Basic Electrical Engineering: AC Circuits

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- Ohm's Law and Resistance

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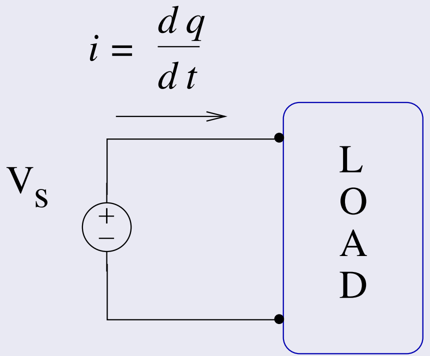

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- Current (Ampere) is the rate of charge flow in some direction through a medium from source to load or vice-versa

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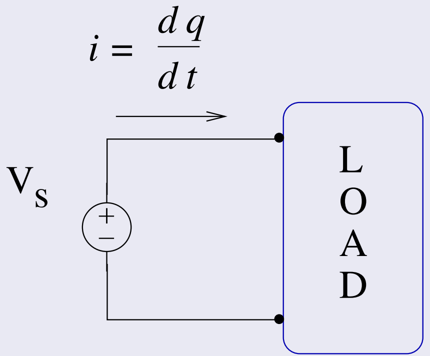

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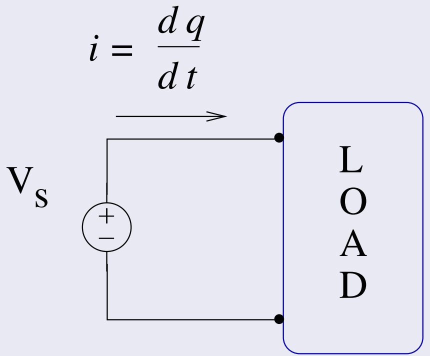

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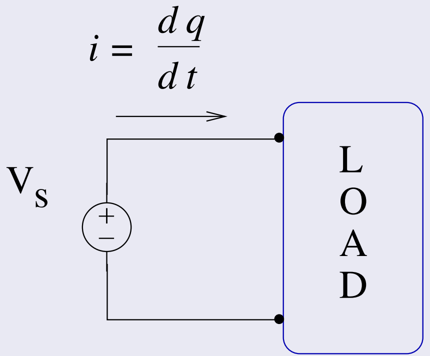

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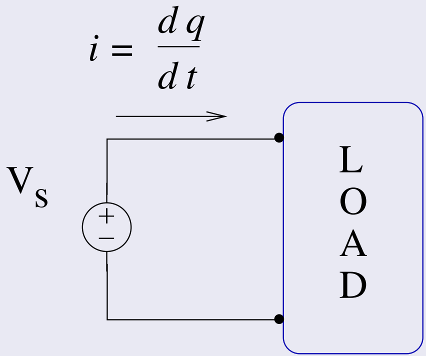

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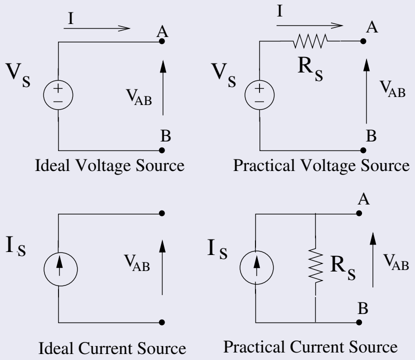
Voltage and Current Sources

Independent Sources



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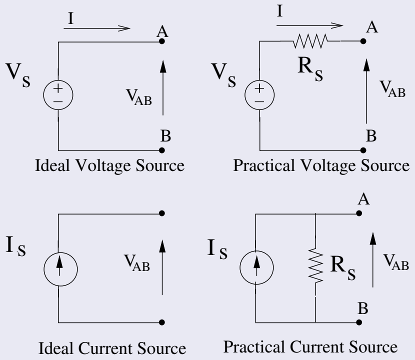

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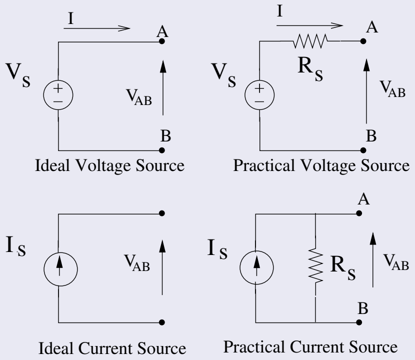

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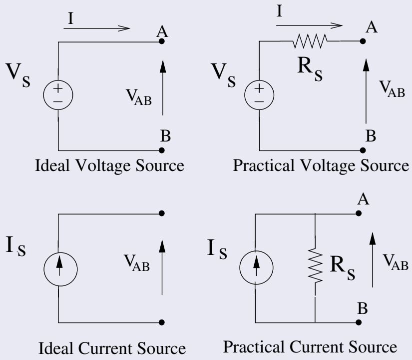

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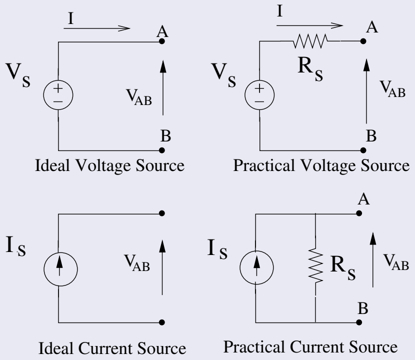

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Electrical Quantities and their dimesions

Current is denoted by symbol I is the amount of charge per unit time, $i(t) = \frac{dq(t)}{dt}$ OR $I = \frac{Q}{t}$, the unit is $\frac{Coulomb}{sec}$ OR $Ampere$

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Electric Power (Unit: Watt): $P = Voltage \cdot Current$

$V = \frac{P}{I}$ $\qquad$ $V = \frac{Work}{time} \cdot \frac{time}{Q}$, $V = \frac{W}{Q}$

Electro Motive Force (Unit Volt) does not have unit of force , but is a driving force to produce electric current when connected to electrical load. Typically, it is the terminal voltage of a open circuited Battery ifference in Potentials between the two points. Its unit is *Volt*. Th e potential sources of e.m.f. are:

1. The electrodes of dissimilar materials immersed in an electrolyte, as in primary and secondary cells, i.e. batteries.
2. The relative movement of a conductor and a magnetic flux, as in electric generators; this source can, alternatively, be expressed as the variation of magnetic flux linked with a coil.
3. The difference of temperature between junctions of dissimilar metals, as in thermo-junctions.

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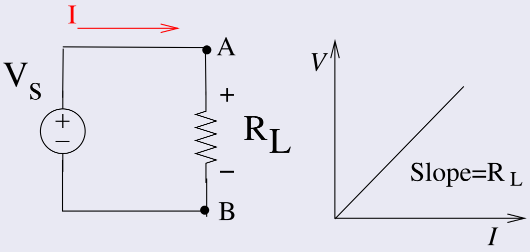

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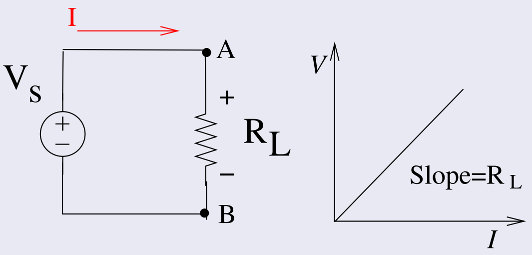

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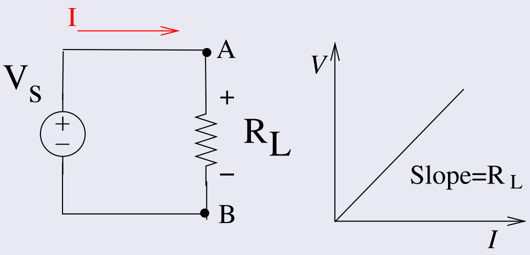

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- The resistance of a wire is expressed as $R = \frac{\rho \cdot length}{Area}$, where ρ is a constant for given conductor material (metal) and is called **Resistivity**, $(\Omega \cdot meters)$,temperature dependent

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Q: Why equivalent resistance needs to be known to analyse the network?

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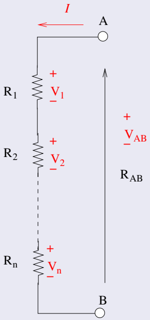

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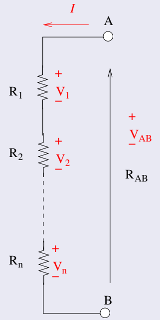

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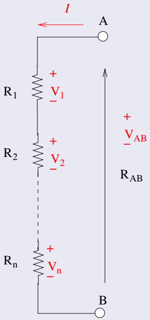

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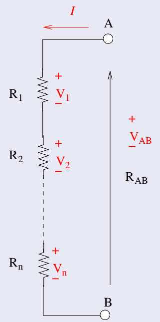

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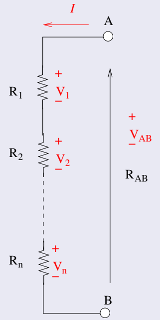

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$$V_1 = I \cdot R_1 = \frac{R_1}{R_{AB}} \cdot V_{AB}$$

$$V_2 = \frac{R_2}{R_{AB}} \cdot V_{AB} \cdots V_n = \frac{R_n}{R_{AB}} \cdot V_{AB}$$

Voltage Sharing Formula

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In Parallel connection, the Voltage across each resistor is same but current would be different. Let I the net current flowing through the circuit. Therefore, let equivalent resistance of the network is: R_{AB}

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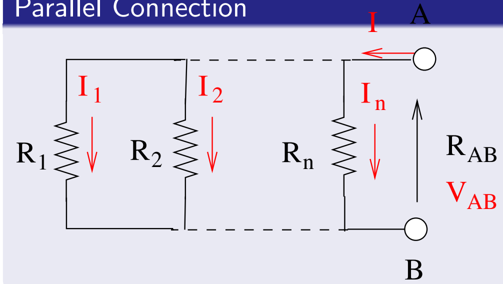

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$$R_{AB} = \frac{1}{\frac{I_1}{V_{AB}} + \frac{I_2}{V_{AB}} + \cdots + \frac{I_n}{V_{AB}}}$$

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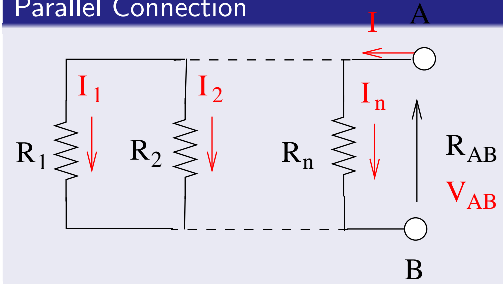

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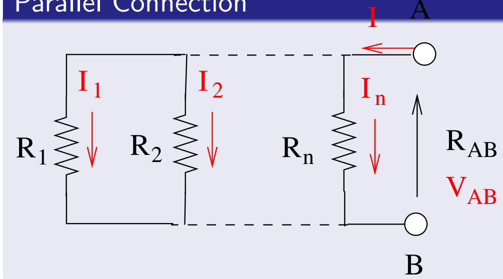

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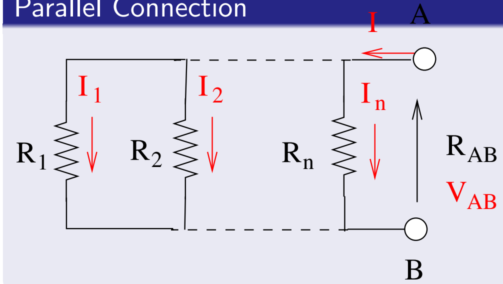

$$R_{AB} = \frac{V_{AB}}{I} = \frac{V_{AB}}{I_1 + I_2 + ... + I_n}$$

$$V_{AB} = I_1 \cdot R_1 = I_2 \cdot R_2 = \cdot\cdot = I_n \cdot R_n = I \cdot R_{AB}$$

$$R_{AB} = \frac{1}{\frac{I_1}{V_{AB}} + \frac{I_2}{V_{AB}} + \cdots + \frac{I_n}{V_{AB}}}$$

$$R_{AB} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

$$I_1 = I \cdot \frac{R_{AB}}{R1}; I_2 = I \cdot \frac{R_{AB}}{R2}; \cdots I_n = I \cdot \frac{R_{AB}}{R_n}$$

Current Sharing Rule

To find Equivalent Resistance

In **Series-Parallel connection**, the resistors are seen in series and parallel combination as **Ladder Network**. let equivalent resistance of the network is: R_{AB}

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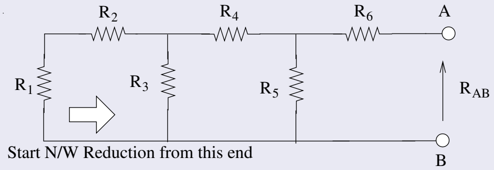
Series-Parallel Connection



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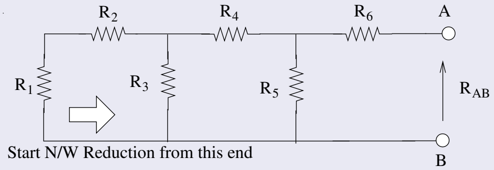
Series-Parallel Connection



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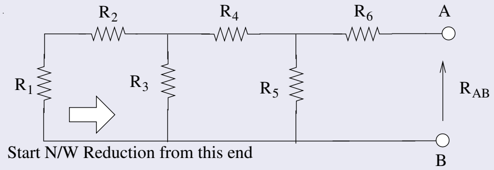

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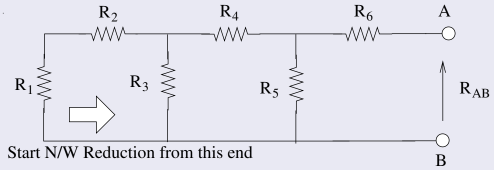

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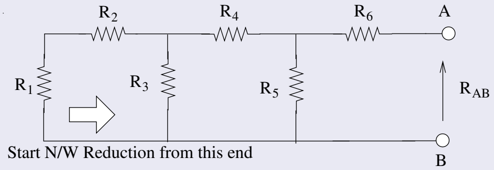

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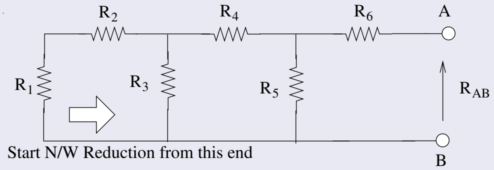

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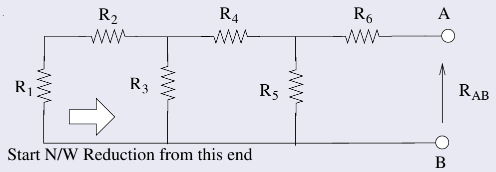

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6. $R_{AB} = R_{12345} + R_6$

To find Equivalent Resistance

Now let us see what happens when a shorting link is introduced in the circuit

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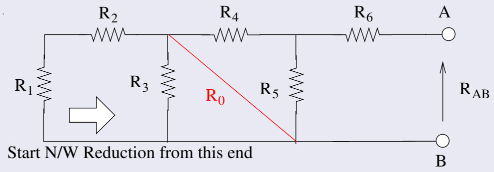
Concept of Short



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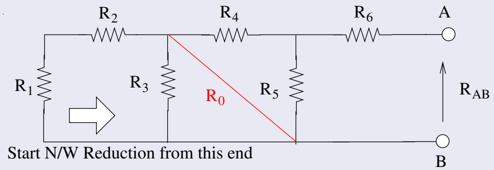

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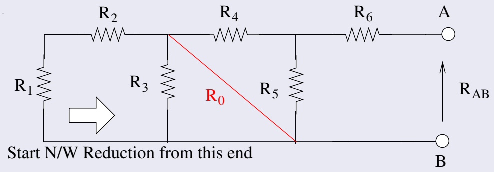

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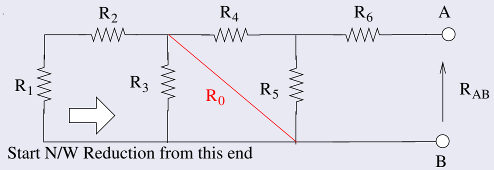

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4. This leads to $R_{1230} = \frac{R_{123} \cdot R_0}{R_{123}+R_0} = 0$

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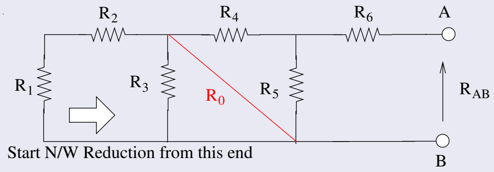

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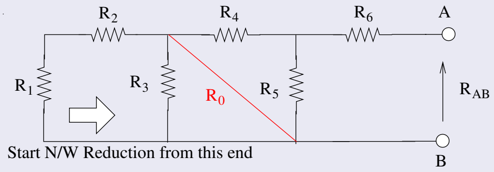

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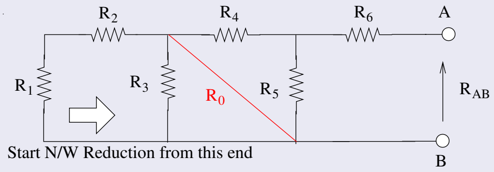

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6. $R_{12345} = \frac{R_4 \cdot R_5}{R_4 + R_5}$
7. $R_{AB} = R_{12345} + R_6$ This is less than the previous resistor

To find Equivalent Resistance: Example

Now let us see what happens when an additional resistor R_7 is introduced in the circuit as shown in Fig. below

To find Equivalent Resistance: Example

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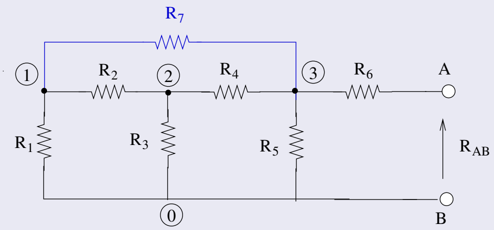
Need of Delta-Star Transformation



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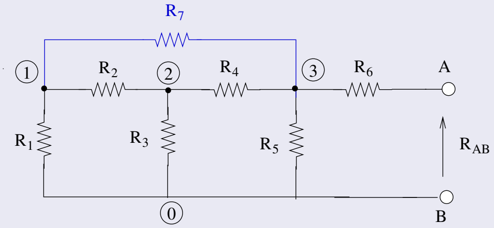

1. Now, the Resistors R_1 and R_2 can not be connected in series.

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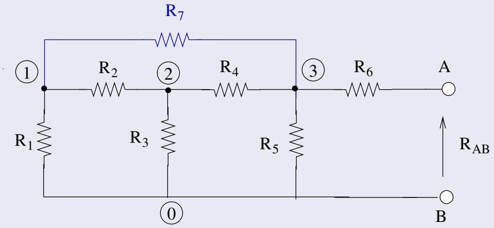

1. Now, the Resistors R_1 and R_2 can not be connected in series.
2. The resistors R_7 can not be seen as parrallel to resistor R_2 OR resistor R_4

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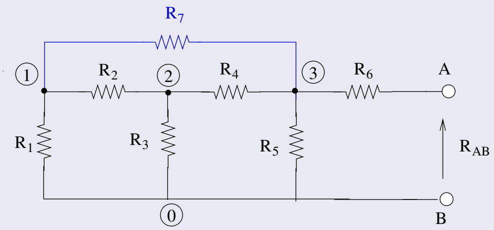

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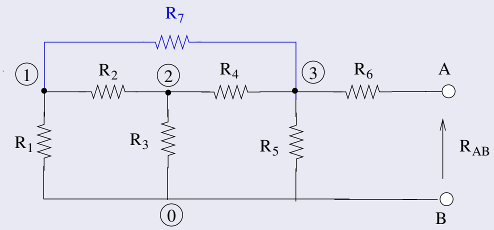

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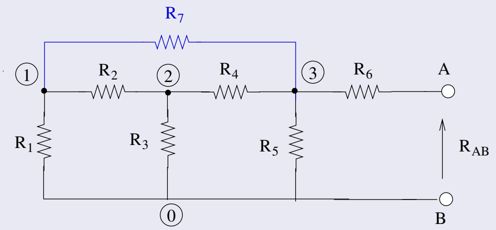
Need of Delta-Star Transformation



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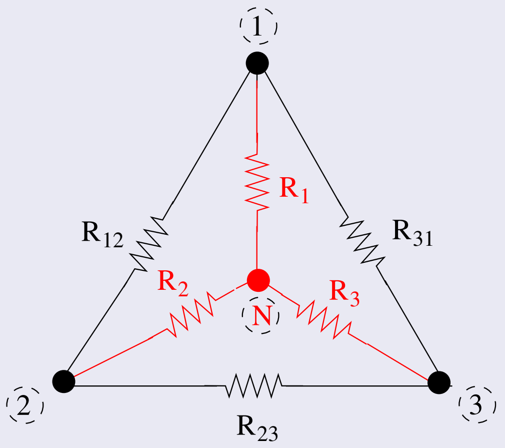
3. Therefore, the series parallel technique of network reduction fails.
4. We can use **Delta-Star Transformation** or **Star-Delta Transformation**
5. Here, resistor R_7 forms Delta (nodes 1,2 and 3)with resistor R_2 and R_4. Then, converting this into equivalent Delta can solve the problem.OR Resistor R_2,R_3 and R_4 forms a Star(nodes 1,3 and 0), transform Star-Delta

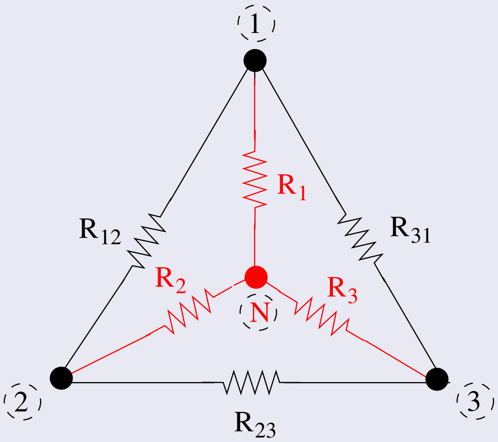
To find Equivalent Resistance

Delta-Star Transformation



To find Equivalent Resistance

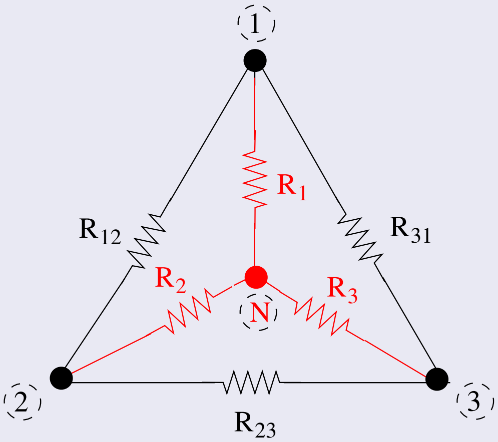
Delta-Star Transformation



Looking at nodes 1 and 2, we write and equate equivalent restor from both Delta and Star Network as:

To find Equivalent Resistance

Delta-Star Transformation

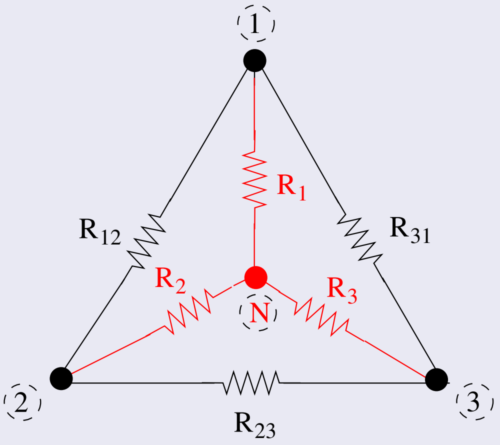


Looking at nodes 1 and 2, we write and equate equivalent restor from both Delta and Star Network as:

$$R_1 + R_2 = \frac{R_{12} \cdot (R_{23} + R_{31})}{(R_{12} + R_{23} + R_{31})} \quad (1)$$

To find Equivalent Resistance

Delta-Star Transformation



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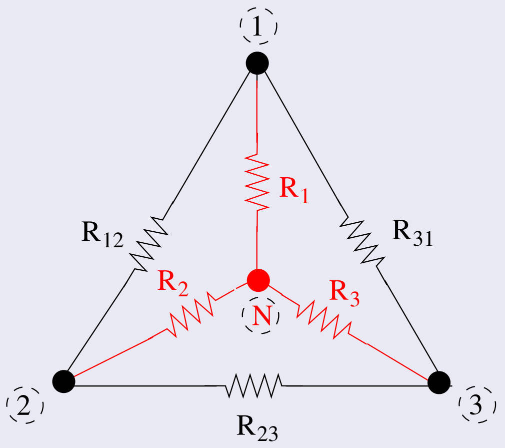
Similarily, for node pairs 2-3 and 3-1, we write:

$$R_2 + R_3 = \frac{R_{23} \cdot (R_{31} + R_{12})}{(R_{12} + R_{23} + R_{31})} \qquad (2)$$

To find Equivalent Resistance

Delta-Star Transformation



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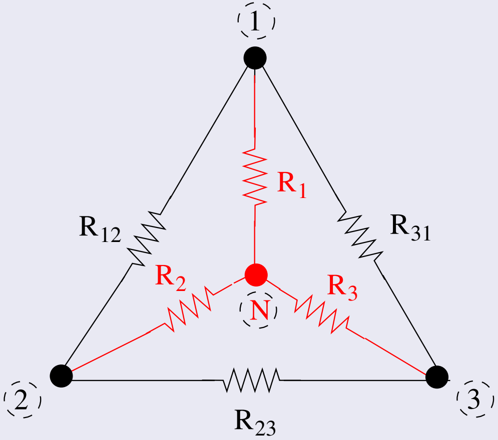
$$R_3 + R_1 = \frac{R_{31} \cdot (R_{12} + R_{23})}{(R_{12} + R_{23} + R_{31})} \qquad (3)$$

To find Equivalent Resistance

Delta-Star Transformation



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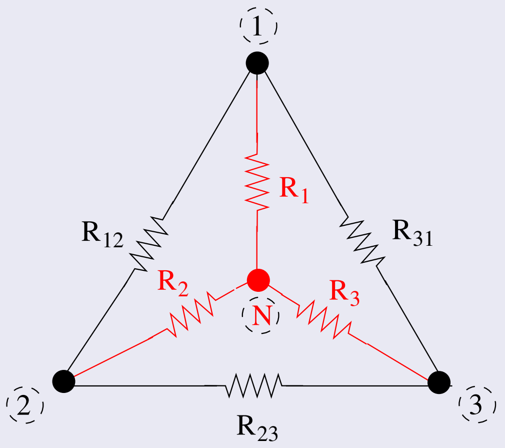
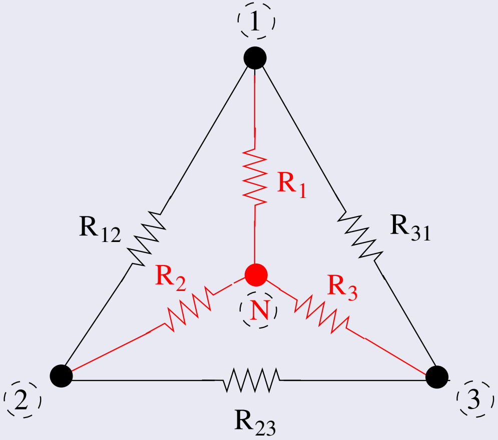


Then Perform the operation on equations: (1)-(2)+(3)

To find Equivalent Resistance

Delta-Star Transformation



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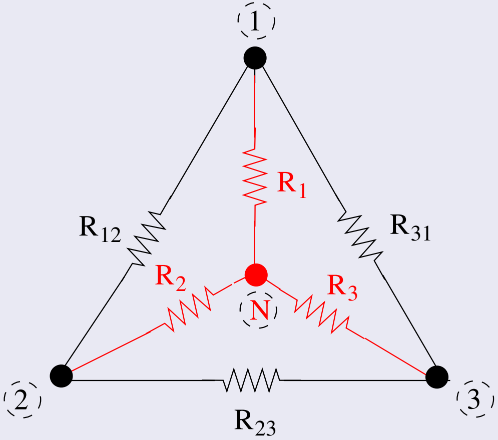
Delta-Star Transformation

$$R_1 = \frac{R_{12} \cdot R_{31}}{(R_{12} + R_{23} + R_{31})}$$

To find Equivalent Resistance

Delta-Star Transformation



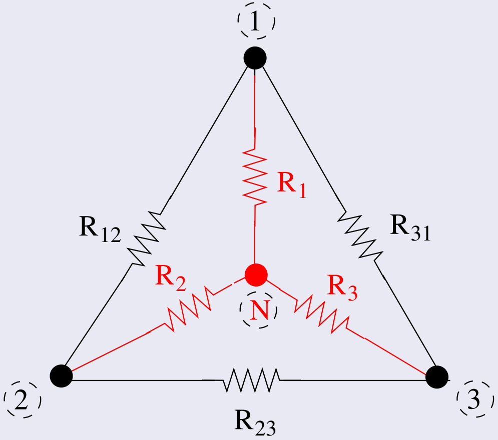
Then Perform the operation on equations: (1)-(2)+(3)

Delta-Star Transformation

$$R_1 = \frac{R_{12} \cdot R_{31}}{(R_{12} + R_{23} + R_{31})} \tag{4}$$

Similarly, we can perform (2)-(3)+(1) and (3)-(1)+(2), we write:

Delta-Star Transformation



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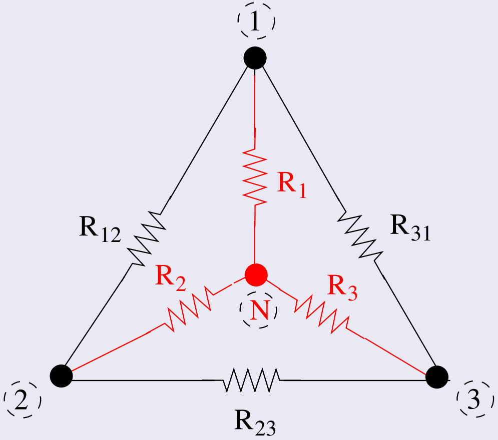
To find Equivalent Resistance

Delta-Star Transformation



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$$R_1 = \frac{R_{12} \cdot R_{31}}{(R_{12} + R_{23} + R_{31})} \tag{4}$$

Similarly, we can perform (2)-(3)+(1) and (3)-(1)+(2), we write:

$$R_2 = \frac{R_{12} \cdot R_{23}}{(R_{12} + R_{23} + R_{31})} \tag{5}$$

$$R_3 = \frac{R_{23} \cdot R_{31}}{(R_{12} + R_{23} + R_{31})} \tag{6}$$

To find Equivalent Resistance

Following operations are performed on equations:(4), (5) and (6)

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$$R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1 = \\ = \frac{(R_{12} \cdot R_{23} \cdot R_{31})}{(R_{12} + R_{23} + R_{31})}$$

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Therefore substituting for R_3 as the term shown with red color, we can write:

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Therefore substituting for R_3 as the term shown with red color, we can write:

Star-Delta Transformation

$$R_{12} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_3}$$

To find Equivalent Resistance

Following operations are performed on equations:(4), (5) and (6) (4)*(5)+(5)*(6)+(6)*(4)

$$R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1 = \\ = \frac{(R_{12} \cdot R_{23} \cdot R_{31})}{(R_{12} + R_{23} + R_{31})}$$

Therefore substituting for R_3 as the term shown with red color, we can write:

Star-Delta Transformation

$$R_{12} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_3} \tag{7}$$

Similarily,

$$R_{23} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_1}$$

To find Equivalent Resistance

Following operations are performed on equations:(4), (5) and (6) (4)*(5)+(5)*(6)+(6)*(4)

$$R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1 = \\ = \frac{(R_{12} \cdot R_{23} \cdot R_{31})}{(R_{12} + R_{23} + R_{31})}$$

Therefore substituting for R_3 as the term shown with red color, we can write:

Star-Delta Transformation

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Similarily,

$$R_{23} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_1} \tag{8}$$

$$R_{31} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_2}$$

To find Equivalent Resistance

Following operations are performed on equations:(4), (5) and (6) (4)*(5)+(5)*(6)+(6)*(4)

$$R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1 = \\ = \frac{(R_{12} \cdot R_{23} \cdot R_{31})}{(R_{12} + R_{23} + R_{31})}$$

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Similarily,

$$R_{23} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_1} \tag{8}$$

$$R_{31} = \frac{R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1}{R_2} \tag{9}$$

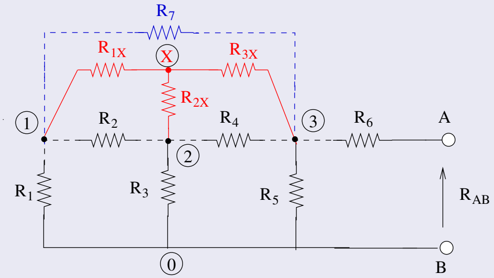
To find Equivalent Resistance: Example-1

Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

To find Equivalent Resistance: Example-1

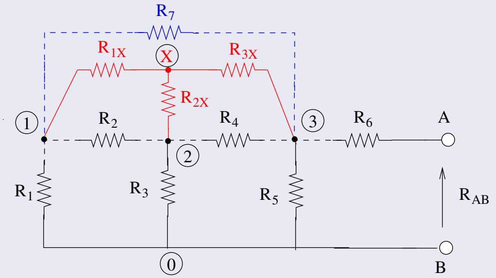
Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

Delta-Star Transformation



Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

Delta-Star Transformation

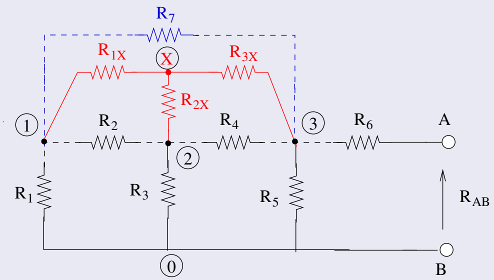


By using equations: (4), (5) and (6)

$$R1X = \frac{R_2 \cdot R_7}{R_2 + R_4 + R_7}$$

Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

Delta-Star Transformation



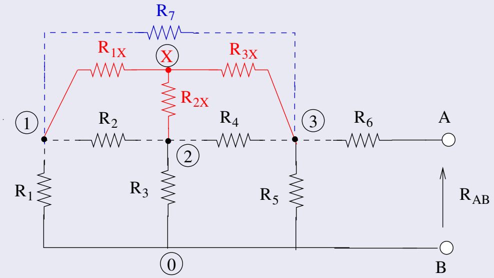
By using equations: (4), (5) and (6)

$$R1X = \frac{R_2 \cdot R_7}{R_2 + R_4 + R_7}$$

$$R2X = \frac{R_2 \cdot R_4}{R_2 + R_4 + R_7}$$

Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

Delta-Star Transformation

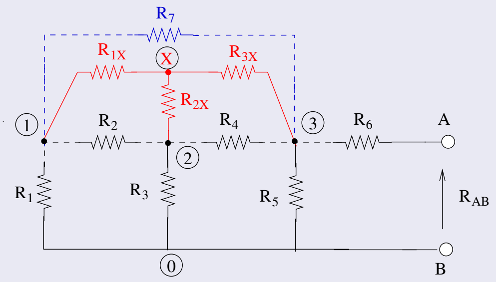


By using equations: (4), (5) and (6)

$$R1X = \frac{R_2 \cdot R_7}{R_2 + R_4 + R_7}$$
$$R2X = \frac{R_2 \cdot R_4}{R_2 + R_4 + R_7}$$
$$R3X = \frac{R_4 \cdot R_7}{R_2 + R_4 + R_7}$$

Now we shall solve this problem by existing Delta: (R_2,R_4 & R_7) connections to Star: (R_{1X},R_{2X} & R_{3X}) Network by Delta-Star Transformation.

Delta-Star Transformation



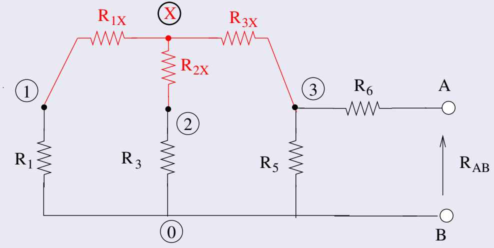
By using equations: (4), (5) and (6)

$$R1X = \frac{R_2 \cdot R_7}{R_2 + R_4 + R_7}$$

$$R2X = \frac{R_2 \cdot R_4}{R_2 + R_4 + R_7}$$

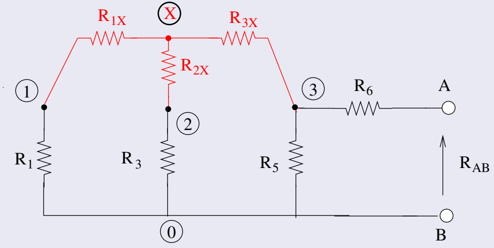
$$R3X = \frac{R_4 \cdot R_7}{R_2 + R_4 + R_7}$$

Delta-Star Transformation



To find Equivalent Resistance: Example-1

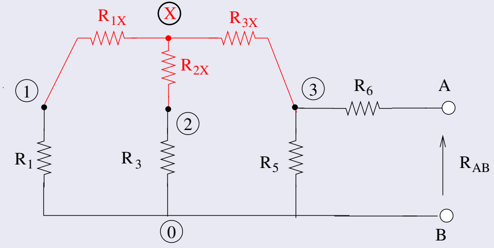
Delta-Star Transformation



Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

To find Equivalent Resistance: Example-1

Delta-Star Transformation



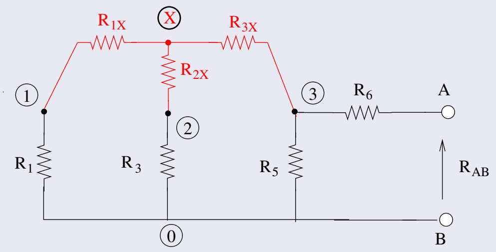
Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

We can now use series-parallel technique

- $R_{11X} = R_1 + R_{1X}$, $R_{23X} = R_3 + R_{2X}$

To find Equivalent Resistance: Example-1

Delta-Star Transformation

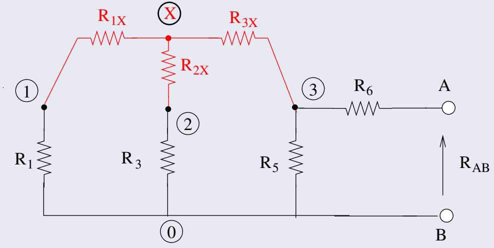


Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

We can now use series-parallel technique

- $R_{11X} = R_1 + R_{1X}$, $R_{23X} = R_3 + R_{2X}$
- $R_{1123X} = \frac{R_{11X} \cdot R_{23X}}{R_{11X} + R_{23X}}$

Delta-Star Transformation



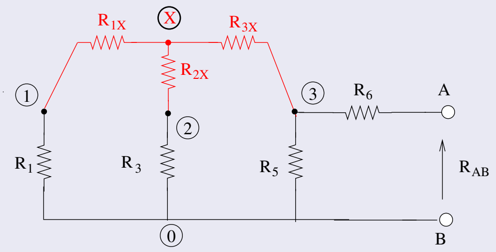
Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

We can now use series-parallel technique

- $R_{11X} = R_1 + R_{1X}$, $R_{23X} = R_3 + R_{2X}$
- $R_{1123X} = \frac{R_{11X} \cdot R_{23X}}{R_{11X} + R_{23X}}$
- $R_{11233X} = R_{1123X} + R_{3X}$

To find Equivalent Resistance: Example-1

Delta-Star Transformation



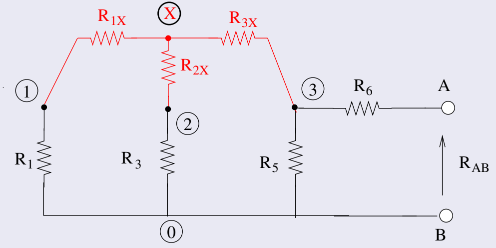
Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

We can now use series-parallel technique

- $R_{11X} = R_1 + R_{1X}$, $R_{23X} = R_3 + R_{2X}$
- $R_{1123X} = \frac{R_{11X} \cdot R_{23X}}{R_{11X} + R_{23X}}$
- $R_{11233X} = R_{1123X} + R_{3X}$
- $R_{112335X} = \frac{R_{11233X} \cdot R_5}{R_{11233X} + R_5}$

To find Equivalent Resistance: Example-1

Delta-Star Transformation



Now, we have to analyse new network and neglect the resistors (R_2,R_4 & R_7). A new node X is created.

We can now use series-parallel technique

- $R_{11X} = R_1 + R_{1X}$, $R_{23X} = R_3 + R_{2X}$
- $R_{1123X} = \frac{R_{11X} \cdot R_{23X}}{R_{11X} + R_{23X}}$
- $R_{11233X} = R_{1123X} + R_{3X}$
- $R_{112335X} = \frac{R_{11233X} \cdot R_5}{R_{11233X} + R_5}$
- $R_{AB} = R_{112335X} + R_6$

To find Equivalent Resistance: Example-2

Now we shall solve this problem by existing Star: (R_2,R_3 & R_4) connections to new Delta: (R_{10},R_{30} & R_{13}) Network by Star-Delta Transformation.

To find Equivalent Resistance: Example-2

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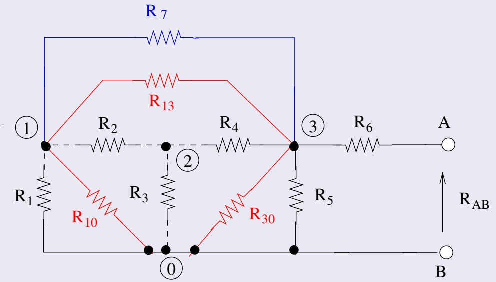
Delta-Star Transformation



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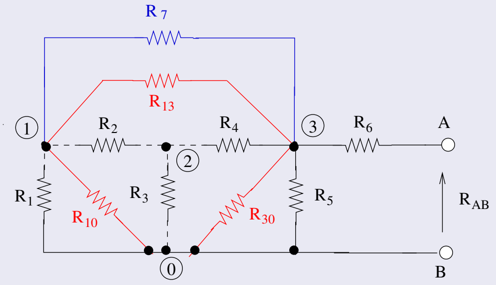
Delta-Star Transformation



By using equations: (7), (8) and (9)

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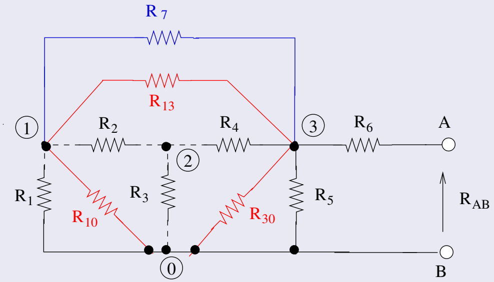


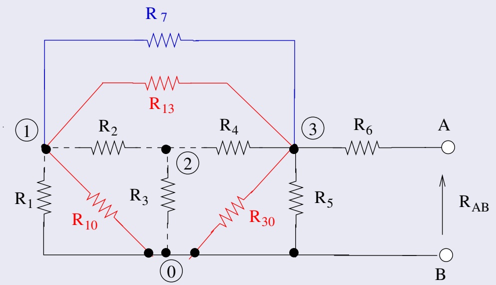
By using equations: (7), (8) and (9)

Star-Delta Transformation

$$R_{10} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_4}$$

Now we shall solve this problem by existing Star: (R_2,R_3 & R_4) connections to new Delta: (R_{10},R_{30} & R_{13}) Network by Star-Delta Transformation.

Delta-Star Transformation



By using equations: (7), (8) and (9)

Star-Delta Transformation

$$R_{10} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_4} \quad (10)$$

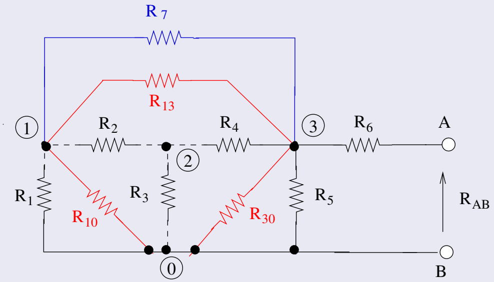
Similarily,

$$R_{30} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_2}$$

To find Equivalent Resistance: Example-2

Now we shall solve this problem by existing Star: (R_2,R_3 & R_4) connections to new Delta: (R_{10},R_{30} & R_{13}) Network by Star-Delta Transformation.

Delta-Star Transformation



By using equations: (7), (8) and (9)

Star-Delta Transformation

$$R_{10} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_4} \tag{10}$$

Similarly,

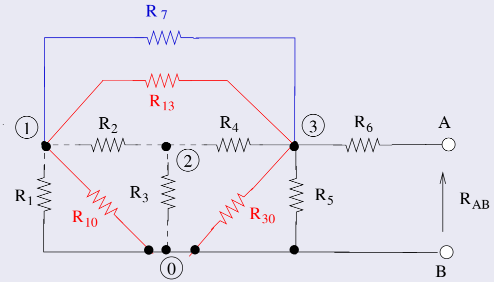
$$R_{30} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_2} \tag{11}$$

$$R_{13} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_3}$$

To find Equivalent Resistance: Example-2

Now we shall solve this problem by existing Star: (R_2,R_3 & R_4) connections to new Delta: (R_{10},R_{30} & R_{13}) Network by Star-Delta Transformation.

Delta-Star Transformation



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$$R_{10} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_4} \qquad (10)$$

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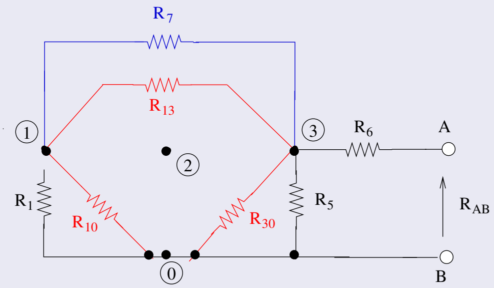
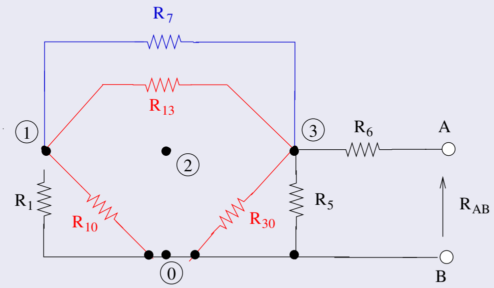
$$R_{13} = \frac{R_2 \cdot R_3 + R_3 \cdot R_4 + R_2 \cdot R_4}{R_3} \qquad (12)$$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



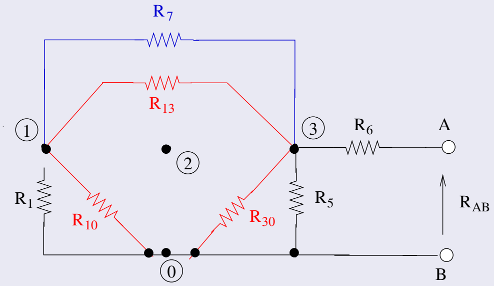
Star-Delta Transformation



Now, we have to analyse new network and neglect the resistors (R_2,R_3 & R_4). The node (2) will vanish now in the new network.

To find Equivalent Resistance: Example-2

Star-Delta Transformation



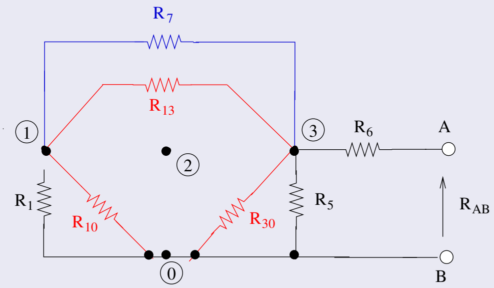
Now, we have to analyse new network and neglect the resistors (R_2,R_3 & R_4). The node (2) will vanish now in the new network.

We can now use series-parallel technique

- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



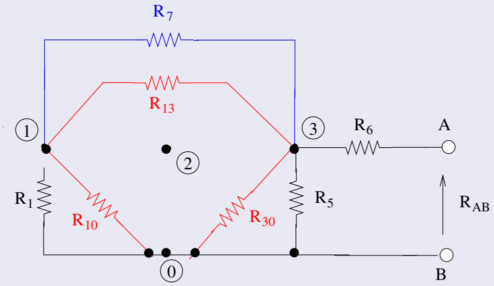
Now, we have to analyse new network and neglect the resistors (R_2,R_3 & R_4). The node (2) will vanish now in the new network.

We can now use series-parallel technique

- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$
- $R_{101} = \frac{R_{10} \cdot R_1}{R_{10} + R_1}$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



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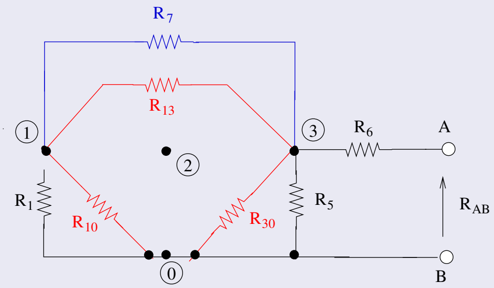
- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$
- $R_{101} = \frac{R_{10} \cdot R_1}{R_{10} + R_1}$
- $R_{305} = \frac{R_{30} \cdot R_5}{R_{30} + R_5}$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



Now, we have to analyse new network and neglect the resistors (R_2,R_3 & R_4). The node (2) will vanish now in the new network.

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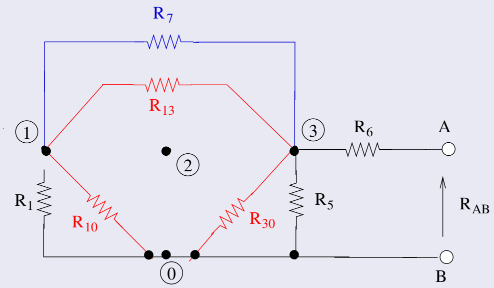
- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$
- $R_{101} = \frac{R_{10} \cdot R_1}{R_{10} + R_1}$
- $R_{305} = \frac{R_{30} \cdot R_5}{R_{30} + R_5}$
- $R_{137101} = R_{137} + R_{101}$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



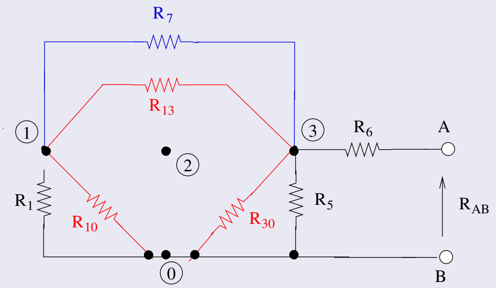
Now, we have to analyse new network and neglect the resistors (R_2,R_3 & R_4). The node (2) will vanish now in the new network.

We can now use series-parallel technique

- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$
- $R_{101} = \frac{R_{10} \cdot R_1}{R_{10} + R_1}$
- $R_{305} = \frac{R_{30} \cdot R_5}{R_{30} + R_5}$
- $R_{137101} = R_{137} + R_{101}$
- $R_{137101305} = \frac{R_{137101} \cdot R_{305}}{R_{137101} + R_{305}}$

To find Equivalent Resistance: Example-2

Star-Delta Transformation



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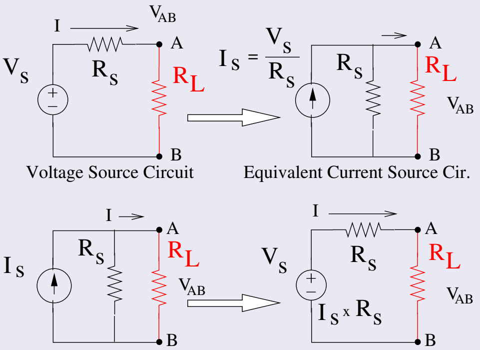
- $R_{137} = \frac{R_{13} \cdot R_7}{R_{13} + R_7}$
- $R_{101} = \frac{R_{10} \cdot R_1}{R_{10} + R_1}$
- $R_{305} = \frac{R_{30} \cdot R_5}{R_{30} + R_5}$
- $R_{137101} = R_{137} + R_{101}$
- $R_{137101305} = \frac{R_{137101} \cdot R_{305}}{R_{137101} + R_{305}}$
- $R_{AB} = R_{137101305} + R_6$

Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

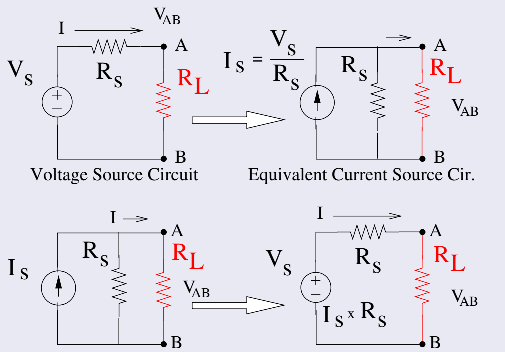
Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

Source Transformation



Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

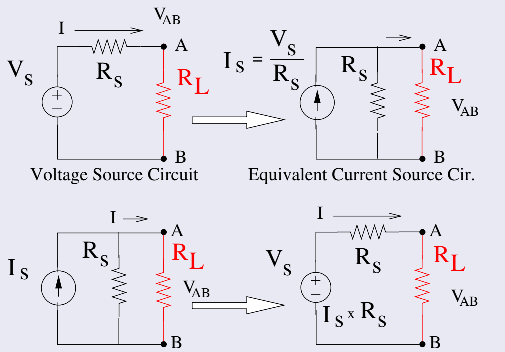
Source Transformation



Let us assume that this voltage source circuit can be transformed to an equivalent current source circuit with a parallel resistor of value R_s. Due to equivalence, the terminal current in both the circuit should be equal.

Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

Source Transformation

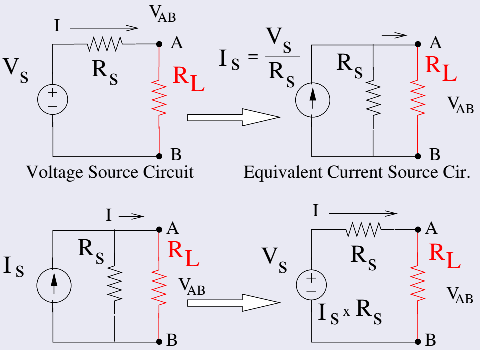


Let us assume that this voltage source circuit can be transformed to an equivalent current source circuit with a parallel resistor of value R_s. Due to equivalence, the terminal current in both the circuit should be equal.

Let an external load resistor R_L be connected at the terminal A-B of both the circuits.

Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

Source Transformation



Let us assume that this voltage source circuit can be transformed to an equivalent current source circuit with a parallel resistor of value R_s. Due to equivalence, the terminal current in both the circuit should be equal.

Let an external load resistor R_L be connected at the terminal A-B of both the circuits.

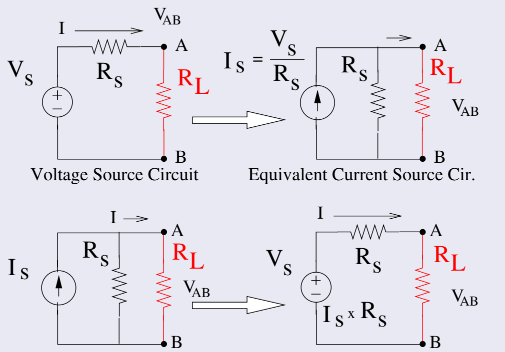
If we equate the current produced by both the circuits in the load resistor, we get:

$$\frac{V_s}{R_s + R_L} = I_s \cdot \frac{R_s}{R_s + R_L}$$

Circuit Analysis by Source Transformation

Voltage to Current Source Transformation: Let us consider a primary circuit as Voltage source with voltage V_s and having a series resistor having value R_s.

Source Transformation



Let us assume that this voltage source circuit can be transformed to an equivalent current source circuit with a parallel resistor of value R_s. Due to equivalence, the terminal current in both the circuit should be equal.

Let an external load resistor R_L be connected at the terminal A-B of both the circuits.

If we equate the current produced by both the circuits in the load resistor, we get:

$$\frac{V_s}{R_s + R_L} = I_s \cdot \frac{R_s}{R_s + R_L}$$

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Current to Voltage Source Transformation: Let us consider a primary circuit as Current source with value I_s and having a parallel resistor with value R_s.

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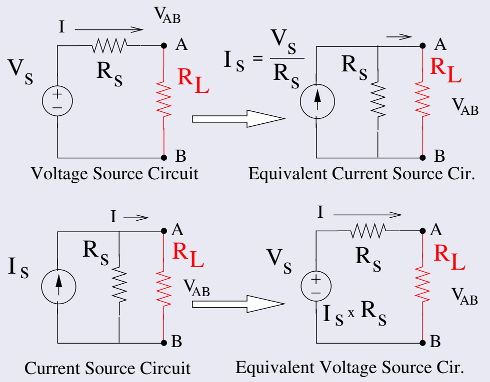

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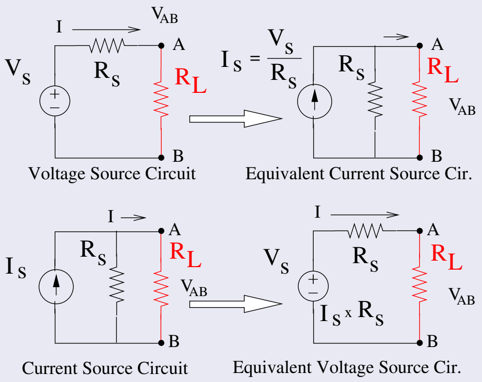

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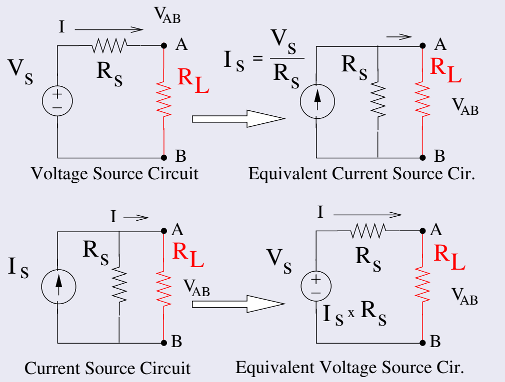

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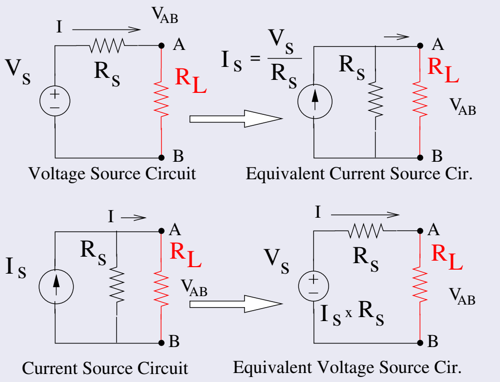

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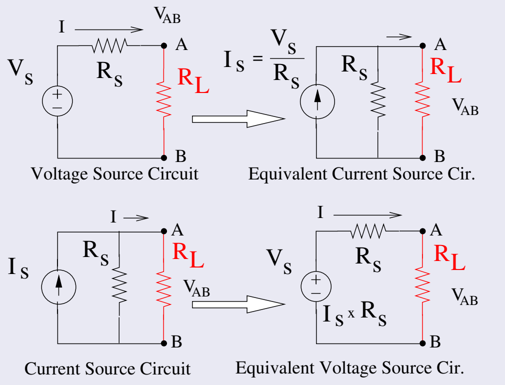

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Circuit Analysis by Source Transformation: Example

Example: Let us consider a circuit as shown below. The objective is to find current through the resistor R_2 to be evaluated by Source Transformation Technique.

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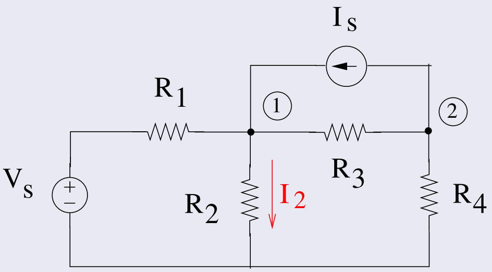

Example: Let us consider a circuit as shown below. The objective is to find current through the resistor R_2 to be evaluated by Source Transformation Technique.

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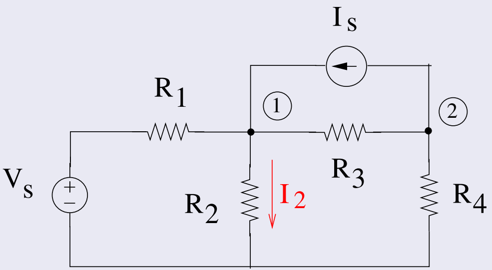
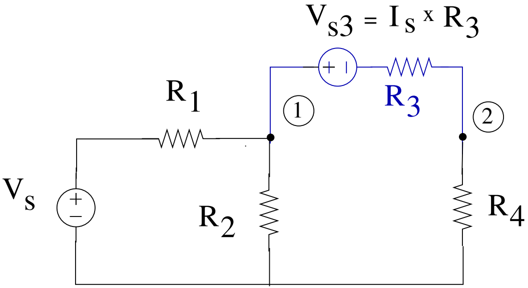
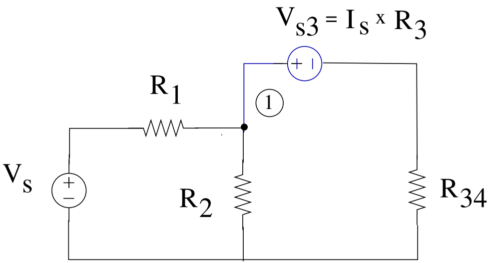


Now let us transform the current source I_s alomg with parallel resistor R_3 to an equivalent voltage source V_{S3} snd s series resistor R_3. We can write $V_{S3} = I_s \cdot R_3$.



Now solve $R_{34} = R_3 + R4$, as series combination.



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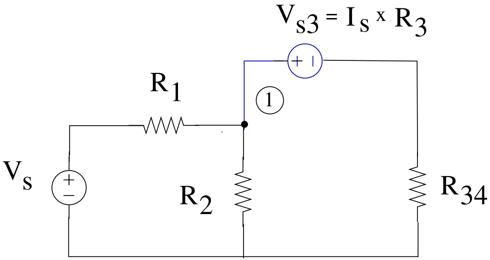

Now transform the voltage source V_s3 alongwith series resistor R_{34}, to a current source $I_{s334} = \frac{V_s3}{R_{34}}$ with a parrallel resistor R_{34}.

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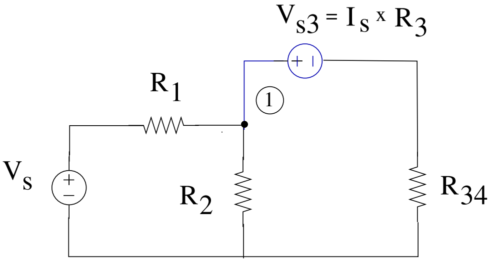

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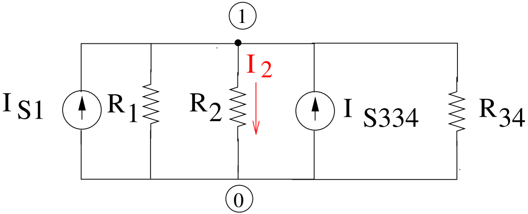
Now, transform voltage source V_s into an equivalent current source I_{s1} with a parallel resistor R_1.



Since, both current sources are connected between same pair of nodes and they are in the same direction, we can get resultant current as $I_{S1334} = I_{s1} + I_{s334}$.

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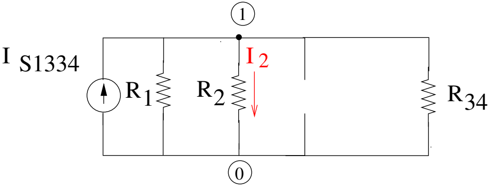

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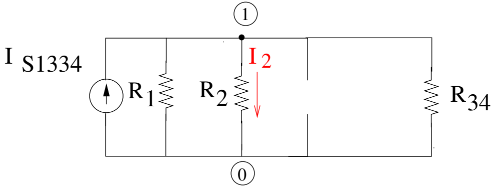

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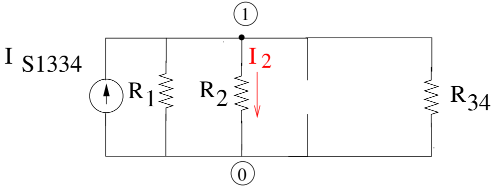

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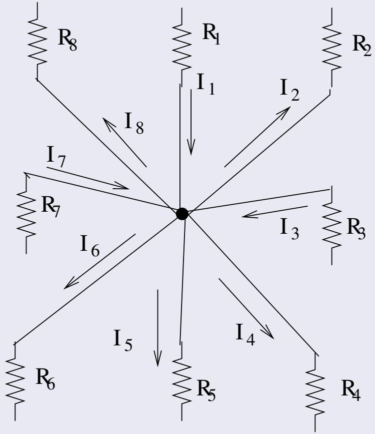
Finally, the current I_2 can be computed from following equation:

$$I_2 = I_{S1334} \cdot \frac{R_{134}}{R_2 + R_{134}}$$

Kirchoff's Lawa;

Kirchoff's Current Law



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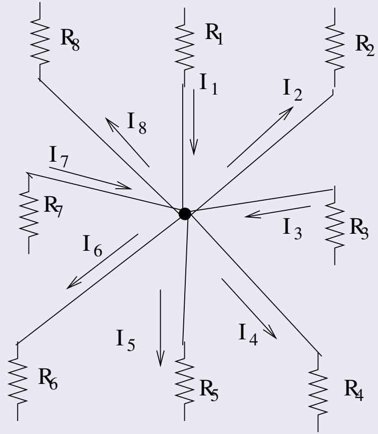

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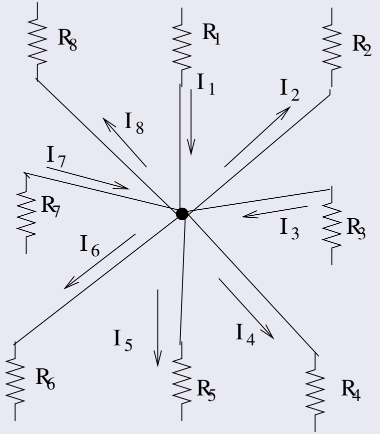

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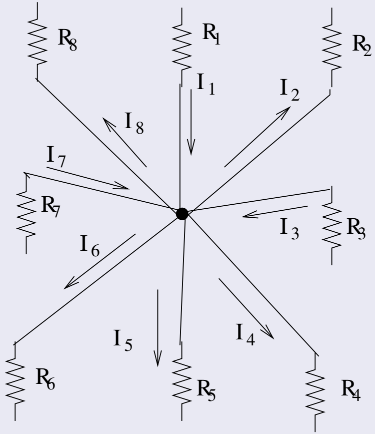

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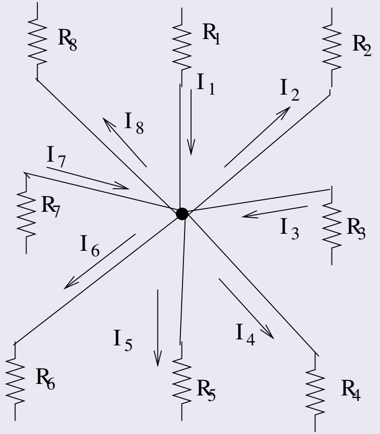

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Sign-Convention Entering current is positive (+ve) and leaving current is negative (-ve).

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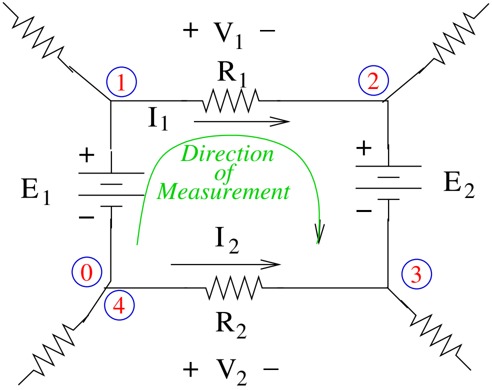

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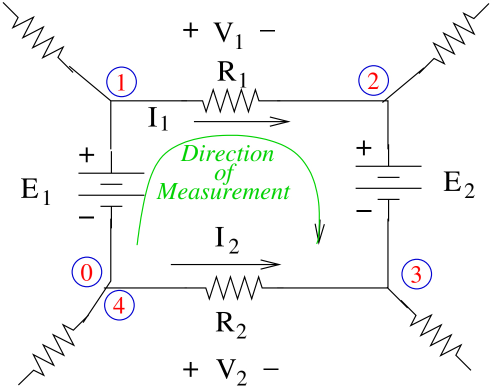

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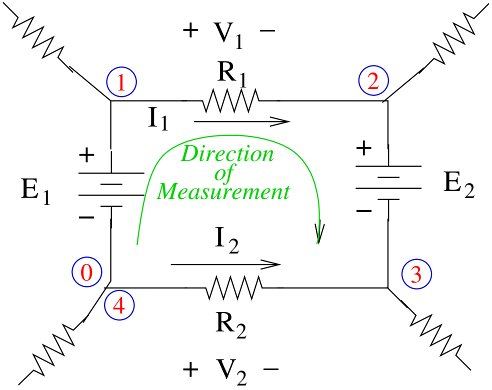

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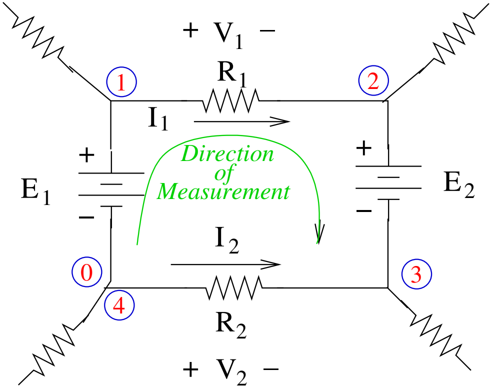

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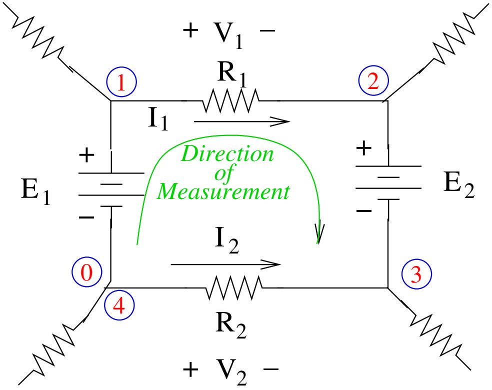

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Sign-Convention In the direction of measurement, if a voltage is meaured from -ve polarity to +ve polarity, considered as (+ve) and vice-versa (as negative (-ve)).

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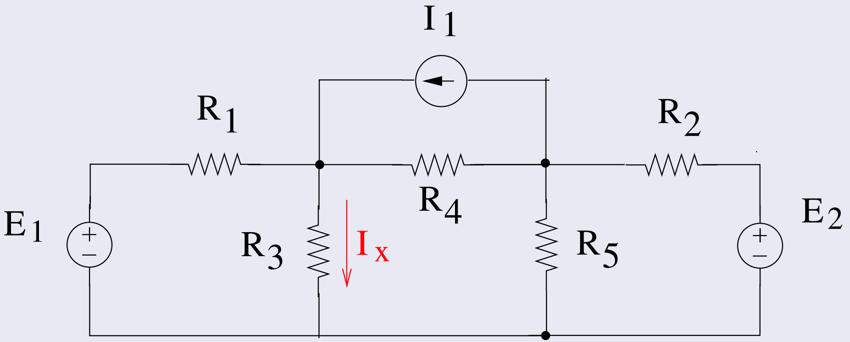
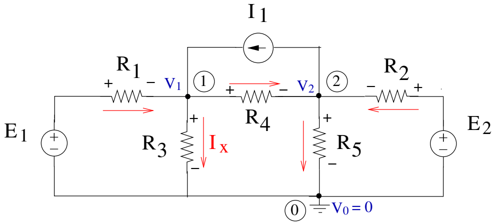
Example

Example: To find the current I_x as shown in the figure below by Nodal Analysis.



Example



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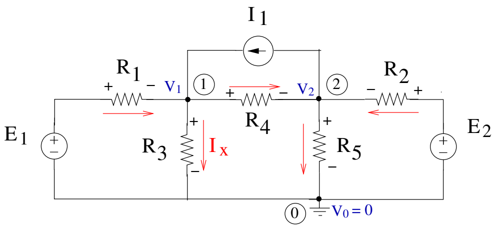

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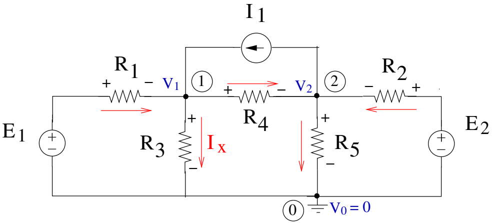
Example



1. The circuit has two independent nodes (1-2) and One node is identified as groumd node or reference node (0).
2. Assigned V_1 and $V2$ as node voltages to the corresponding independent nodes with reference to the zero or reference node and assume that $V_1 > V_2$ as inequalities between the node voltages.

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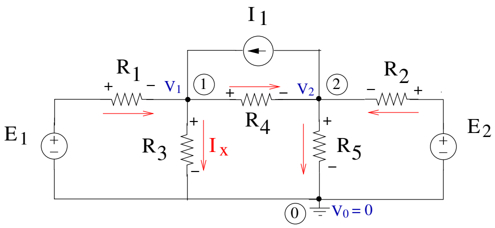

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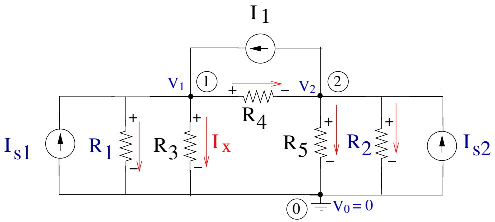

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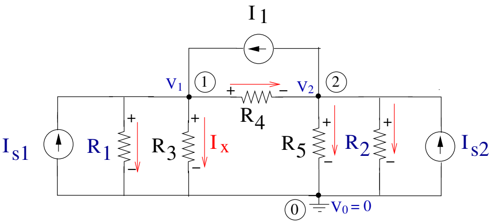

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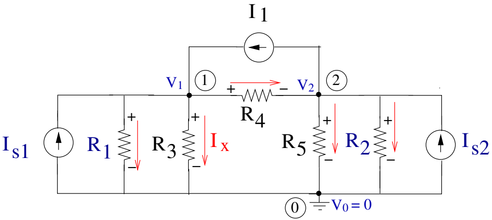

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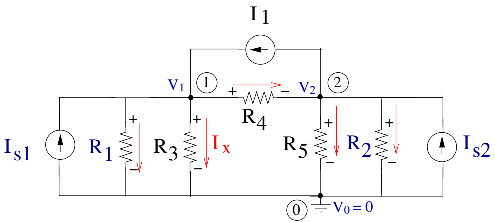

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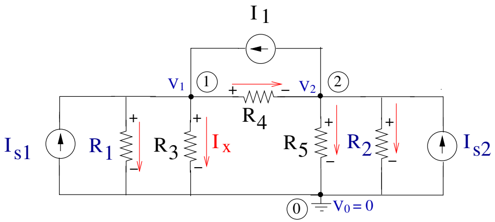

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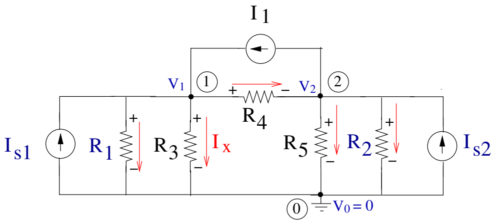

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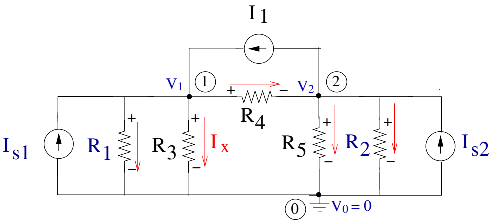
Applying KCL at Node-1 will results in equation (13) and KCL at Node-2 will results in equation (14).

$$I_{s1} - \frac{V_1}{R_1} - \frac{V_1}{R_3} - \frac{V_1 - V_2}{R_4} + I_1 = 0 \quad (13)$$

$$I_{s2} - \frac{V_2}{R_2} - \frac{V_2}{R_5} + \frac{V_1 - V_2}{R_4} - I_1 = 0 \quad (14)$$

Example



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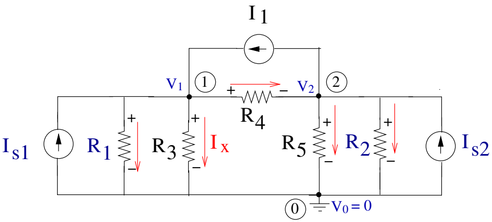
Applying KCL at Node-1 will results in equation (13) and KCL at Node-2 will results in equation (14).

$$I_{s1} - \frac{V_1}{R_1} - \frac{V_1}{R_3} - \frac{V_1 - V_2}{R_4} + I_1 = 0 \quad (13)$$

$$I_{s2} - \frac{V_2}{R_2} - \frac{V_2}{R_5} + \frac{V_1 - V_2}{R_4} - I_1 = 0 \quad (14)$$

Please note that here, only unknown quantitites are node voltages V_1 and V_2.

Example



1. Solving equations (13) and (14), simultaneously, we can find the unknown node voltages V_1 and V_2.

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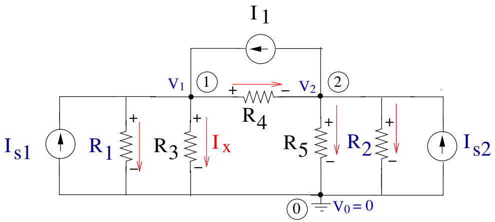

1. Solving equations (13) and (14), simultaneously, we can find the unknown node voltages V_1 and V_2.
2. Finally we can find current through any branch of the network. However, we can find current $I_x = \frac{V_1}{R_3}$ since it is specifically asked in the exercise.

KVL and Ohm's Law : Steps to be followd for generalised circuit Evaluation. Objective is to frame a procedure to compute the unkmown mesh current for complete analysis of the given circuit.

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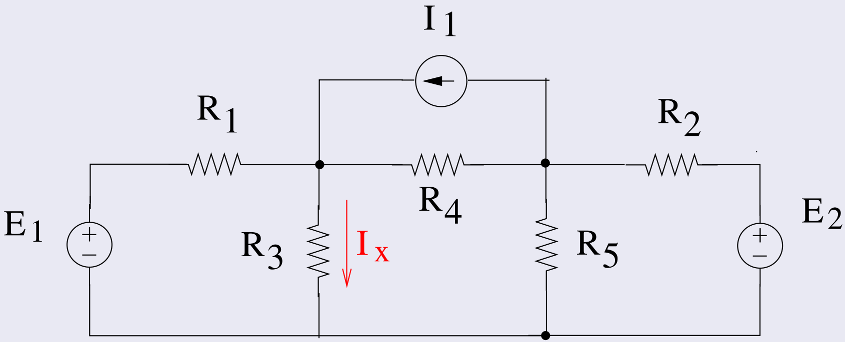
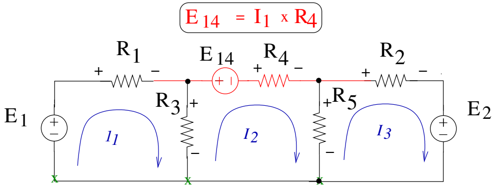
Example

Example: To find the current I_x as shown in the figure below by Mesh Analysis.

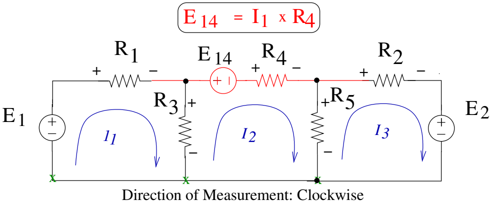


Example



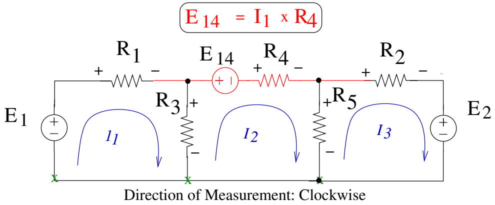
Direction of Measurement: Clockwise

Example



1. The circuit has three independent meshes/windows (1-3).

Example



1. The circuit has three independent meshes/windows (1-3).
2. We assign I_1, I_2 and I_3 as mesh currents corresponding to these meshes and assume that $I_1 > I_2 > I_3$ as inequalities between them.

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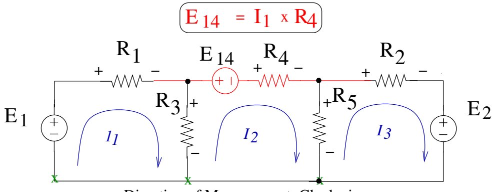

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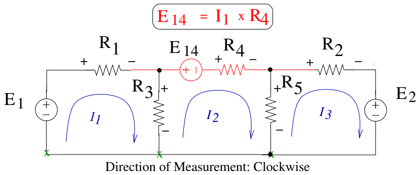
2. We assign I_1,I_2 and I_3 as mesh currents corresponding to these meshes and assume that $I_1 > I_2 > I_3$ as inequalities between them.
3. We then transform the current source I_1 to the equivalent voltage source $E_{14} = I_1 \cdot R_4$
4. Now mark the polarity voltage drop across each resistor depending on the direction of the mesh current

Example


E 14 = I1 x R4
R1
E 14
R4
R2
E1
R3
R5
E2
I1
I2
I3
Direction of Measurement: Clockwise

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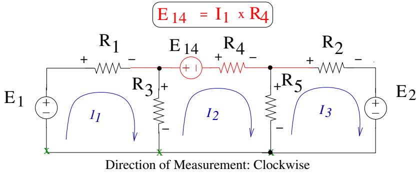

- Now, start writting KVL equation for each mesh by assuming direction ofs, the resulting equations for Mesh-1 to Mesh-3 are given below, sequentially.

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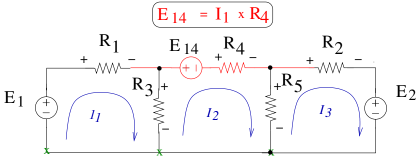

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E_1 - I_1 \cdot R_1 - (I_1 - I_2) \cdot R_3 &= 0 \\
(I_1 - I_2) \cdot R_3 - E_{14} - I_2 \cdot R_4 - (I_2 - I_3) \cdot R_5 &= 0 \\
(I_2 - I_3) \cdot R_5 - I_3 \cdot R_2 - E2 &= 0
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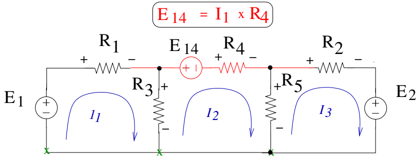

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Now, by solving above three equations, simultaneously, the three unknown mesh currents can be computed. The current I_x can be computed by solving $(I_1 - I_2)$.

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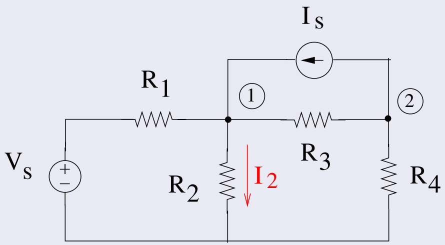
5. **Deactivation of Current Sorce**: For Current source, replace it with a open circuit or by a wire with infinite resistance

Example-1: To find current I_2 in the circuit below

Superposition Theorem: Example



$$I_2 = I_{2X} + I_{2Y}$$

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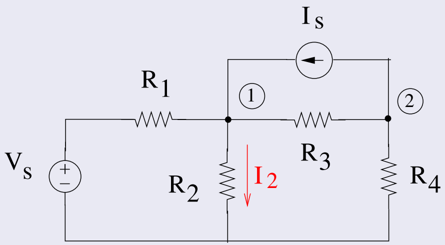

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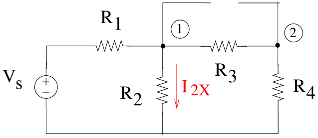
Considering Voltage source V_s only



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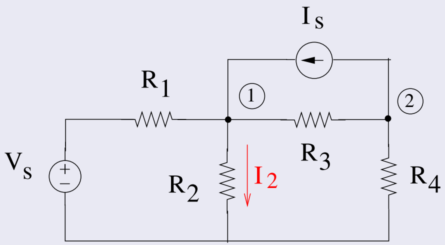

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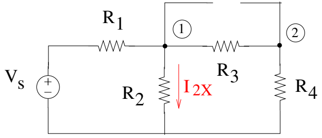

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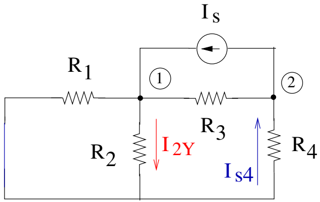

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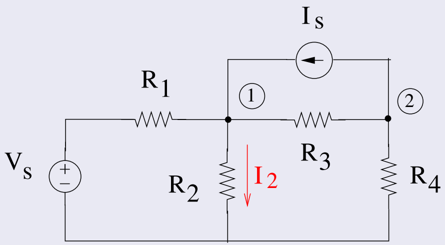

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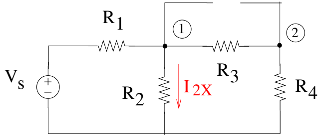

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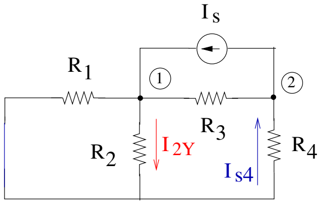

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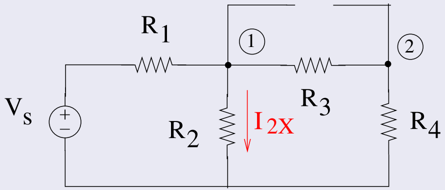

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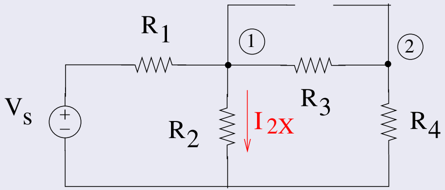


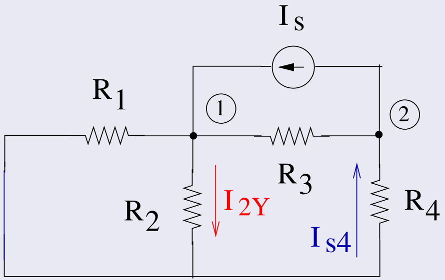
Considering Current V_s only
Compute I_{2X}:

$$R_{234} = \frac{R_2 \cdot (R_3 + R_4)}{R_2 + R_3 + R_4}$$

$$I_{2X} = \frac{1}{R_2} \cdot V_s \cdot \frac{R_{234}}{R_1 + R_{234}}$$

Circuit-2: To compute current I_{2Y} in the circuit below

Superposition Theorem: Example



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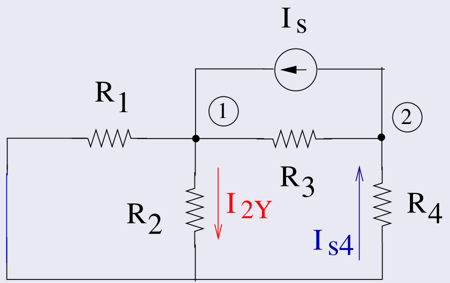


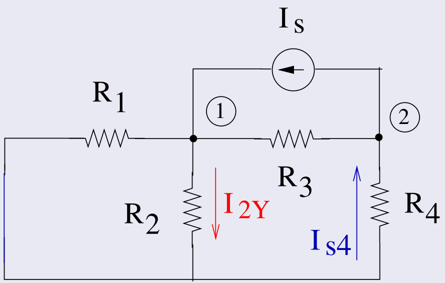
Considering Current I_s only

Compute I_{2X}:

$$R_{12} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Circuit-2: To compute current I_{2Y} in the circuit below

Superposition Theorem: Example



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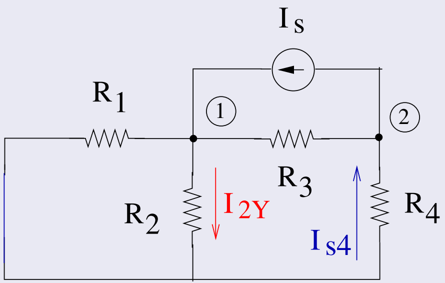

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Superposition Theorem

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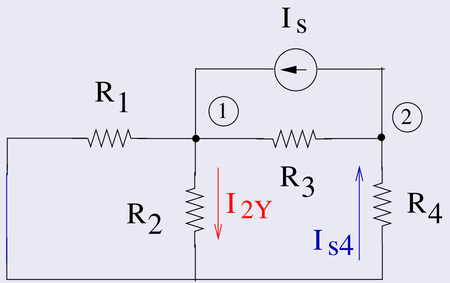

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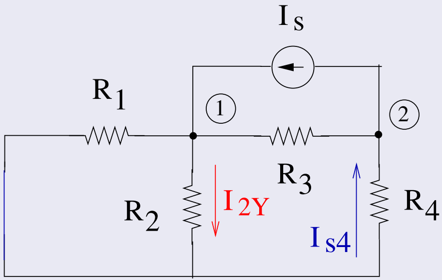
Superposition Theorem: Example



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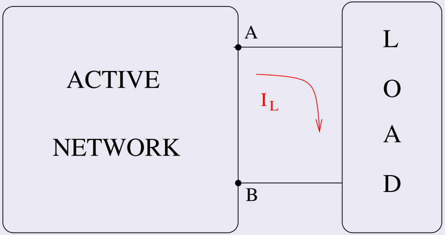
Generalised Active Electrical Network

An active network consists of one or more energy sources. A load branch may be passive circuit branch or active branch. Both Thevenin and Norton Theorem are applied to simplify and evaluate the given network.

Generalised Network



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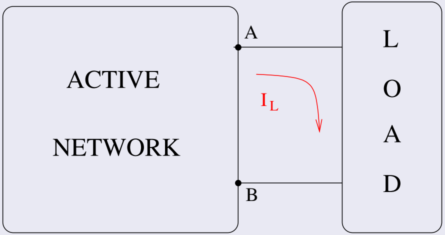
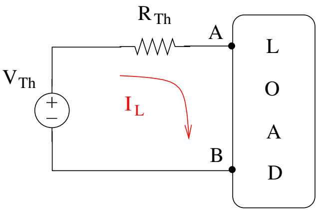
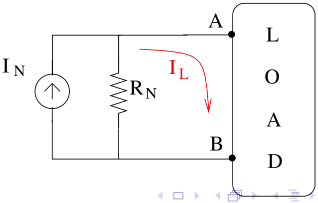


Thevenin's Equivalent Circuit



Norton's Equivalent Circuit



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Thevenin's and Norton's Theorem

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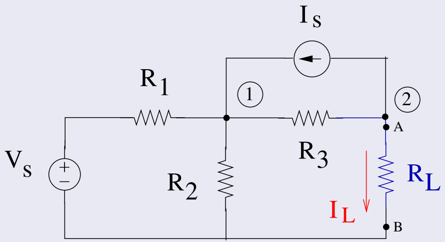
Circuit-1: To compute current I_L in the circuit below

Sample Example



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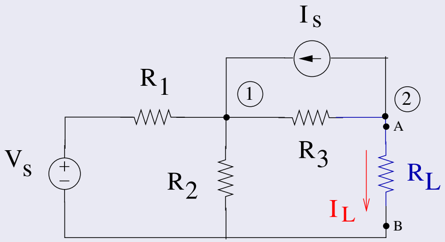
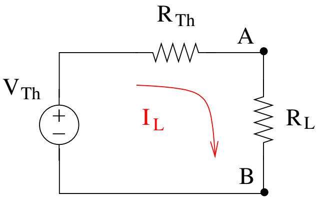
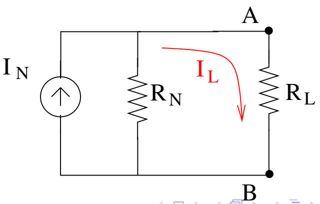


Thevenin's Equivalent Circuit

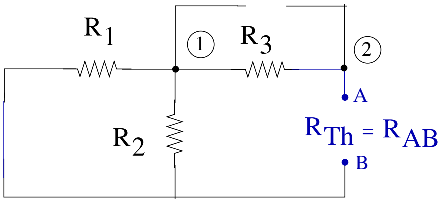


Norton's Equivalent Circuit



Sample Example:1

To find R_{Th}, Thevenin's Resistance



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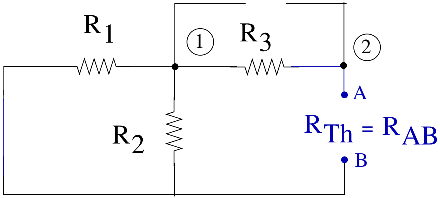

R_L is removed. An active network is reduced to its passive equivalent.

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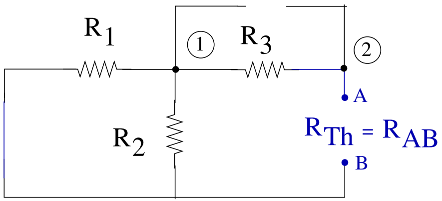

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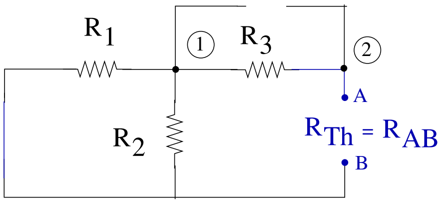

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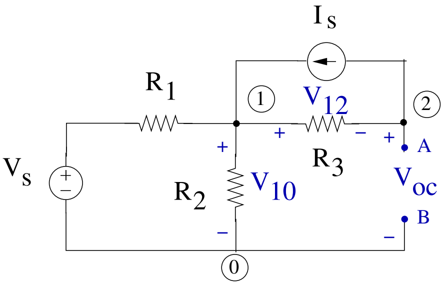

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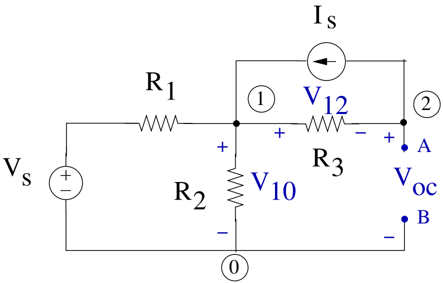

By Kirchoff's Voltage Law

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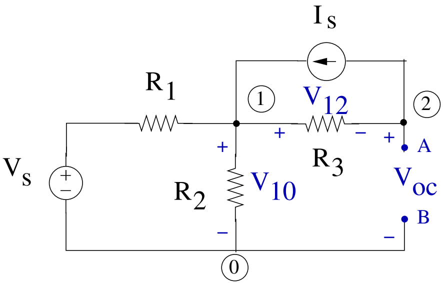

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Finally, the load current I_L by Thevenin's Theorem is given as:

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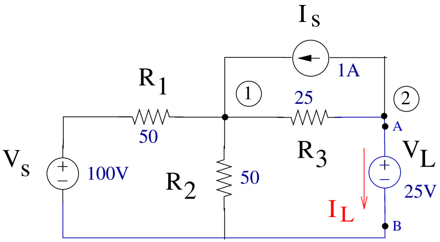
Sample Example:2

Now, let us take an example when the load branch is consisting of an Independent source.



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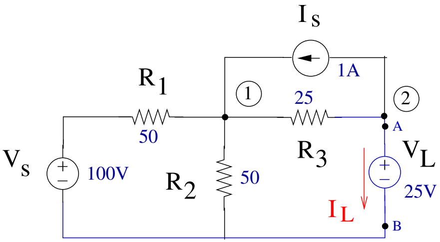

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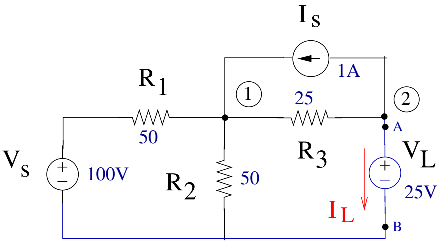

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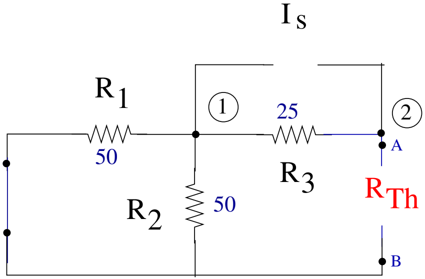

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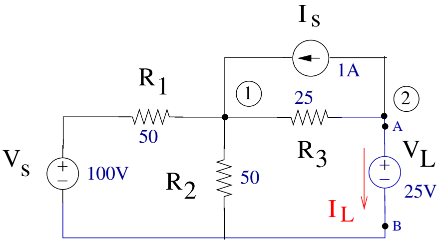

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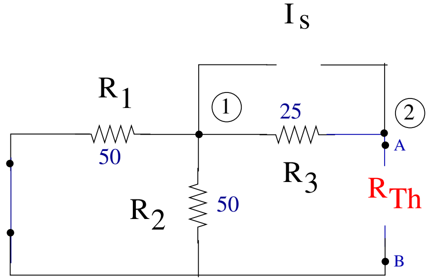

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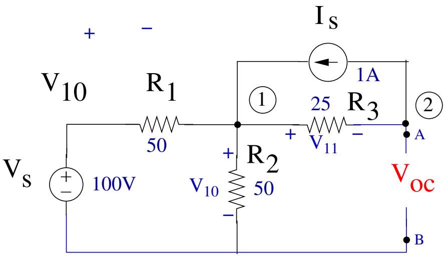

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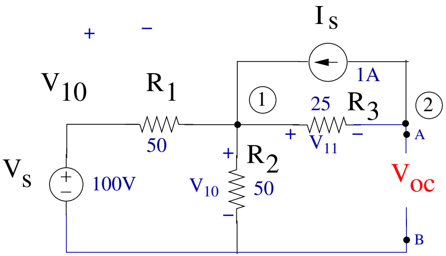

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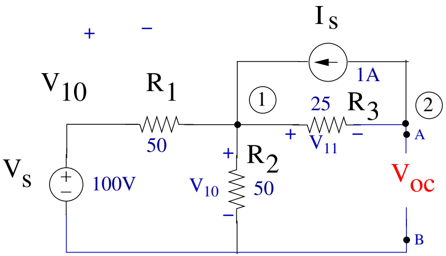

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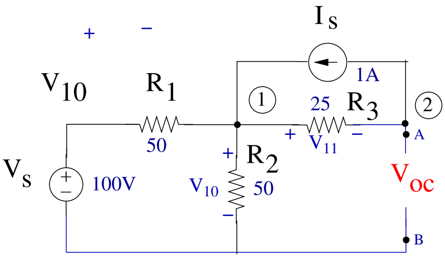

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Solving Thevenin's Equivalent Circuit

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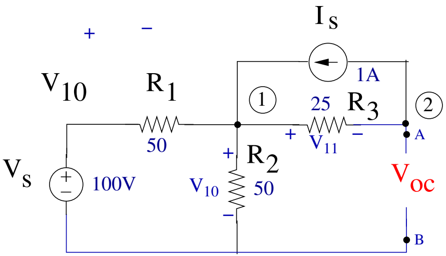

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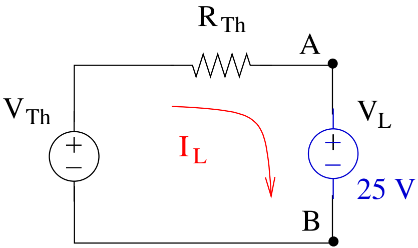

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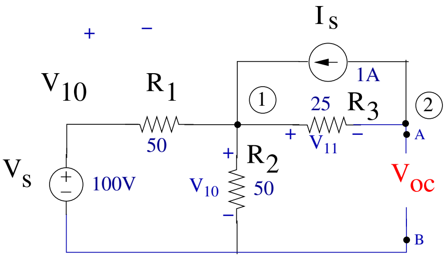

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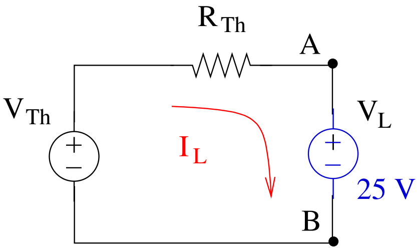
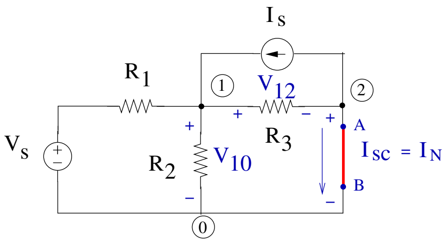


$$I_L = \frac{V_{Th} - V_L}{R_{Th}}$$
$$= \frac{75}{50} = 1.5A$$

Sample Example-1

To find I_N, Norton's Current Source



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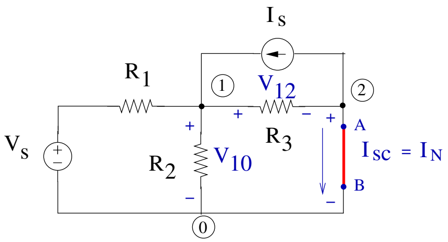

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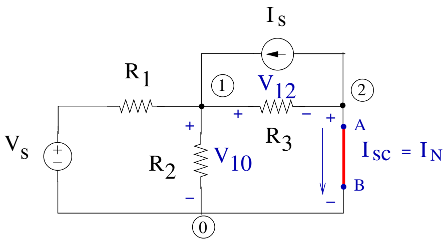

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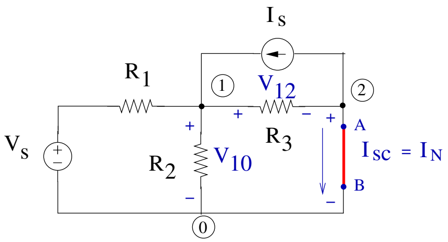

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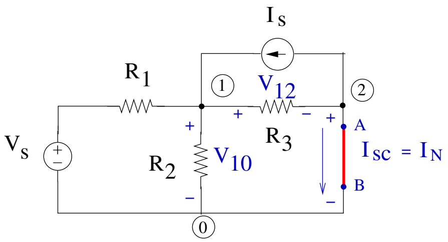

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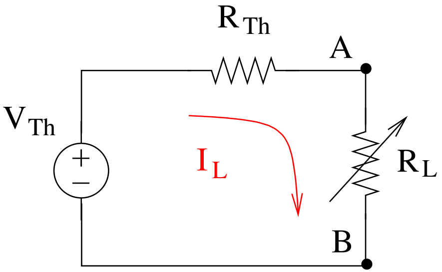
Maximum Power in a load resistor



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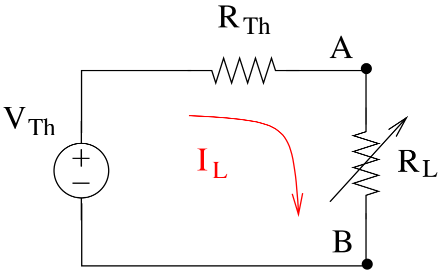

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Maximum Power Transfer Theorem

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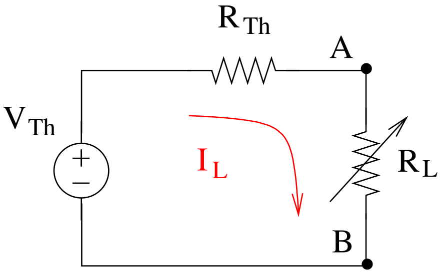

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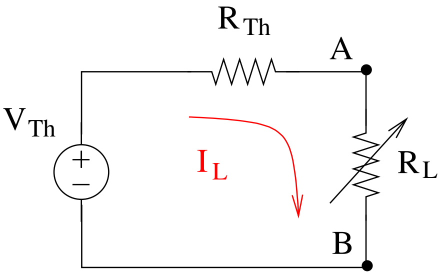

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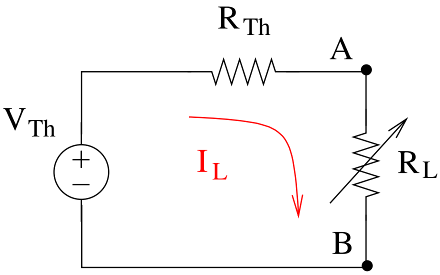

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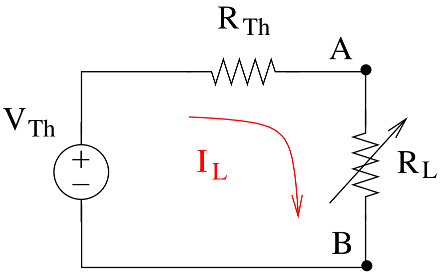

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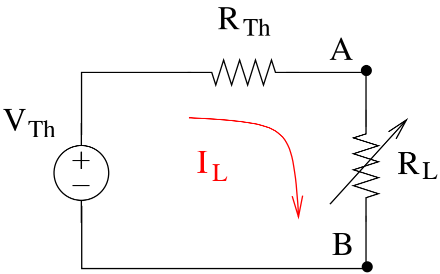
The leads to the Condition for Maximum Power Transfer

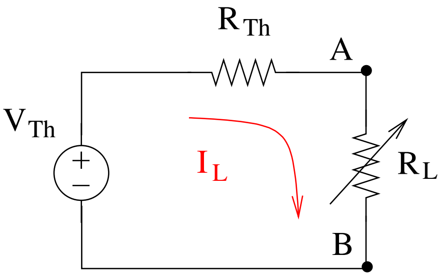
$$R_L = R_{Th}$$

Maximum Power in a load resistor by Theven's Theorem



Let $R_{Th} = 100$, $V_Th = 12$V, R_L is varying from 0 to 300. The power consumed in R_L is plotted against the load Resistor.

Maximum Power in a load resistor by Theven's Theorem



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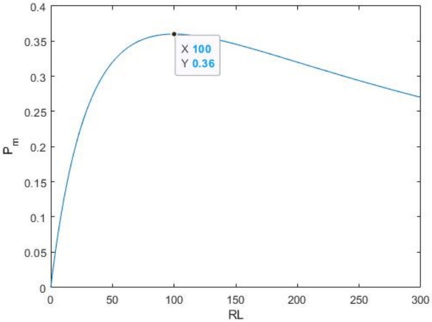
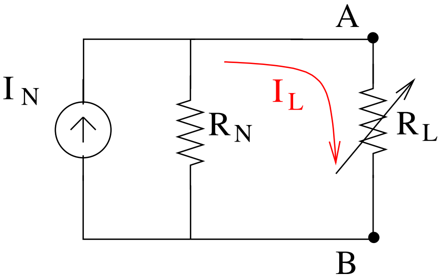


This clearely verifies the condition of maximum power transfer.

Maximum Power in a load resistor by Norton's Theorem



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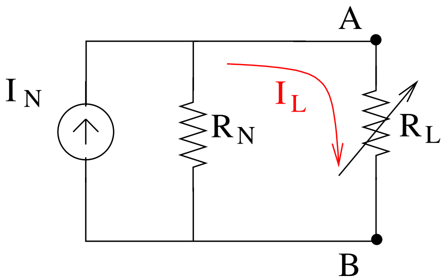

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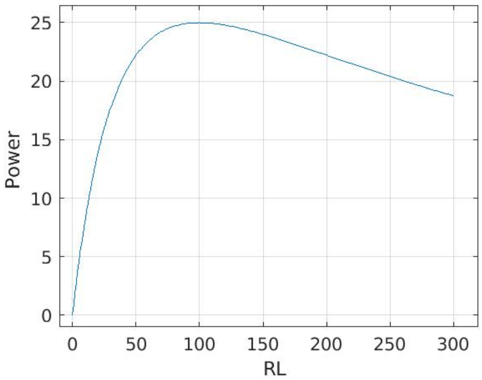

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6. Sometimes we may use conditions at $t = \infty$; these are called final conditions. Final conditions are normally described as the values of the state variable after long time from the instance of switching and therefore describes the new network equilibrium condition.

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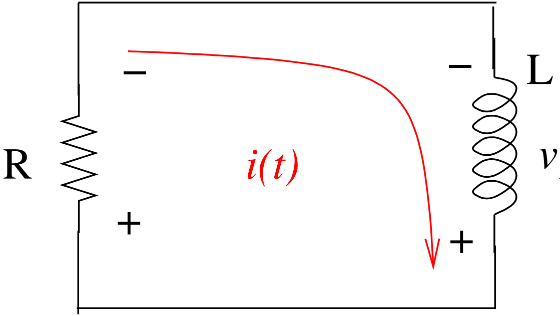
4. Initial conditions in an electric circuit depend on the state of the network prior to $t = 0^+$, and the network structure at $t = 0^+$, after switching.

The **source-free** response is called as natural response.
Consider a simple R-L circuit as shown below. The network has no excitation, but assumed that there is some initial current I_0 present in the network prior to t=0 where the analysis starts, as inductor is an energy storing device,



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

Natural Response in R-L Circuit

By applying Kirchhoff's Voltage Law (KVL),

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Natural Response in R-L Circuit

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$$R \cdot i(t) + L \cdot \frac{di(t)}{dt} = 0$$

$$\frac{di}{dt} + \frac{R}{L} \cdot i(t) = 0 \qquad (15)$$

This equation is in the form of homogeneous linear differential equation with constant co-efficients. Let us assume that the solution is obtained in general form:

By applying Kirchhoff's Voltage Law (KVL),

$$R \cdot i(t) + L \cdot \frac{di(t)}{dt} = 0$$

$$\frac{di}{dt} + \frac{R}{L} \cdot i(t) = 0 \tag{15}$$

This equation is in the form of homogeneous linear differential equation with constant co-efficients. Let us assume that the solution is obtained in general form:

$$i(t) = A \cdot e^{\alpha t} \tag{16}$$

Natural Response in R-L Circuit

By applying Kirchhoff's Voltage Law (KVL),

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This equation is in the form of homogeneous linear differential equation with constant co-efficients. Let us assume that the solution is obtained in general form:

$$i(t) = A \cdot e^{\alpha t} \qquad (16)$$

At $t = 0, i(t) = I_0$, substituting in equn:(16)

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$$i(0) = I_0 = A$$

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Which will make:

$$i(t) = I_0 \cdot e^{\alpha t} \qquad (17)$$

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$$(\alpha + \frac{R}{L}) \cdot (I_0 \cdot e^{\alpha t}) = 0$$

$$\alpha = \frac{-R}{L}$$

$$i(t) = I_0 \cdot e^{\frac{-R}{L} \cdot t}$$

Time Constant of R-L Circuit

$$i(t) = I_0 \cdot e^{\frac{-R}{L} \cdot t}$$

$$i(t) = I_0 \cdot e^{\frac{-t}{\tau}}$$

Time Constant of R-L Circuit

$$
\begin{aligned}
i(t) &= I_0 \cdot e^{\frac{-R}{L} \cdot t} \\
i(t) &= I_0 \cdot e^{\frac{-t}{\tau}}
\end{aligned}
$$

At $t = \tau$

$$
\begin{aligned}
i(\tau) &= I_0 \cdot e^{\frac{-\tau}{\tau}} \\
&= I_0 \cdot 0.368
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Let $I_0 = 1$ A, R=10 Ω, L=79.57 μ
Then let us define $\tau = \frac{L}{R}$, Therefore, here, $\tau = 7.957\mu$ sec. The symbol τ is called as **Time-Constant** of R-L Circuit. Following is the plot for i(t) at above parameters.

Time Constant of R-L Circuit

$$i(t) = I_0 \cdot e^{\frac{-R}{L} \cdot t}$$
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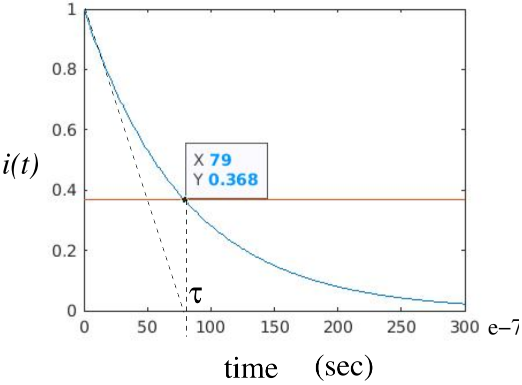
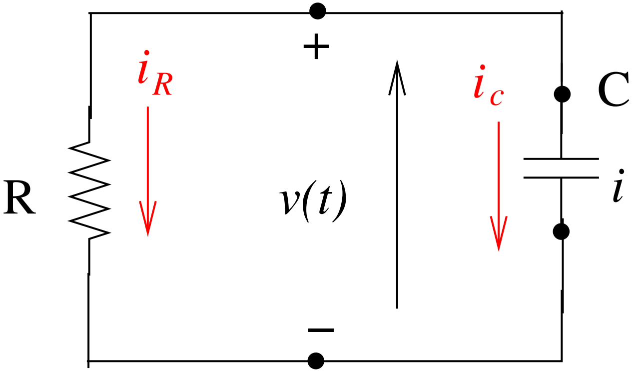
Draw a tangent to $i(t)$ curve at t=0, the line cuts the time-axis at $t = \tau$.



Consider a simple R-C circuit as shown below. The network has no excitation, but assume that there is some initial voltage V_0 present across the capacitor prior to t=0, where the analysis starts, as the capacitor is an energy storing device.



$$i_c = C\frac{dv}{dt}$$

By applying Kirchhoff's Current Law (KCL),

Natural Response in R-C Circuit

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$$\frac{v(t)}{R} + C \cdot \frac{dv(t)}{dt} = 0$$

Where, v(t) is an instantaneous voltage across the capacitor.

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$$\beta = \frac{-1}{R \cdot C}$$

$$v(t) = V_0 \cdot e^{\frac{-t}{R \cdot C}}$$

Time Constant of R-C Circuit

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\begin{aligned}
v(t) &= V_0 \cdot e^{\frac{-t}{R \cdot C}} \\
v(t) &= I_0 \cdot e^{\frac{-t}{\tau}}
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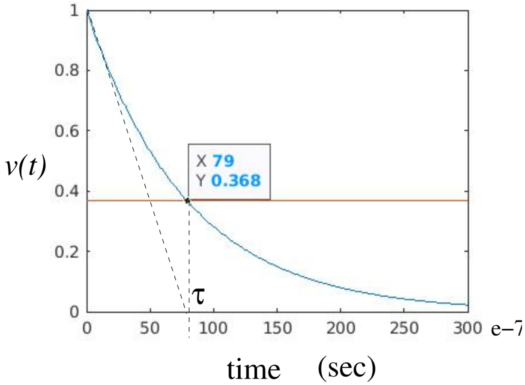

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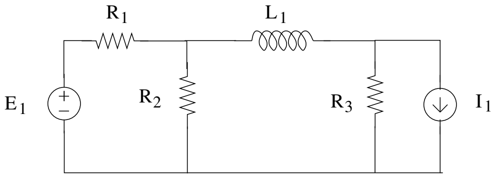

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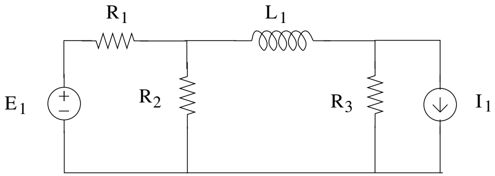

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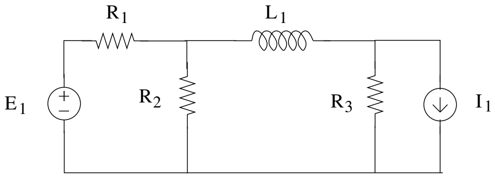

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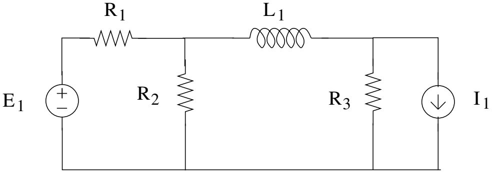

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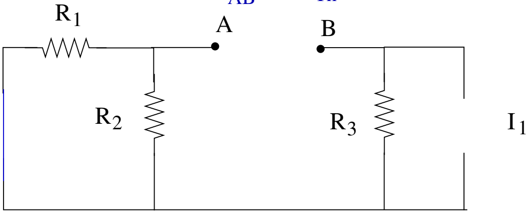
Passive equivalent circuit to find Thevenin's resistance

$R_{AB} = R_{Th}$



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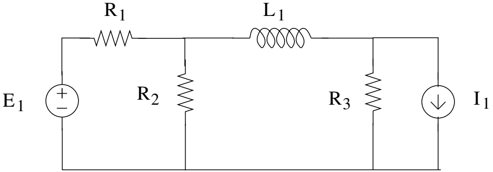

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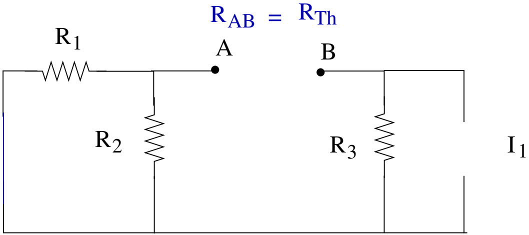

$$R_{Th} = R_{AB} = R_3 + \frac{R_1 \cdot R_2}{R_1 + R_2}$$

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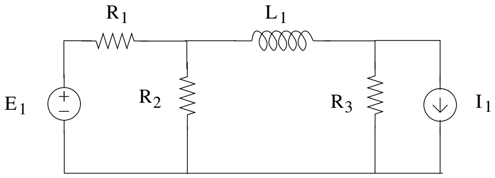

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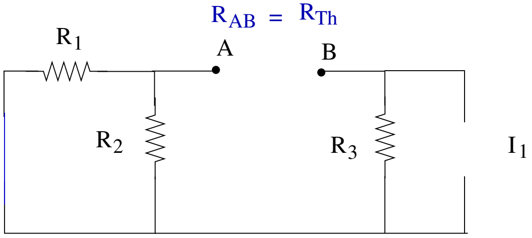
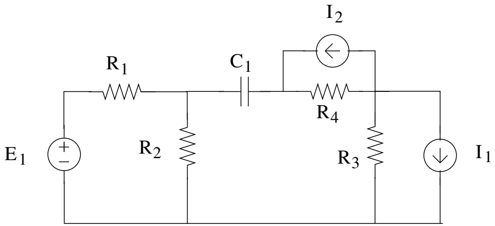


$$R_{Th} = R_{AB} = R_3 + \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Therefore time-constant of the given circuit is given as: $\tau = \frac{L_1}{R_{Th}}$.

Example-2 Find the time constant of the circuit shown below.



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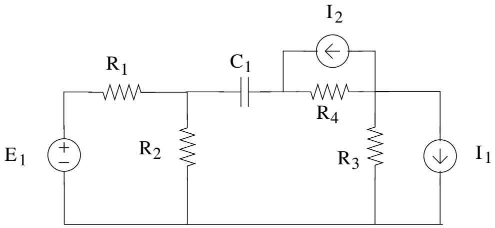

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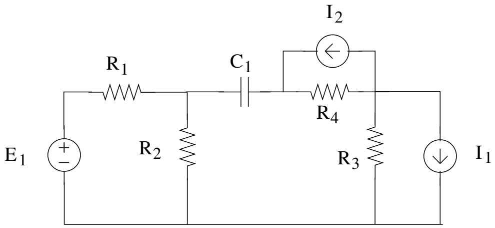

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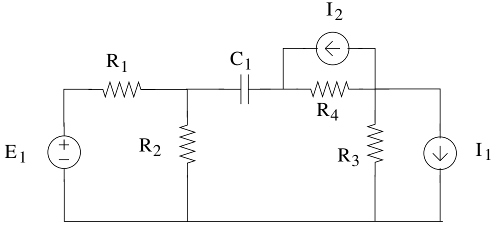

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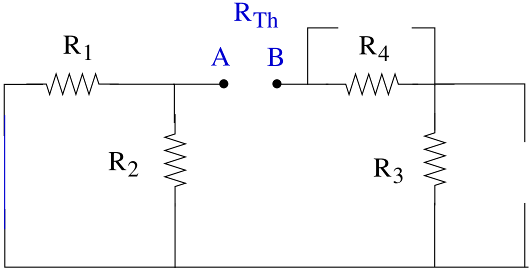

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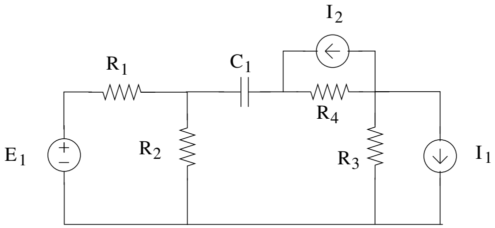

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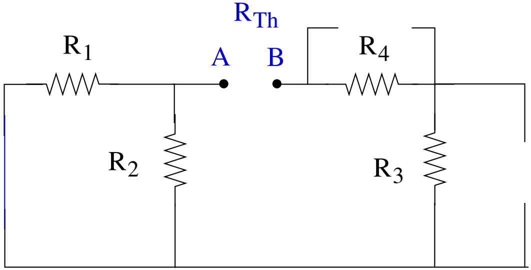

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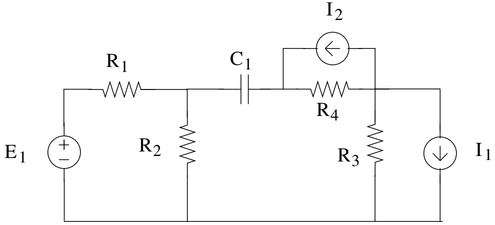

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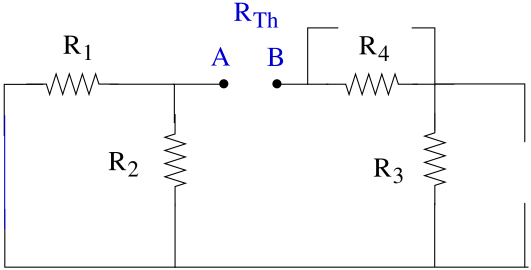

$$R_{Th} = R_{AB} = R_4 + R_3 + \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Therefore time-constant of the given circuit is given as: $\tau = R_{Th} \cdot C_1$.

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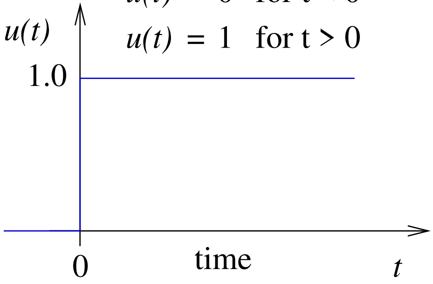
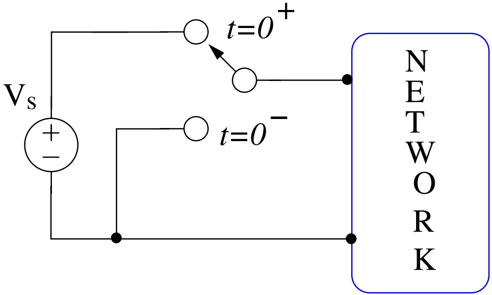
$$u(t) = 1 \quad \text{for } t > 0$$





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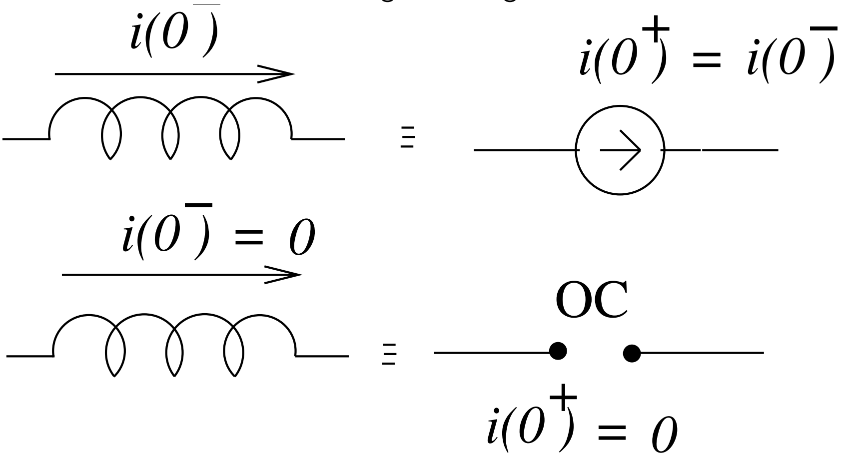

Transient Behavoir of a Capacitor

A Capacitor is an energy storing device. Capacitor Voltage does not change its state during switching.

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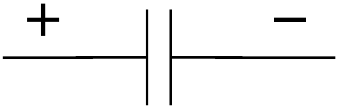
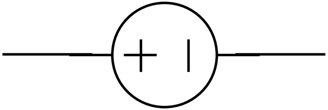
$v(0^-)$

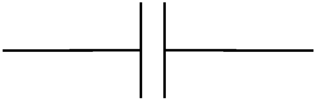


$\equiv$

$v(0^+) = v(0^-)$



$v(0^-) = 0$



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SC

Steady state Behavoir of an Inductor and a Capacitor

During steady state (SS), an inductor follows the following equation:

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During steady state (SS), a Capacitor follows the following equation:

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During SS, under DC excitation, the change in capacitor voltage with respect to time is zero. Therefore, during SS it acts as an open circuit.

Analysis of Step Response in R-L Circuit

Let us analyse the time domain response of R-L Circuit described in following figure:

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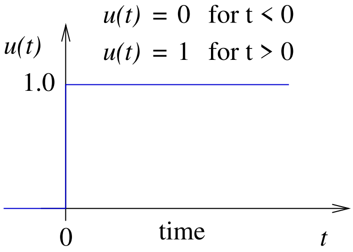
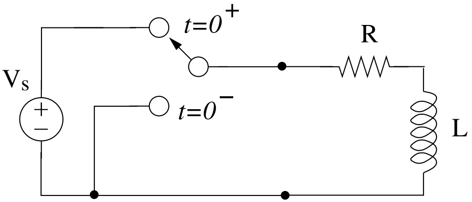
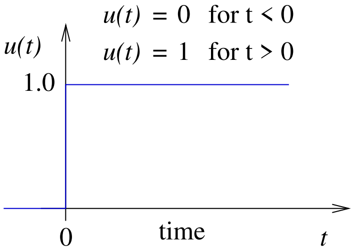
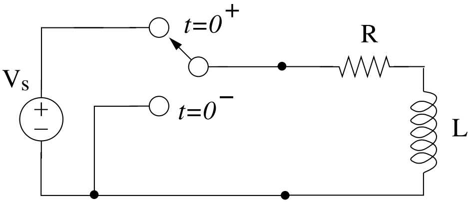




Analysis of Step Response in R-L Circuit

Let us analyse the time domain response of R-L Circuit described in following figure:





The assumption is the initial inductor current prior to t=0 is zero. Therefore.

$$i(0)^{-} = i(0)^{+} = 0.$$

At t=0 and onwards, the current $i(t)$ can be solved by following diiferential equation obtained by applying KVL:

Analysis of Step Response in R-L Circuit

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2. Apply the initial and steady state condition to get the particular solution.

Analysis of Step Response in R-L Circuit

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The Natual Response

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The solution to homogeneous differential equation with constant coefficientis given as:

$$i_n = A \cdot e^{\frac{-R}{L} \cdot t} = A \cdot e^{\frac{-t}{\tau}}$$

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The Forced Response

Since the forcing function is constant for $t > 0$, the particular solution is assumed be constant as $i_t = I$. Therefore, substituting this in eq:(26),

$$L \cdot \frac{dI}{dt} + R \cdot I \quad = V_s$$

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The Forced Response

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$$L \cdot \frac{dI}{dt} + R \cdot I \quad = V_s$$

Since I is constant, $\frac{dI}{dt} = 0$, $I = \frac{V_s}{R} = I_f$ is called as Particular Solution.

The Complete Response

$$i(t) = i_n + i_f = A \cdot e^{\frac{-t}{\tau}} + \frac{V_s}{R} \qquad (23)$$

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Now, substituting initial condition as $i0^- = i0^+ = 0$

$$i(0) = A + \frac{V_s}{R} = 0$$

The Complete Response

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Now, substituting initial condition as $i0^- = i0^+ = 0$

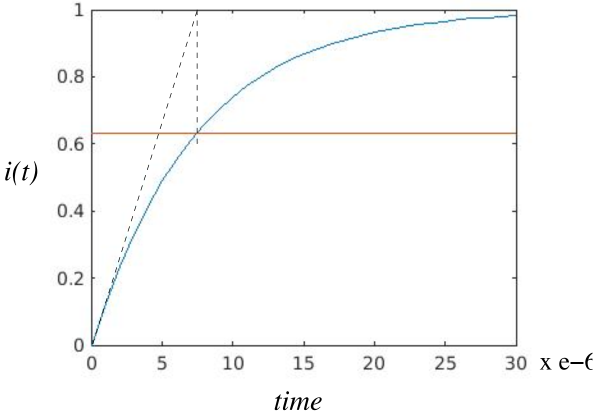
$$i(0) = A + \frac{V_s}{R} = 0$$

Therefore, $A = -\frac{V_s}{R}$, hence, substituting this in eq:(24), we get final solution as:

$$i(t) = \frac{V_s}{R} \cdot \left(1 - e^{\frac{-R}{L} \cdot t}\right)$$

Let $V_s = 1$ V, R=1 Ω, L=79.57μH

$$i(t) = \left(1 - e^{\frac{-1}{79.57\mu}}\right)$$



The Complete Response with non-zero initial condition

$$i(t) = i_n + i_f = A \cdot e^{\frac{-t}{\tau}} + \frac{V_s}{R} \qquad (24)$$

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Analysis of Step Response in R-L Circuit

The Complete Response with non-zero initial condition

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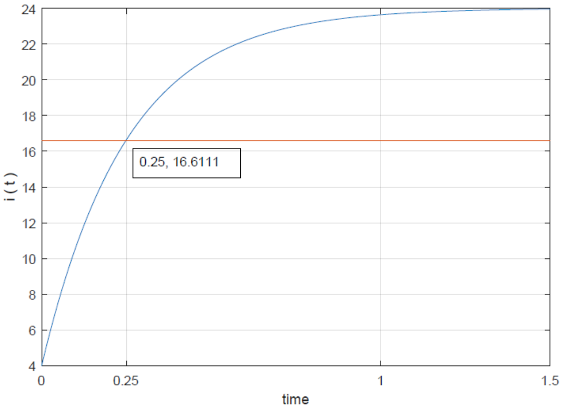
Therefore, $A = -\frac{V_s}{R} + I_0$, hence, substituting this in eq:(24), we get final solution as:

$$i(t) = \frac{V_s}{R} \cdot \left(1 - e^{\frac{-R}{L} \cdot t}\right) + I_0 \cdot e^{\frac{-R}{L} \cdot t}$$

Let $V_s = 40$V, $I_0 = 4$A, R=2 Ω, L=0.5H

$$i(t) = 4\, e^{\frac{-t}{0.25}} + 20\left(1 - e^{\frac{-t}{0.25}}\right) \quad .$$

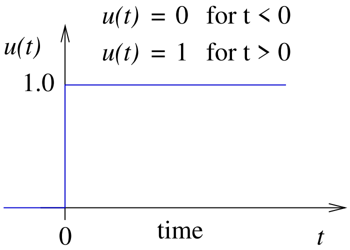


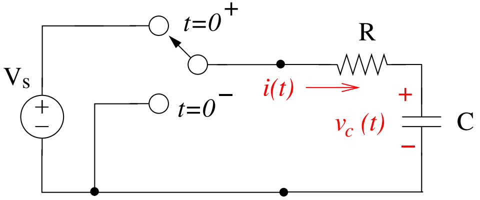
Transient Response of R-L Circuit

Let us analyse the time domain response of R-C Circuit described in following figure:

Analysis of Step Response in R-C Circuit

Let us analyse the time domain response of R-C Circuit described in following figure:





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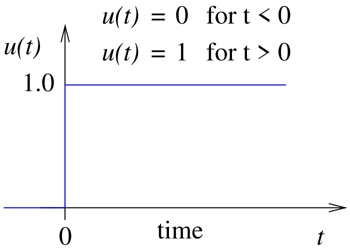

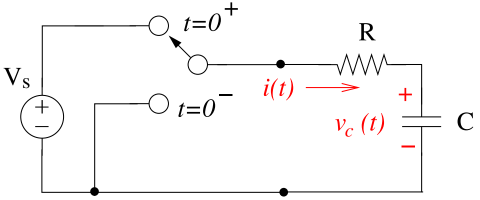

The assumption is the initial capacitor voltage prior to t=0 is zero. Therefore.

$$v_c(0)^- = v_c(0)^+ = 0.$$

Analysis of Step Response in R-C Circuit

At t=0 and onwards, $i = C \cdot \frac{dv_c}{dt}$. The voltage $v_c(t)$ can be solved by following diiferential equation obtained by applying KVL:

Analysis of Step Response in R-C Circuit

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$$R \cdot C \cdot \frac{dv_c}{dt} + v_c = V_s \quad (26)$$

Analysis of Step Response in R-C Circuit

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This is a non-homogeneous differential equation with constant coefficients.

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Analysis of Step Response in R-C Circuit

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Analysis of Step Response in R-C Circuit

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The Natual Response

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The solution to homogeneous differential equation with constant coefficientis is given as:

$$v_n = A \cdot e^{\frac{-t}{R \cdot C}} = A \cdot e^{\frac{-t}{\tau}}$$

The Natual Response

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The Forced Response

Since the forcing function is constant for $t > 0$, the particular solution is assumed be constant as $v_c t = V_c$. Therefore, substituting this in eq:(26),

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The Natual Response

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Since V_c is constant, $\frac{dV_c}{dt} = 0$, $V_c = V_s = v_f$ is called as Particular Solution.

The Complete Response with zero Initial Condition

$$v_c(t) = v_n + v_f = A \cdot e^{\frac{-t}{\tau}} + V_s \quad (28)$$

The Complete Response with zero Initial Condition

$$v_c(t) = v_n + v_f = A \cdot e^{\frac{-t}{\tau}} + V_s \quad (28)$$

Now, substituting initial condition as $v_c 0^- = v_c 0^+ = 0$

$$v_c(0) = A + V_s = 0$$

The Complete Response with zero Initial Condition

$$v_c(t) = v_n + v_f = A \cdot e^{\frac{-t}{\tau}} + V_s \quad (28)$$

Now, substituting initial condition as $v_c 0^- = v_c 0^+ = 0$

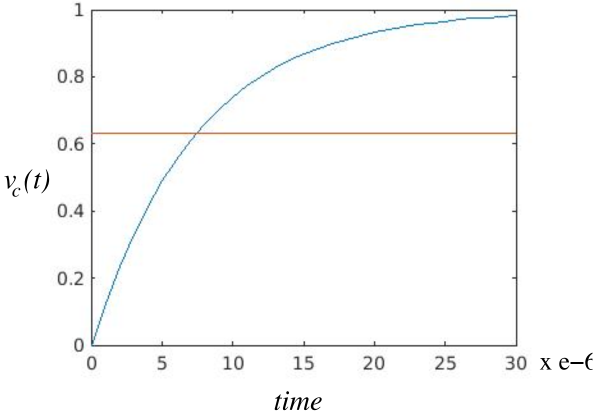
$$v_c(0) = A + V_s = 0$$

Therefore, $A = -V_s$, hence, substituting this in eq:(29), we get final solution as:

$$v_c(t) = V_s \cdot \left(1 - e^{\frac{-t}{R \cdot C}}\right)$$

Let $V_s = 1$ V, R=1 Ω, C=79.57μH

$$v_c(t) = \left(1 - e^{\frac{-1}{79.57\mu}}\right)$$



The Complete Response with Non-zero Initial Condition

$$v_c(t) = v_n + v_f = A \cdot e^{\frac{-t}{\tau}} + V_s \quad (29)$$

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$$v_c(0) = A + V_s = V_0$$

The Complete Response with Non-zero Initial Condition

$$v_c(t) = v_n + v_f = A \cdot e^{\frac{-t}{\tau}} + V_s \quad (29)$$

Now, substituting initial condition as $v_c 0^- = v_c 0^+ = V_0$

$$v_c(0) = A + V_s = V_0$$

Therefore, $A = V_0 - V_s$, hence, substituting this in eq:(29), we get final solution as:

$$v_c(t) = V_s \cdot \left(1 - e^{\frac{-t}{R \cdot C}}\right) + V_0 \cdot e^{\frac{-t}{R \cdot C}}$$

Let $V_s = 100\text{V}, V_0 = 12\text{V}$ R=10 Ω, C=100μH

$$v_c(t) = 100\left(1 - e^{\frac{-1}{1e-3}}\right) + 12\ e^{\frac{-1}{1e-3}}$$