$
- Multiply by 8000: $8V_1 - 40 + V_1 + 4V_1 - 4V_2 = 0 \Rightarrow$
- **$13V_1 - 4V_2 = 40$ (1)**

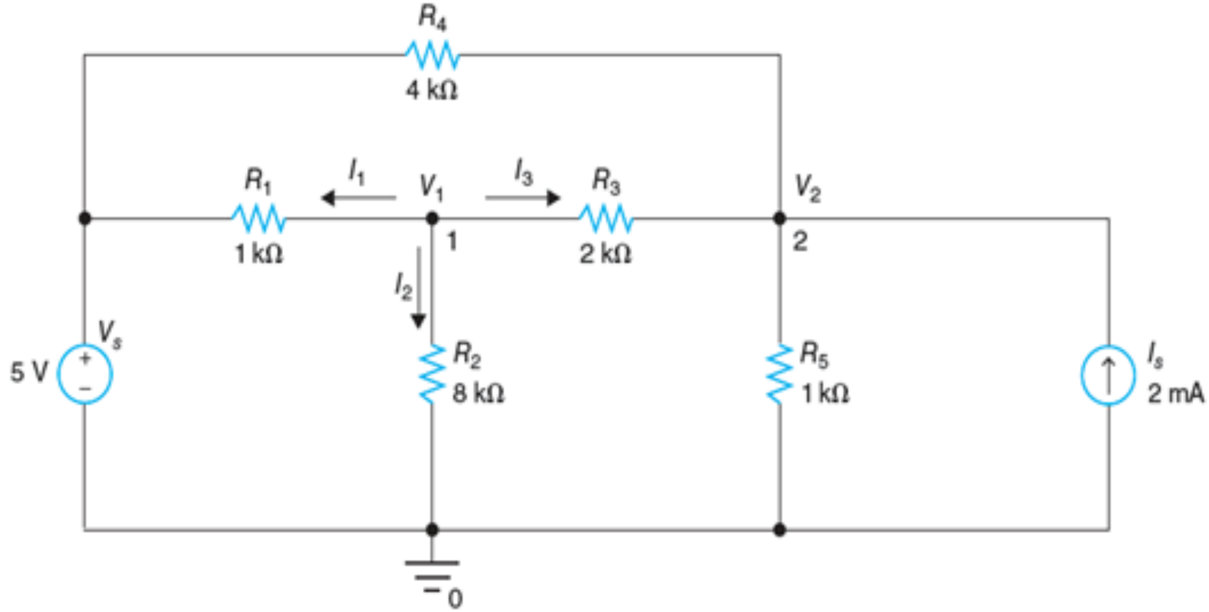
EXAMPLE 3.2



- At node 2, $I_4 + I_5 + I_6 + I_7 = 0 \Rightarrow \dfrac{V_2 - 5}{4000} + \dfrac{V_2}{1000} + \dfrac{V_2 - V_1}{2000} - 0.002 = 0$

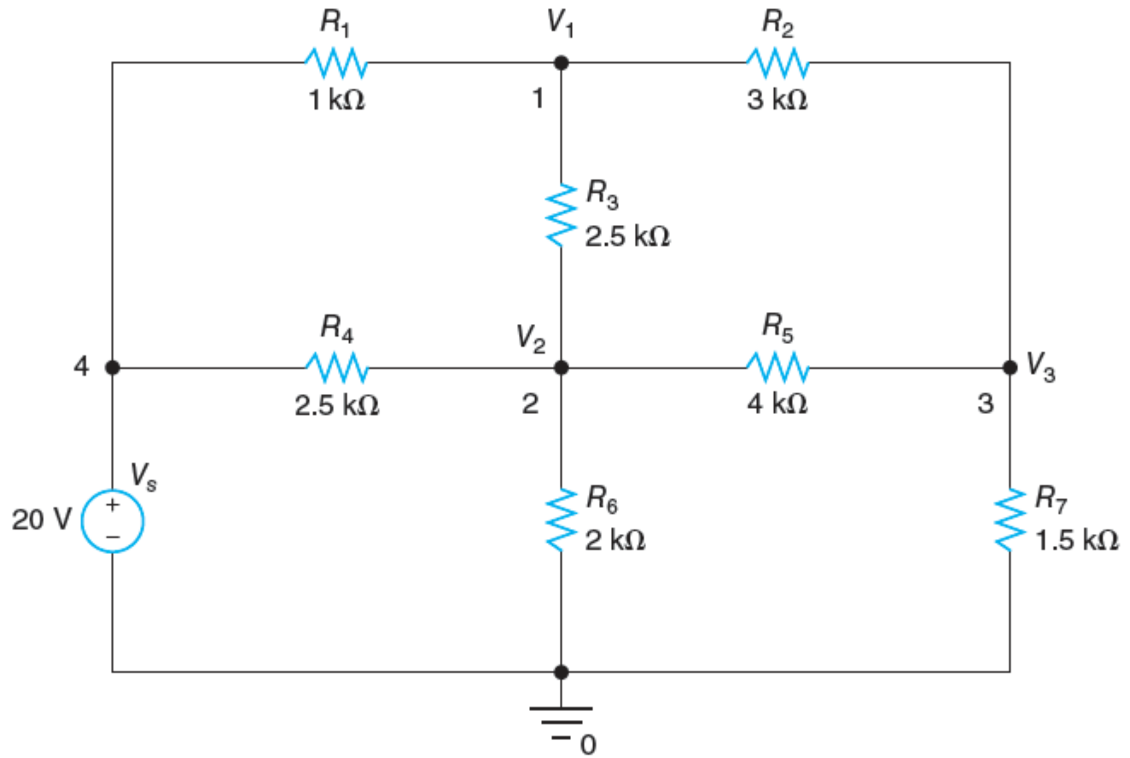
- Multiply by 4000: $V_2 - 5 + 4V_2 + 2V_2 - 2V_1 - 8 = 0 \Rightarrow$
  $-2V_1 + 7V_2 = 13$ (2)

EXAMPLE 3.2



- At node 1, $13V_1 - 4V_2 = 40$ (1)
- At node 2, $-2V_1 + 7V_2 = 13$ (2)
- Solve (1) for V_2 ➔ $V_2 = 3.25V_1 - 10$ (3)
- Substitute (3) into (2): $-2V_1 + 7(3.25V_1 - 10) = 13$
- $20.75V_1 = 83$, $\mathbf{V_1 = 4\ V}$
- From Equation (3), $\mathbf{V_2 = 3\ V}$

EXAMPLE 3.3



- Find V_1, V_2, V_3

- Sum the currents at node 1:

$$\frac{V_1 - 20}{1000} + \frac{V_1 - V_2}{2500} + \frac{V_1 - V_3}{3000} = 0$$

- Multiply by 15000:

$15V_1 - 300 + 6V_1 - 6V_2 + 5V_1 - 5V_3 = 0 \Rightarrow$

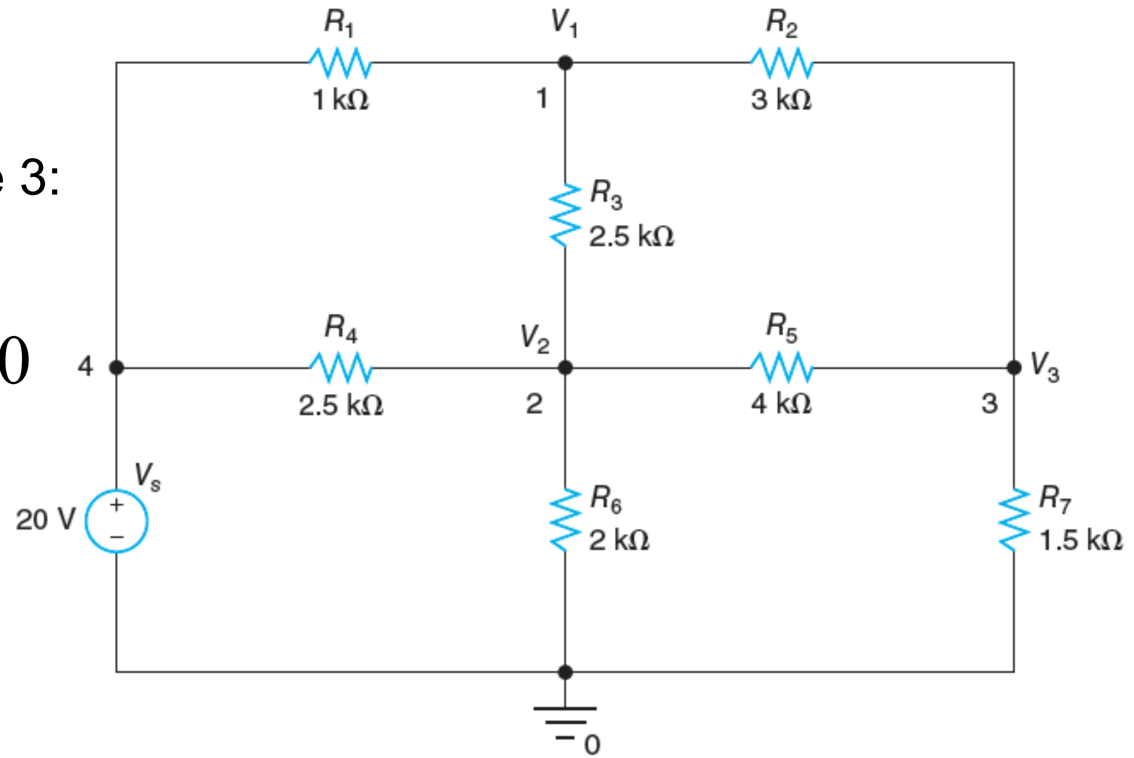
$\mathbf{26V_1 - 6V_2 - 5V_3 = 300}$ **(1)**

- Sum the currents leaving node 2 ➔ $\frac{V_2 - 20}{2500} + \frac{V_2 - V_1}{2500} + \frac{V_2 - V_3}{4000} + \frac{V_2}{2000} = 0$

- Multiply by 20000: $8V_2 - 160 + 8V_2 - 8V_1 + 5V_2 - 5V_3 + 10V_2 = 0 \Rightarrow$

$\mathbf{-8V_1 + 31V_2 - 5V_3 = 160}$ **(2)**

EXAMPLE 3.3



- Sum the currents leaving node 3:

$$\frac{V_3 - V_1}{3000} + \frac{V_3 - V_2}{4000} + \frac{V_3}{1500} = 0$$

- Multiply by 12000:
  $4V_3 - 4V_1 + 3V_3 - 3V_2 + 8V_3 = 0 \Rightarrow -4V_1 - 3V_2 + 15V_3 = 0 \qquad (3)$

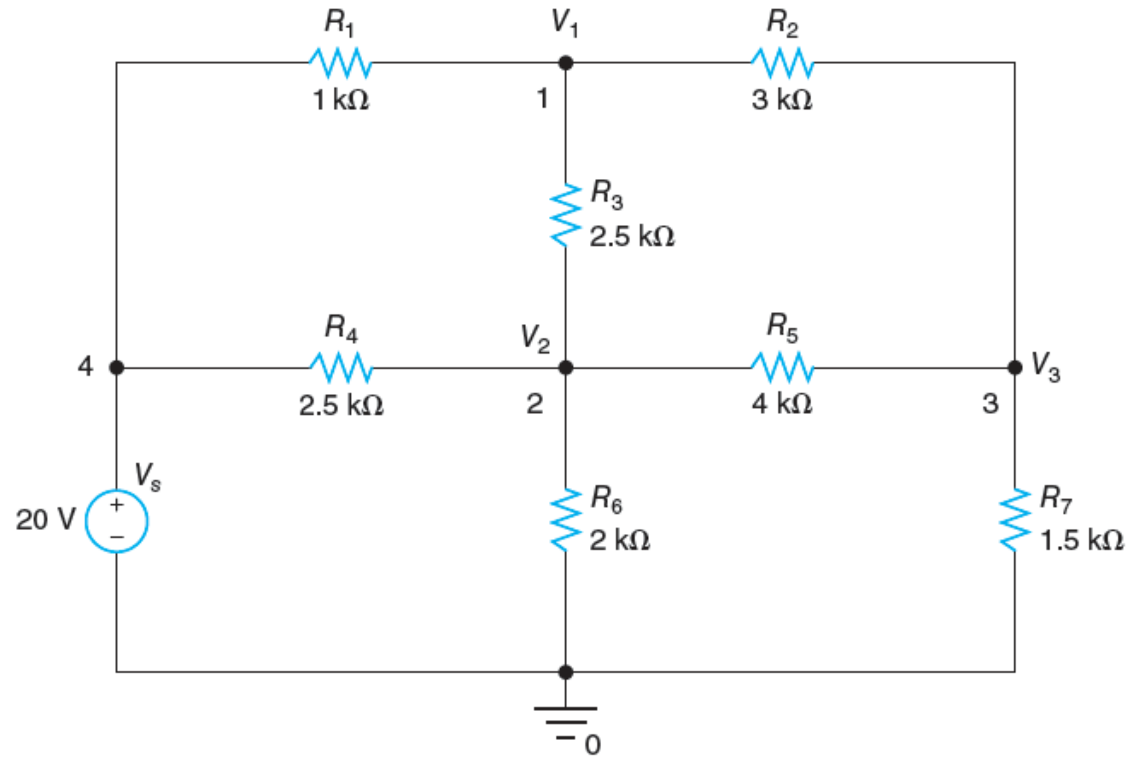
- Multiply (1) ($26V_1 - 6V_2 - 5V_3 = 300$) by 3 ➔ $78V_1 - 18V_2 - 15V_3 = 900 \qquad (4)$

- **Add (3) and (4) ➔ $74V_1 - 21V_2 = 900$ (5)**

- Multiply (2) ($-8V_1 + 31V_2 - 5V_3 = 160$) by 3: $-24V_1 + 93V_2 - 15V_3 = 480$ (6)

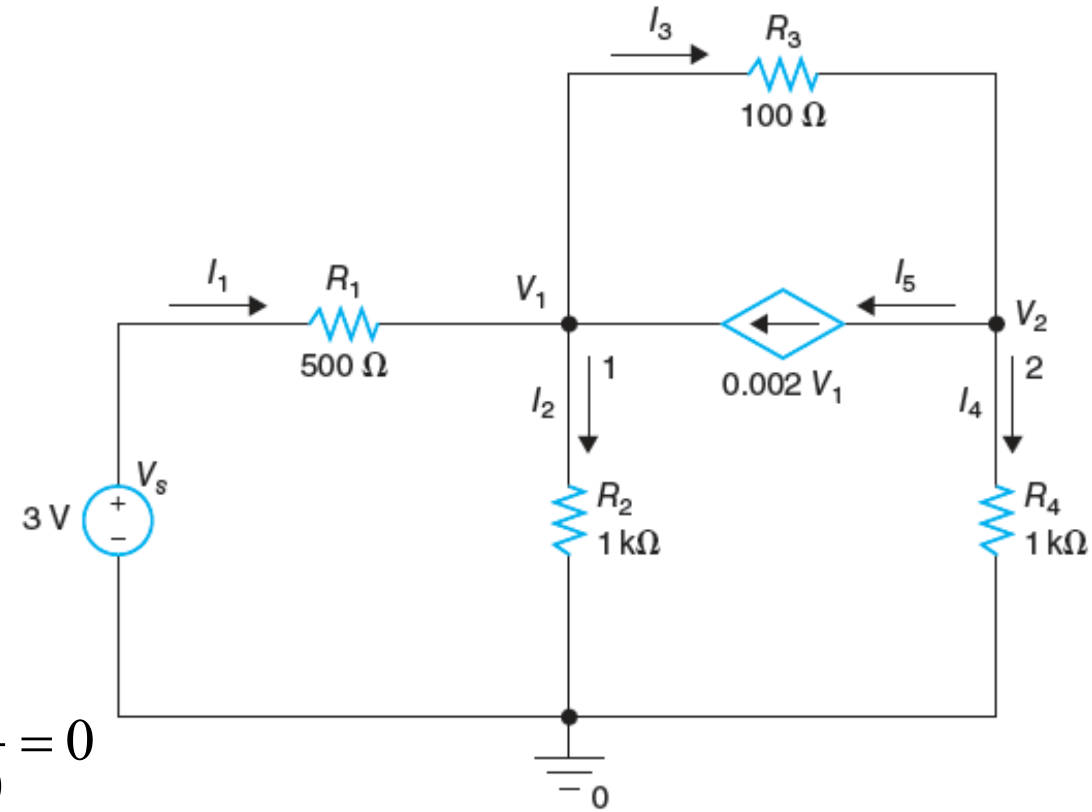
- **Add (3) and (6): $-28V_1 + 90V_2 = 480$ (7)**

EXAMPLE 3.3



- Multiply (5) ($74V_1 – 21V_2 = 900$)by 30 ➔ $2220V_1 – 630V_2 = 27000$ (8)
- Multiply (7) ($– 28V_1 + 90V_2 = 480$) by 7 ➔ $– 196V_1 + 630V_2 = 3360$ (9)
- Add (8) and (9) ➔ $2024V_1 = 30360$ ➔ $\mathbf{V_1 = 15\ V}$ **(11)**
- Substitute (11) in (8) ➔ $\mathbf{V_2} = (2220V_1 – 27000)/630$ **= 10 V** (12)
- Substitute (11) and (12) in (1) ➔ $\mathbf{V_3} = (26V_1 – 6V_2 – 300)/5$ **= 6 V**

EXAMPLE 3.4

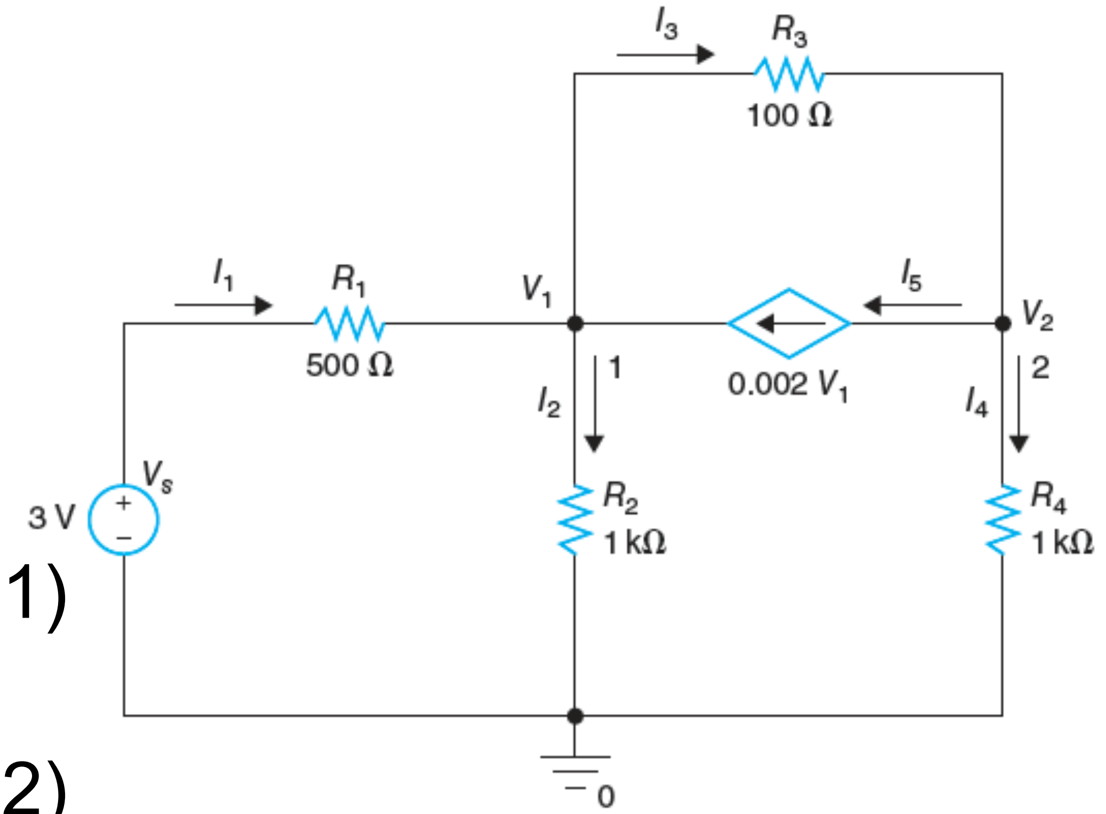


- Find V_1 and V_2
- At node 1:

$$\frac{V_1-3}{500}+\frac{V_1-V_2}{100}-0.002V_1+\frac{V_1}{1000}=0$$

- Multiply by 1000 ➔ $2V_1 - 6 + 10V_1 - 10V_2 - 2V_1 + V_1 = 0 \Rightarrow$ **$11V_1 - 10V_2 = 6$ (1)**
- Sum the currents leaving node 2: $\dfrac{V_2-V_1}{100}+0.002V_1+\dfrac{V_2}{1000}=0$
- Multiply by 1000 ➔ $10V_2 - 10V_1 + 2V_1 + V_2 = 0 \Rightarrow$ **$-8V_1 + 11V_2 = 0$ (2)**

EXAMPLE 3.4

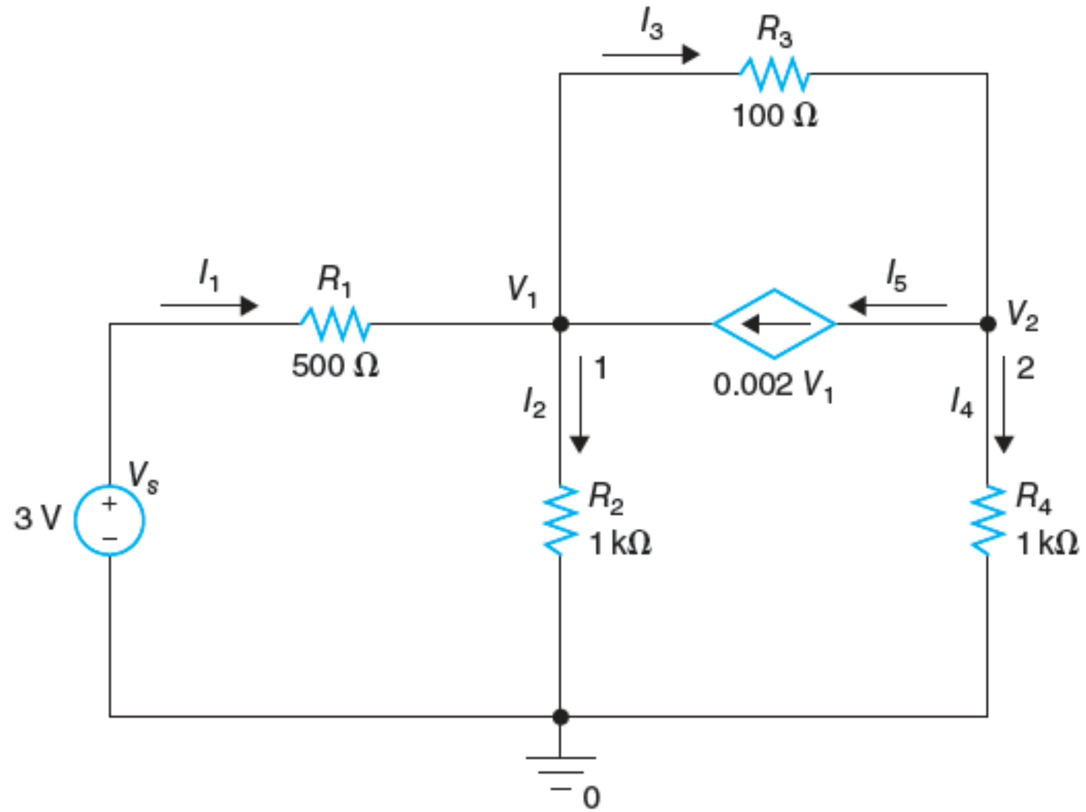


- At node 1,
  $11V_1 - 10V_2 = 6$ (1)
- At node 2,
  $-8V_1 + 11V_2 = 0$ (2)

- Multiply (1) by 8 → $88V_1 - 80V_2 = 48$ (3)
- Multiply (2) by 11 → $-88V_1 + 121V_2 = 0$ (4)

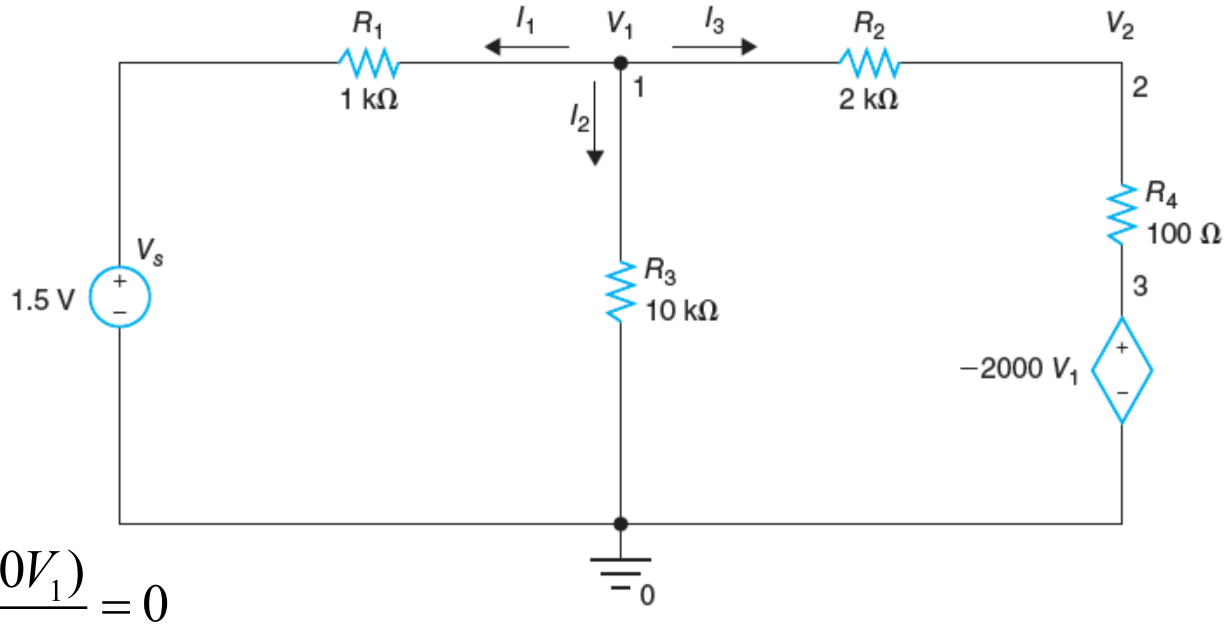
- Add (3) and (4) → $41V_2 = 48$ → $\mathbf{V_2 = 1.1707\ V}$
- From (2), $\mathbf{V_1} = (11/8)V_2 \mathbf{= 1.6098\ V}$

EXAMPLE 3.4



- Currents:
- $I_1 = (V_s - V_1)/R_1 = 2.7805$ mA
- $I_2 = V_1/R_2 = 1.6098$ mA
- $I_3 = (V_1 - V_2)/R_3 = 4.3902$ mA
- $I_4 = V_2/R_4 = 1.1707$ mA
- $I_5 = 0.002V_1 = 3.2195$ mA

EXAMPLE 3.5



- Find V_1 and V_2
- Sum the currents leaving node 1:

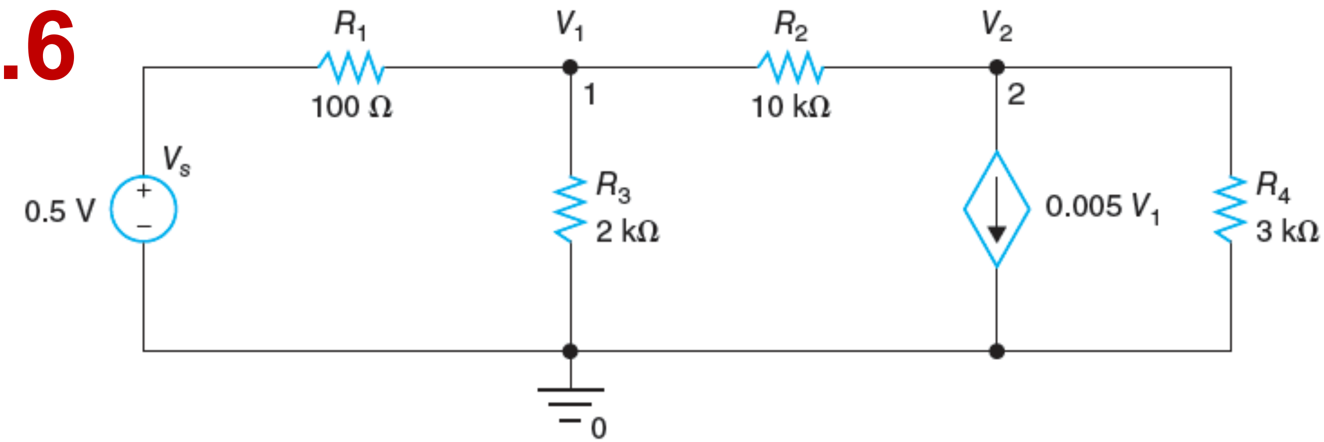
$$\frac{V_1 - 1.5}{1000} + \frac{V_1}{10000} + \frac{V_1 - (-2000V_1)}{2100} = 0$$

- Multiply by 21000 ➔ $21V_1 - 31.5 + 2.1V_1 + 10V_1 + 20000V_1 = 0$ ➔ $20033.1V_1 = 31.5$ ➔ $\mathbf{V_1 = 1.5724\ mV}$

- $\mathbf{I_3}$ = $[V_1 - (-2000V_1)]/2100$ = **1.4982mA**

- $\mathbf{V_2}$ = $V_1 - R_2 I_3$ = **–2.9949 V**

EXAMPLE 3.6



- Find V_1 and V_2.
- Sum the currents leaving node 1: $$\frac{V_1 - 0.5}{100} + \frac{V_1}{2000} + \frac{V_1 - V_2}{10000} = 0$$
- Multiply by 10000 ➔ $100V_1 - 50 + 5V_1 + V_1 - V_2 = 0 \Rightarrow 106V_1 - V_2 = 50 \Rightarrow$
- $V_2 = 106V_1 - 50$ (1)
- Sum the currents leaving node 2: $$\frac{V_2 - V_1}{10000} + 0.005V_1 + \frac{V_2}{3000} = 0$$
- Multiply by 30000 ➔ $3V_2 - 3V_1 + 150V_1 + 10V_2 = 0$ ➔ $147V_1 + 13V_2 = 0$ (2)
- Substitute (1) in (2) ➔ $147V_1 + 13(106V_1 - 50) = 0$ ➔ $1525V_1 = 650 \Rightarrow$
- $V_1 = 0.42623$ V
- $V_2 = 106V_1 - 50 = -4.8197$ V

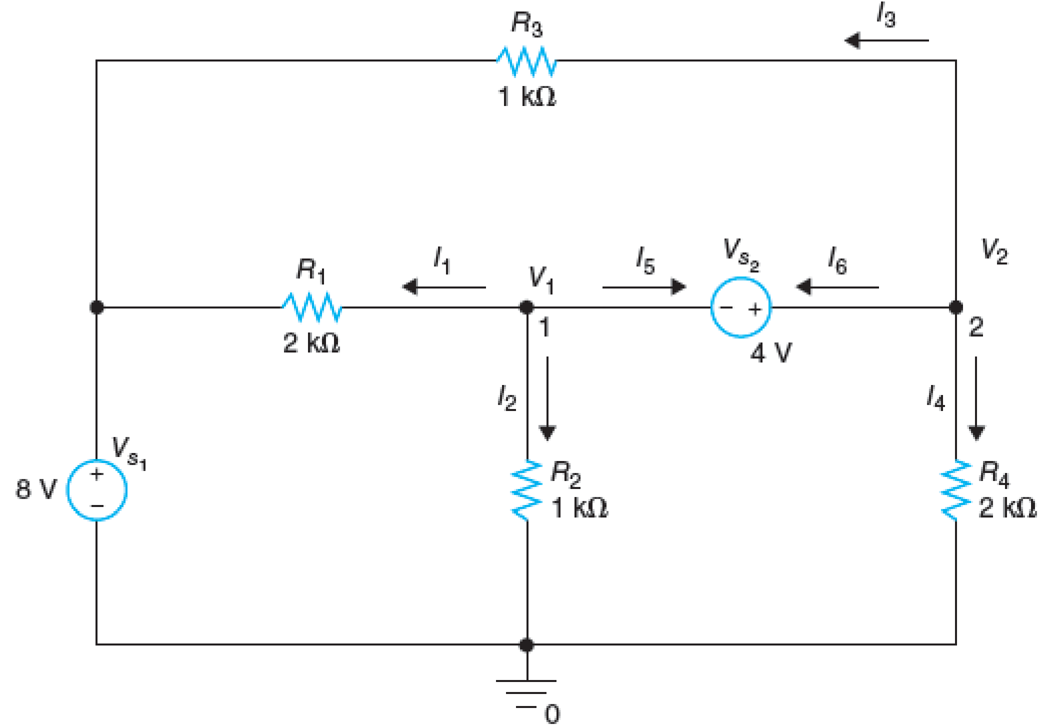
Supernode

- If there is a voltage source in a circuit between two nodes whose voltages are unknown, we do not know the current through the voltage source, and it is not possible to write the node equations for the two nodes that include the voltage source. In this case, combine the two nodes to form a supernode.

- We can then write the node equation for this supernode.

- One additional equation, commonly referred to as a constraint equation relating the two node voltages, can be obtained by representing the voltage source as a potential drop or as a potential rise between the two nodes.

Supernode

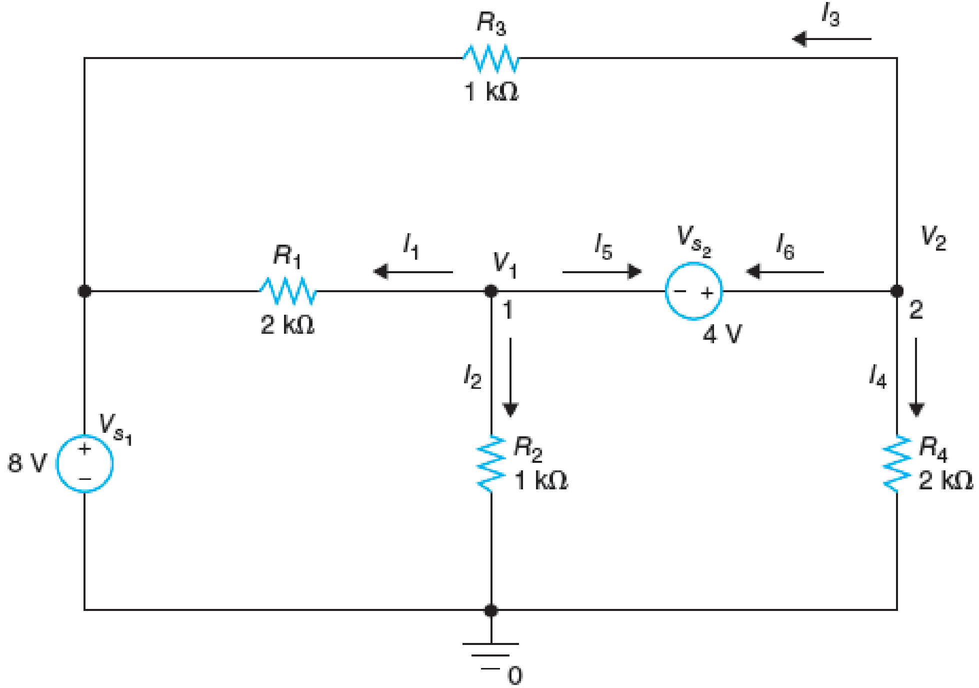


- Unknown currents I_5, I_6 through V_{s2}.

- The currents I_5, I_6 flow in opposite direction. Thus, we have $I_6 = – I_5$.

- KCL at node 1 ➔ $I_1 + I_2 + I_5 = 0$ (1)
- KCL at node 2 ➔ $I_3 + I_4 + I_6 = I_3 + I_4 – I_5 = 0$ (2)

Supernode

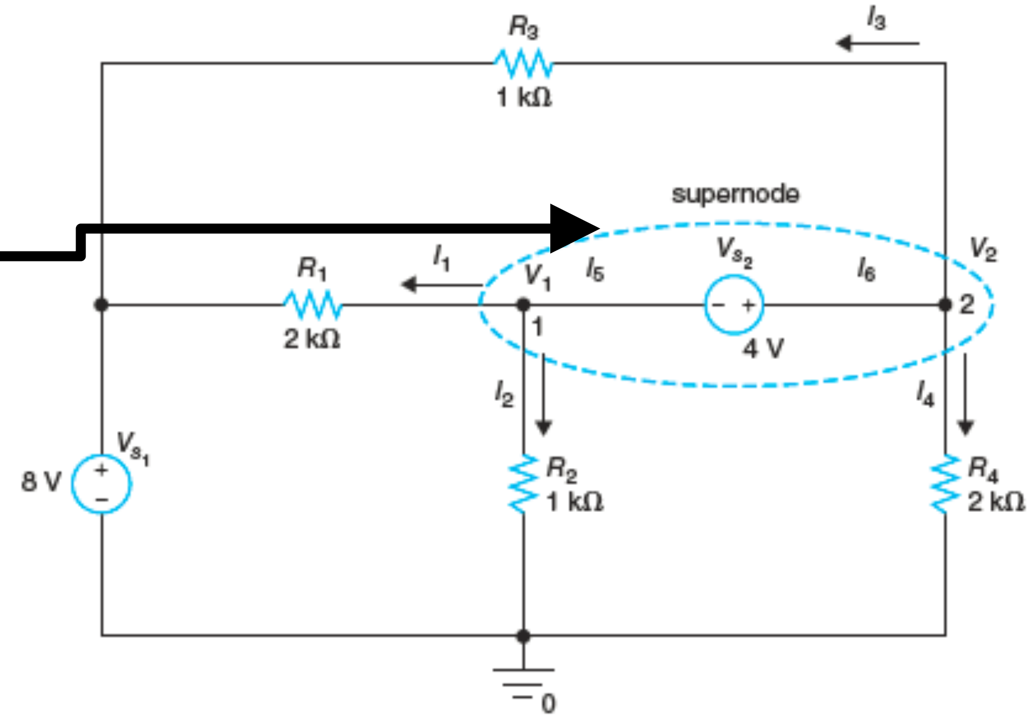


- Adding (1) ($I_1 + I_2 + I_5 = 0$) and ($I_3 + I_4 - I_5 = 0$) (2),
  ➔ $I_1 + I_2 + I_3 + I_4 = 0$ (3)

- (3) is the sum of currents leaving nodes 1 and 2. Since $I_5 + I_6 = 0$, I_5 and I_6 are not included in the sum.

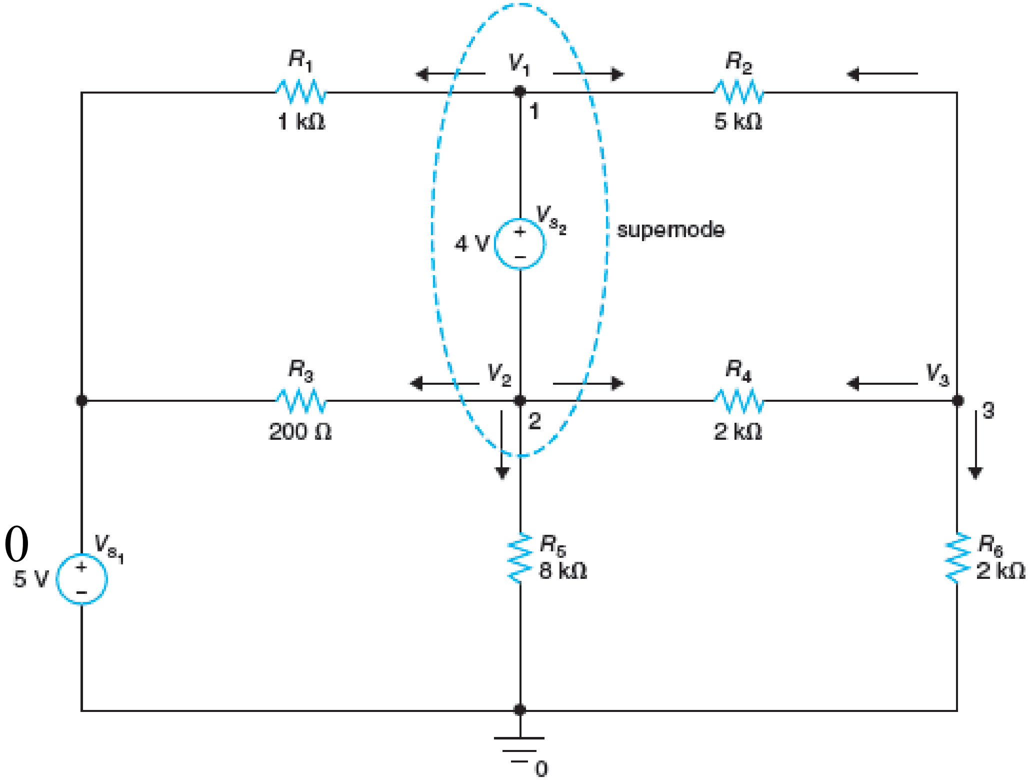
- Since V_2 is 4 V higher than V_1, the constraint equation is given by $V_2 = V_1 + 4$ (4)

Supernode



- The supernode consisting of nodes 1 and 2
- $(I_1 + I_2 + I_3 + I_4 = 0)$ (3)
- $V_2 = V_1 + 4$ (4)
- When writing a node equation for a supernode, sum the currents leaving the supernode, ignoring currents inside the supernode.
- From (3), we have $$\frac{V_1 - 8}{2000} + \frac{V_1}{1000} + \frac{V_2 - 8}{1000} + \frac{V_2}{2000} = 0$$
- Multiply by 2000 ➔ $V_1 - 8 + 2V_1 + 2V_2 - 16 + V_2 = 0 \Rightarrow 3V_1 + 3V_2 = 24$ (5)
- Substitute (4) in (5) ➔ $3V_1 + 3V_1 + 12 = 24 \Rightarrow 6V_1 = 12 \Rightarrow V_1 = 2$ V (6)
- Substitute (6) in (4) ➔ $V_2 = 6$ V

EXAMPLE 3.7



- Find V_1, V_2, and V_3.
- Sum the currents leaving the supernode consisting of node 1 and node 2:

$$\frac{V_1-5}{1000}+\frac{V_1-V_3}{5000}+\frac{V_2-5}{200}+\frac{V_2-V_3}{2000}+\frac{V_2}{8000}=0$$

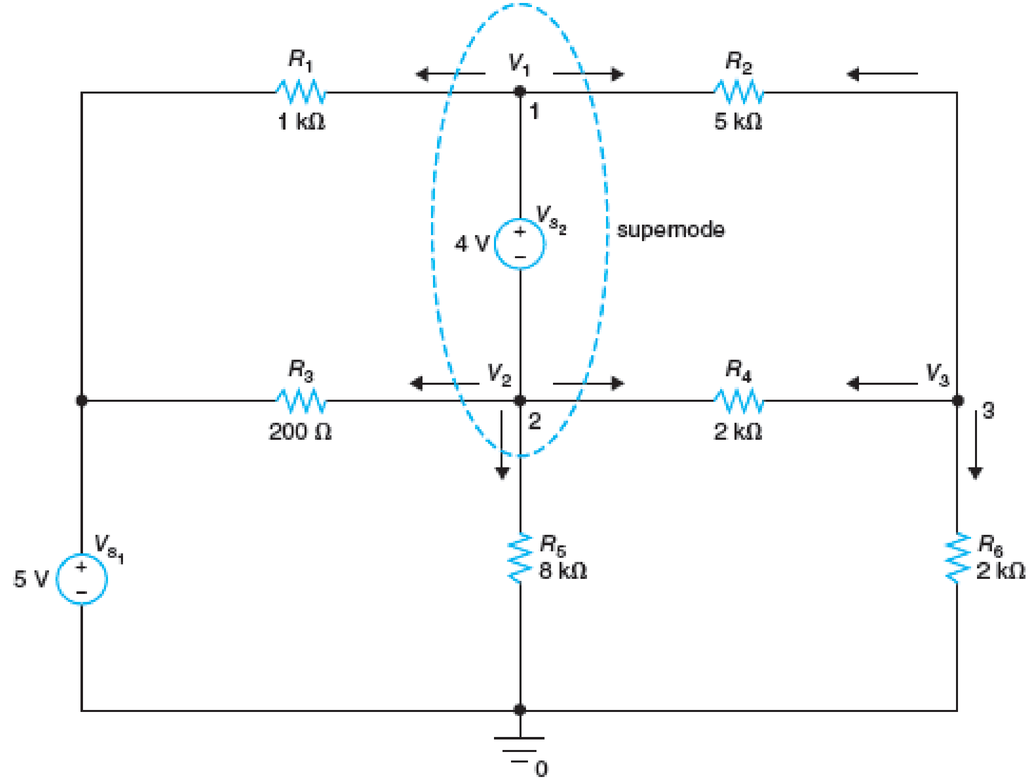
- Multiply by 8000➔
  $8V_1 - 40 + 1.6V_1 - 1.6V_3 + 40V_2 - 200 + 4V_2 - 4V_3 + V_2 \Rightarrow$
  $\mathbf{9.6V_1 + 45V_2 - 5.6V_3 = 240\ (1)}$

- Sum the currents leaving node 3: $\dfrac{V_3-V_1}{5000}+\dfrac{V_3-V_2}{2000}+\dfrac{V_3}{2000}=0$

- Multiply by 10k ➔ $2(V_3 - V_1)+5(V_3 - V_2)+5V_3=0$ ➔ $\mathbf{-2V_1 - 5V_2 + 12V_3 = 0\ (2)}$

- Constraint equation: $\mathbf{V_1 = V_2 + 4\ (3)}$

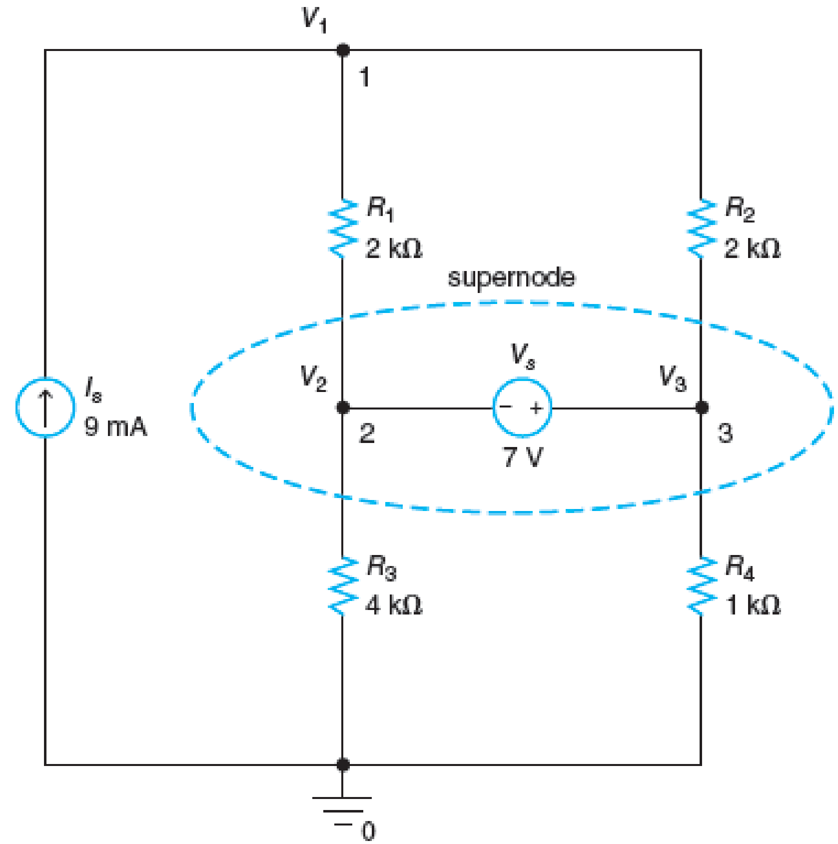
EXAMPLE 3.7



- $9.6V_1 + 45V_2 – 5.6V_3 = 240$ (1)
- $– 2V_1 – 5V_2 + 12V_3 = 0$ (2)
- $V_1 = V_2 + 4$ (3)

- Substitute (3) in (1) ➔ $54.6V_2 – 5.6V_3 = 201.6$ (4)
- Substitute (3) in (2) ➔ $– 7V_2 + 12V_3 = 8$ (5)
- Solve (5) for V_2 ➔ $V_2 = (12/7)V_3 – 8/7$ (6)
- Substitute (6) in (4) ➔ $54.6[(12/7)V_3 – 8/7] – 5.6V_3 = 201.6$ (7)
- Solve (7) for V_3 ➔ $V_3 = (201.6 + 54.6\times8/7)/(54.6\times12/7 – 5.6) = 3$ (8)
- Substitute (8) in (6) ➔ $V_2 = 4$ V (9)
- Substitute (9) in (3) ➔ $V_1 = 8$ V

EXAMPLE 3.8



- Find V_1, V_2, V_3 .
- Constraint equation: $\mathbf{V_3 = V_2 + 7}$ **(1)**
- Sum the currents leaving the supernode consisting of node 2 and node 3:

$$\frac{V_2 - V_1}{2000} + \frac{V_2}{4000} + \frac{V_3 - V_1}{2000} + \frac{V_3}{1000} = 0$$

- Multiply by 4000 ➔

$2V_2 – 2V_1 + V_2 + 2V_3 – 2V_1 + 4V_3 = 0 \Rightarrow$

$– 4V_1 + 3V_2 + 6V_3 = 0 \Rightarrow – 4V_1 + 3V_2 + 6(V_2 + 7) = 0$

$\mathbf{– 4V_1 + 9V_2 = – 42}$ **(2)**

- Sum the currents leaving node 1: $-0.009 + \frac{V_1 - V_2}{2000} + \frac{V_1 - V_3}{2000} = 0$

- Multiply by 2000 ➔ $\mathbf{2V_1 – V_2 – V_3 = 18}$ **(3)**

EXAMPLE 3.8

- $V_3 = V_2 + 7$ (1)
- $-4V_1 + 9V_2 = -42$ (2)
- $2V_1 - V_2 - V_3 = 18$ (3)

- Substitute (1) into (3)

  $2V_1 - V_2 - V_2 - 7 = 18$

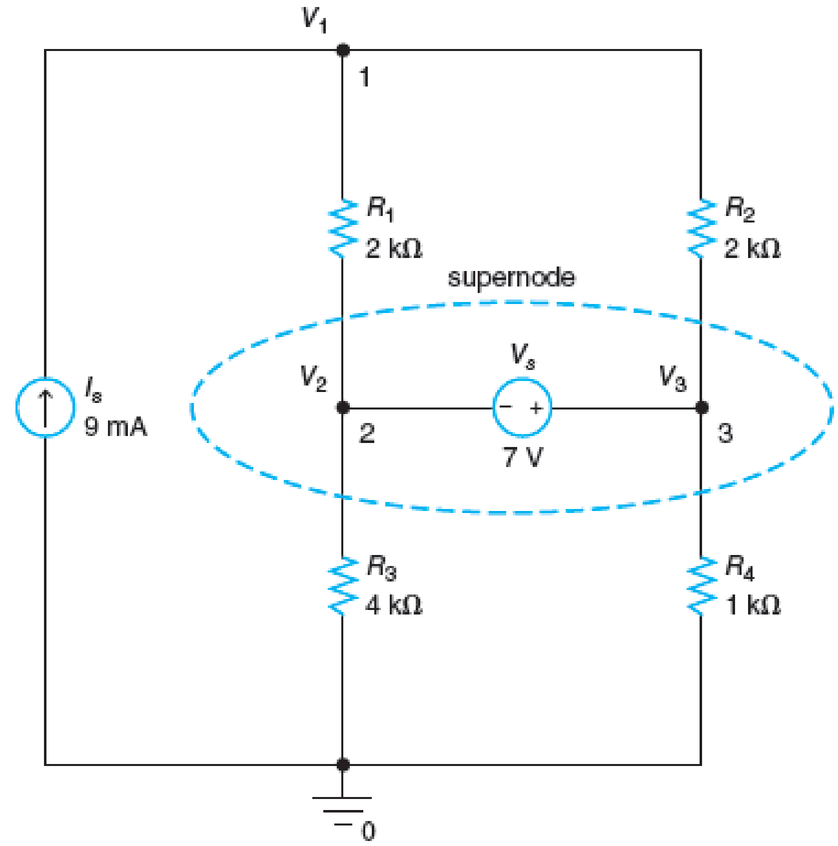
  $\mathbf{2V_1 - 2V_2 = 25}$ **(4)**

- Multiply (4) by 2 ➔ $4V_1 - 4V_2 = 50$ (5)

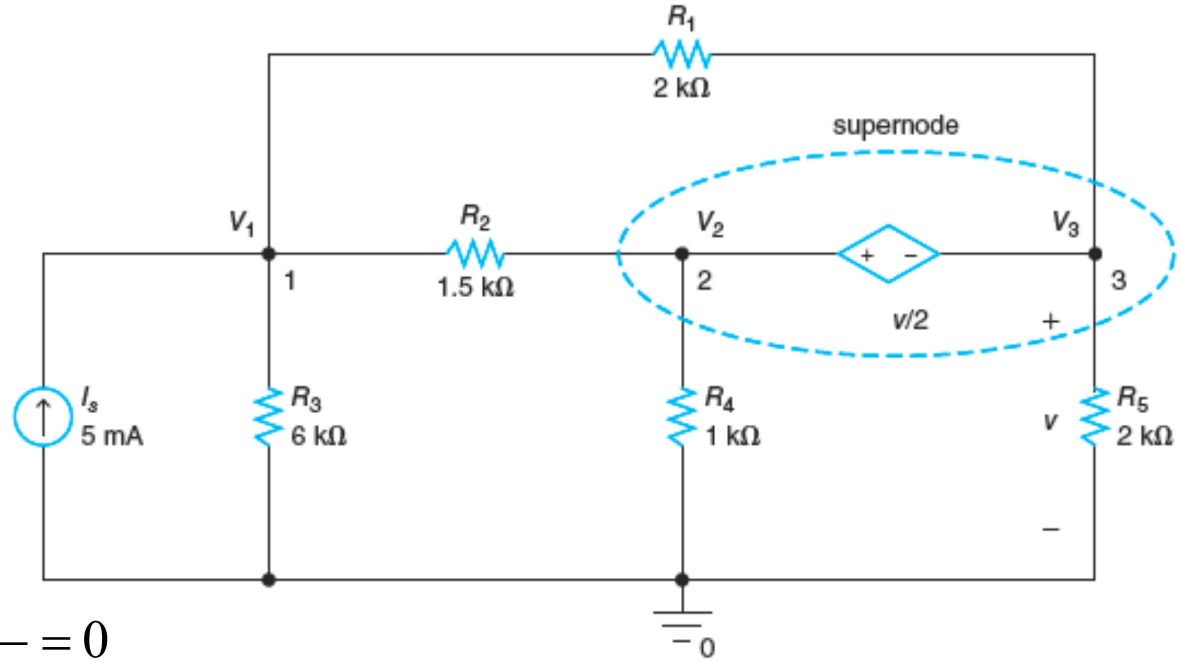
- Add (2) and (5) ➔ $5V_2 = 8 \Rightarrow V_2 = 1.6$ V,

- From (4) ➔ $V_1 = V_2 + 12.5 = 14.1$ V

- From (1) ➔ $V_3 = V_2 + 7 = 8.6$ V



EXAMPLE 3.9



- Find V_1, V_2, $V_{3.}$
- Constraint
  $V_2 = V_3 + V_3/2 = 1.5V_3$ (1)
- Sum the currents leaving supernode:

$$\frac{V_2 - V_1}{1500} + \frac{V_2}{1000} + \frac{V_3 - V_1}{2000} + \frac{V_3}{2000} = 0$$

- Multiply by 6k ➔ $4V_2 - 4V_1 + 6V_2 + 3V_3 - 3V_1 + 3V_3 = 0$
  $\Rightarrow -7V_1 + 10V_2 + 6V_3 = 0 \Rightarrow -7V_1 + 10(1.5V_3) + 6V_3 = 0 \Rightarrow -7V_1 + 21V_3 = 0$
  $\Rightarrow V_1 = 3V_3$ (2)
- Sum the currents leaving node 1: $-0.005 + \dfrac{V_1}{6000} + \dfrac{V_1 - V_2}{1500} + \dfrac{V_1 - V_3}{2000} = 0$
- Multiply by 6k ➔ $V_1 + 4V_1 - 4V_2 + 3V_1 - 3V_3 = 30 \Rightarrow 8(3V_3) - 4(1.5V_3) - 3V_3 = 30$
- $V_3 = 30/15 = 2$ V
- $V_1 = 3V_3 = 6$ V, $V_2 = 1.5V_3 = 3$ V

Summary

- Node Analysis
- Supernode
- What will we study in next lecture.