EECE 250
Network Analysis I

Course syllabus

Prerequisite: Physics III
Corequisite: Differential Equations
Prerequisite for: Network Analysis II and ----

Textbook - Drill Problems

Problem session - homework problems

Course grade

2 Hour exams: 25% each
1 Final exam: 30%
Homework: 10%
Quizzes: 10%
Chapter 2 - Definitions & Units

**International System of Units**
("Metric" or "SI" or "MKS")

Arbitrarily defined units:

Length: meter \((m)\)
Mass: kilogram \((kg)\)
Time: second \((s)\)

Derived units:

Force: newton \((N)\)
Work and energy: joule \((J)\)
Power: watt \((W)\)

Consistency of unit system

SI (International system of units) was adopted in 1960.

Seven basic units:
- meter
- kilogram
- second

Units for other quantities are derived from these seven basic units.
Calorie \rightarrow \text{(1 calorie)} = 4.187 \text{ J}.

- 1 \text{ joule} = 1 \text{ kg m}^2 \text{ s}^{-2}

- \text{kilowatt-hour (kWh)}

\begin{align*}
1 \text{ h} &= 3,600 \text{s} \\
1 \text{ kWh} &= 3.6 \times 10^6 \text{ J}
\end{align*}

- The fundamental unit of power is the watt (W)

\begin{align*}
1 \text{ W} &= 1 \text{ J/s}
\end{align*}

SI uses the decimal system to relate larger and smaller units to the basic unit.
Other arbitrarily defined units:

Electric current: ampere (A)
Temperature: kelvin (K)
Luminous intensity: candela (cd)

Scientific and engineering notation:

\[ 0.0247 \, m = 2.47 \times 10^{-2} \, m = 24.7 \times 10^{-3} \, m \]

Prefixes:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Factor</th>
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<tbody>
<tr>
<td>femto</td>
<td>f</td>
<td>(10^{-15})</td>
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<tr>
<td>pico</td>
<td>p</td>
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<td>nano</td>
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<td>mega</td>
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<td>tera</td>
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<td>(10^{12})</td>
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\[ 0.0247 \, m = 24.7 \, mm \]
Nanotechnology

1 Å = 10⁻¹⁰ m

nm = 10 Å = 10⁻⁹ m

Expressing numbers in "engineering units"

In engineering notation, a quantity is represented by a number between 1 and 999 and an appropriate metric unit using a power divisible by 3.

Example

0.048 W → 48 mW

Instead of

4.8 W

or

4.8 × 10⁻² W

or

48,000 μW

Practice

2.1 A krypton fluoride (KrF) laser emits light at a wavelength of 248 nm.

This is the same as

(a) 0.248 mm
(b) 248 μm
(c) 0.248 μm
(d) 24,800 Å

Do practice problems 2.2 & 2.3 on page 11
Convert the following to engineering notation:

- **a** 1.2 × 10^-5
- **b** 750 mJ
- **c** 1130.52
- **d** 3,500,000,000 bits
- **e** 0.0065 μm
- **f** 13,560,000 Hz
- **g** 0.039 mA
- **h** 49,000 Ω
- **i** 1.173 × 10^-5 mA

For **b**:
- 750 mJ = 750 × 10^-3 J = 0.75 J
- 750 mJ = (750 / 10^9) MJ

For **d**:
- 3,500,000,000 bits = 3.5 Gb

For **e**:
- 0.0065 μm = 6.5 × 10^-9 m
- 0.0065 μm = 6.5 nm

For **f**:
- 13,560,000 Hz = 13.56 MHz

For **g**:
- 0.039 mA = 39 µA = 39 pA

For **h**:
- 49 kΩ

For **i**:
- 1.173 × 10^-5 mA = 11.73 pA
2.2 Electric charge & Coulomb's Law

\[ F_2 \propto \frac{Q_1 Q_2}{R_{12}^2} \]

\[ F_2 = \frac{Q_1 Q_2}{4 \pi \varepsilon_0 R_{12}^2} \quad \text{with } Q_1 \text{ in coulomb (C)} \]

\[ \varepsilon_0 = \frac{1}{36 \pi} \times 10^{-9} \text{ F/m} \]

In SI system, the fundamental unit of charge is the Coulomb.

For an electron:

\[ q = -1.602 \times 10^{-19} \text{ C} \]

Comparisons to mass:

\[ F_2 = G \frac{M_1 M_2}{R_{12}^3} \]

\[ \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \]

*Permittivity of free space.

\[ \varepsilon_0 \] *Dilectric constant.
Electric current (P12)

Charge in motion represents a current: $i(t)$

\[ i = \text{time rate of flow of (positive) charge through a surface (C/s or ampere (A))} \]

\[ i = \frac{Q}{t} \quad \text{or} \quad \frac{\Delta Q}{\Delta t} \quad \text{or} \quad \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dq}{dt} \]

1A corresponds to 1 Coulomb of charge passing through an arbitrary chosen cross section in one second

Examples:

- Conduction electrons in copper wire
- Convection electrons in CRT
- Electrons and holes in semiconductor
From

\[ i = \frac{dq}{dt} \]

\[ dq = idt \]

\[ \int_{t_0}^{t} dq = \int_{t_0}^{t} idt \]

\[ q(t) = \int_{t_0}^{t} idt + q(t_0) \]
Electric potential difference ("voltage")

\[ \Delta U_{AB} = \text{"potential of A with respect to B"} \]
\[ = \text{"potential drop from A to B"} \]
\[ = \text{"potential rise from B to A"} \]

= work per unit charge required to move a test charge from B to A (J/C or volts) (V)

\[ 1 \text{ volt} = 1 \text{ J/C} \]

Alternate representations of a voltage:

\[ \Delta U_i = \Delta U_{AB} = -\Delta U_{BA} \]

+ - signs for \( \Delta U_i \), and identification of points A and B for \( \Delta U_{AB} \) must be shown!
A convention is needed to distinguish between energy supplied to an element and energy supplied by an element.

**Passive Sign Convention**

If a positive current is entering a terminal of the element and an external source must expand energy to establish this current, then terminal A is positive with respect to terminal B.

Alternatively, we may say that terminal B is negative with respect to terminal A.
1-6 Electric power

![Diagram of electric power](https://via.placeholder.com/150)

(Choice of symbols \( v \) and \( i \) corresponds to "passive sign convention")

\[
p = \text{power delivered to the network } N
\]

\[
= \frac{dw}{dt} = \frac{dw}{dq} \frac{dq}{dt}
\]

\[
p = v_i i \text{ (W)}
\]

The symbol \( p \) does not have intrinsic meaning; it must be unambiguously defined for every particular example. 

\[\begin{align*}
P_1 & = \text{power delivered to } N_1 \\
& = -v_i i_1
\end{align*}\]

\[\begin{align*}
P_2 & = \text{power delivered from } N_2 \\
& = -\text{power absorbed by } N_2 \\
& = v_2 i_2
\end{align*}\]

Power delivered to \( N \) = - power delivered by \( N \)
Current arrow is directed into the element at the plus marked terminal.

The power absorbed by the element is \[ P = VI. \]

Alternatively, we can say that the element "generates," or "supplies," a power \[ -VI. \]

Negative absorbed power = positive supplied power

If one joule \((1 J)\) of energy is expended in transferring one Coulomb of charge through the device in one second, then the rate of energy transfer is one Watt.

Example: Fig 2.13 Computer power absorbed by the circuit elements shown below.

\[
\begin{align*}
P_{abs} &= 2V \times 3A \\
&= 6 W
\end{align*}
\]

are equivalent

\[
\begin{align*}
P_{abs} &= (-3A) \times (-2V) \\
&= 6 W
\end{align*}
\]

\[
\begin{align*}
P_{abs} &= (4V)(-5A) \\
&= -20 W
\end{align*}
\]

Negative absorbed power. The element is actually supplying +20W.

The element is a source of energy.

Do practice problems 2.6/8, 4/2.8.
2.6 Find power absorbed by circuit element below:

$$P_{abs} = 220 \times 4.6 \times 10^{-3} W = 1.012 W$$

2.7 Power delivered by circuit element below:

$$\text{power abs.} = (-3.8V)(1.75A)$$

$$\text{power del.} = -\text{power abs. by}$$

$$= 6.65 W$$

2.8 Find power being delivered to circuit element below at $t=5ms$:

$$P = 8e^{-100t}$$

$$P = 8e^{-100(5)} \times 3.2A = -15.53 W$$

(current entering + terminal)
\[ p = \frac{dw}{dt} \]

\[ dw = \int_{t_0}^{t} pdt \]

\[ \int_{t_0}^{t} dw = \int_{t_0}^{t} pdt \]

\[ \omega(t) = \int_{t_0}^{t} pdt + \omega(t_0) \]

\[ = \int_{t_0}^{t} v \cdot idt + \omega(t_0) \]

\[ \Delta \omega = \omega(t) - \omega(t_0) = \int_{t_0}^{t} v \cdot idt \]

\[ = \text{energy delivered to } N \]

\[ \text{during the interval from } t = t_0 \text{ until } t = t. \]
Example

\[ v(t) \]

-5V

0

2 4 6 8

\( t, \text{ ms} \)

\[ i(t) \]

10mA

0

2 4 6 8

\( t, \text{ ms} \)

\[ P(t) = v(t) \cdot i(t) \]

50mW

-50mW

0

2 4 6 8

\( t, \text{ ms} \)

\[ w(t) = \int_0^t P(t) \, dt = \int_0^t 25t \, dt = 25 \left( \frac{t^2}{2} \right) \bigg|_0^t = \frac{25t^2}{2} \]

50 \mu J

12.5 \frac{t^2}{2}

0

2 4 6 8

\( t, \text{ ms} \)

What is equation of this curve in interval \([2 \text{ ms} - 6 \text{ ms}]\)?
The circuit diagram shows a 12 V source with a current $i(t)$ flowing through a 2 A periodic signal. The signal has a period $T$ and is represented over time $t$ in milliseconds.

The equation of line $p(t)$ is given by:

$$i(t) - i(0) = \frac{\left[ (t + \omega_0) - i(0) \right]}{\omega_0} \cdot \left( t - 0 \right)$$

$$i(t) = -0.5 + \frac{9.5}{2.5} \cdot t = -0.5 + 1.25 \omega_0^2 t$$

The average power delivered to the voltage source per cycle is calculated as:

$$P_{av} = \frac{1}{T} \left[ \int_0^3 P(t) \, dt \right] = \frac{1}{3 \times 10^{-3}} \left[ \int_0^{3 \times 10^{-3}} (-6 + 15 \times 10^3 t) \, dt + (6) \Delta t \right]$$

$$P_{av} = \frac{1}{3 \times 10^{-3}} \left[ -6 \times 2 \times 10^{-3} + 15 \times 10^3 \left( \frac{t^2}{2} \right)_{0}^{3 \times 10^{-3}} - 6 \times 1 \times 10^{-3} \right]$$

$$P_{av} = \frac{1}{3 \times 10^{-3}} \left[ -12 \times 10^{-3} + 30 \times 10^{-3} - 6 \times 10^{-3} \right] = 4 \text{ W}$$
Problem 2.9 (page 20)

Find the power absorbed by each element in the circuit below:

\[ P = V \cdot I \]

- If >0 absorbed by
- If <0 delivered by

\[ P = 20V \cdot 5A = 100W \]
\[ P = 8V \cdot (-3A) = -24W \]

- Current source delivers 56W
- Circuit element absorbs 16W

\[ (8V)(2A) = 16W \]
\[ (20V)(4A) = 80W \]

- Element absorbs \(-8V \cdot 5A = -40W\)

\[ \text{sum of power absorbed in circuit is} \]
\[ -56W + 16W - 60W + 160W - 60W = 0 \]

\[ \text{as it should} \]
Voltage and Current Sources

By definition, a simple circuit element is the mathematical model of a two-terminal electrical device. It is completely characterized by its current-voltage characteristics. It cannot be subdivided into other two-terminal devices.

Independent Voltage Sources

![Symbol](image)

An independent voltage source is characterized by a terminal voltage which is completely independent of the current flowing through it. It is an ideal source.

\[ V \rightarrow \text{passive sign convention is satisfied.} \]
\[ \text{The source absorbs the power} \ V I. \]

\[ I \rightarrow \text{power is delivered by the source.} \]

![Diagrams](image)

DC voltage source symbol  Battery symbol  AC voltage source symbol
Independent Current Sources (p. 19)

\[ i_s = I \]

- The current through the element is completely independent of the voltage across it.

- The voltage across \( i_s \) is NOT zero necessarily. It can have any voltage across it.

Dependent Sources (p. 19)

\( K_{r_1} e^a \)  
\( K_{r_2} e^b \)  
\( K_{r_3} e^c \)  
\( K_{r_4} e^d \)

(a) Current controlled current source.
(b) Voltage controlled voltage source.
(c) Voltage controlled current source.
(d) Current controlled voltage source.

Such sources appear in the equivalent circuit models of many electronic devices (see transistors later).

In Figures (a) and (c), \( K \) is dimensionless.

In Fig. (b), \( g \) is a conductance.

In Fig. (d), \( r \) is a resistance.
Examples: dependent or controlled sources

Voltage controlled voltage source

Current controlled current source

Current element
1-7 Networks and network components ("elements")

Electric network: an interconnected set of (two-terminal) components

Components can be passive or active

**Passive component**: average power delivered to the component must be nonnegative

- Resistor
- Inductor
- Capacitor
- Transformer

**Active component** ("source"): average power delivered to the component can be negative

\[ i = 2.5 \text{ mA} \]

\[ v = 10 \sin 100t \text{ V} \]

\[ v = 12 \text{ V} \]

Independent sources

Do practice problems!
A point at which two or more elements have a common connection is called a node.

Traversing through a network between 2 nodes, if no node is encountered more than once, then the set of nodes and elements that we have gone through is defined as a **PATH**. If the node at which we started is the same as the node at which we ended, the path is, by definition, a closed path or **LOOP**.

**BRANCH** is a single path in a network, composed of one simple element and the node at each end of that element.

A path is a particular collection of branches.

---

**Ex:**

A network with 5 branches and 3 nodes.

---

How many nodes and branches?
Chapter 2   Network Equations and Simple Networks

2-4 Ohm's "law"

\[ R = \frac{V}{I} \text{ or ohms (Ω)} \]

For any two-terminal device, linear or nonlinear,

\[ v = Ri \]

For a linear resistor, resistance \( R \) is constant— independent of \( v \) and \( i \)

\[ i = \frac{1}{R} v = G v \]

Conductance \( G = \frac{i}{v} \text{ A/V or mhos (Ω)} \) or siemens (S)
Network diagram representation:

\[ v = Ri \]

\[ v = -Ri \]

Power delivered to R:

\[ P = vi \]
\[ = (Ri)i \]
\[ = Ri^2 \]
\[ = \frac{v^2}{R} \left\{ \text{agree} \rightarrow \right\} = \frac{v^2}{R} \]

Example:

\[
\begin{array}{c|c|c}
20\text{mA} & \begin{array}{c}
\text{2} \\
\text{4} \\
\text{6} \\
\text{8}
\end{array} & t, \text{ms} \\
-10\text{mA} & & \\
\end{array}
\]

\[
\begin{array}{c|c|c}
400\text{mW} & \end{array}
\]

\[
\begin{array}{c|c|c}
100\text{mW} & \end{array}
\]

DO PRACTICE PROBLEMS (2.10/2.11/2.12) P.24
**Kirchhoff's laws (PP 39 → 78)**

**Kirchhoff's current law (KCL)**

The (algebraic) sum of currents directed toward a junction (node) is zero.

\[ i_1 - i_2 - i_3 + i_4 + i_5 = 0 \]

OR: \[ -i_1 + i_2 + i_3 - i_4 - i_5 = 0 \]

**KCL is a network application of the principle of conservation of charge.**

**Generalization to supernodes**

![Diagram of supernodes](image)

\[ i_1 + i_2 + i_3 + i_4 + i_5 = 0 \]

\[ i_6 + i_7 + i_8 - i_4 - i_5 = 0 \]
For A and B together:

\[ i_1 + i_2 + i_3 + i_6 + i_7 + i_8 = 0 \]

Generalized KCL: the sum of currents directed toward any set of nodes is zero.

e.g.:

For AB: \[-i_1 - i_3 - i_4 - i_5 = 0\]

For D: \[i_4 + i_5 + i_6 = 0\]

For BC: \[i_1 + i_2 - i_5 - i_6 = 0\]

For ABC: \[i_1, i_2, -i_4 - i_5 - i_6 = 0\]

Practice problem 3.1 (p.38)
Count the number of branches and modes in the circuit below.

If $i_x = 3\, \text{A}$ and the 18V source delivers 8A of current, what is the value of $R_A$?

**Number of branches:**

- 0 \equiv 2
- 3 \equiv 4

3 modes / 5 branches

**Given**
- $i_x = 3\, \text{A}$
- 18V source delivers 8A.

**Unknown**
- $R_A$

**Supermode**

$$i_A + i_x = 21$$

$R_A = 1\, \Omega$

$$18 = R_A \cdot i_A \quad \text{(i_A = 18A)}$$

$$i_X = 3\, \text{A}$$
Kirchhoff's voltage law (KVL)

The sum of all voltage drops (or rises) around any closed path is zero.

$$v_1 + v_2 - v_3 + v_4 = 0$$

or $$-v_1 - v_2 + v_3 - v_4 = 0$$

or $$-v_{AB} + v_{BC} + v_{CD} + v_{DA} = 0$$

KVL is a network application of the principle of conservation of energy.

For a multi-loop network:
"Windows" or "Mesh or loop that does not contain any other loop within it.

\[ u_4 + u_2 - u_1 = 0 \]
\[ u_5 + u_3 - u_2 = 0 \]
\[ u_6 - u_5 - u_4 = 0 \]

Other loops:

\[ u_4 + u_5 + u_3 - u_1 = 0 \]
\[ u_6 + u_3 - u_1 = 0 \]
by adding the 3 equations above.

For a planar network with \( N \) nodes (junctions of 2 or more branches) and \( B \) branches (elements or components), the number of "windows" is

\[ B - N + 1 \]
Find $N_{R_2}$ and $N_x$ by applying KVL.

**Loop:** $c \rightarrow e \rightarrow b \rightarrow c$ going clockwise

$4 + N_{R_2} - 36 = 0$

$\Rightarrow N_{R_2} = 32 \text{V}$

$4 - 36 + 12 + 14 + N_x = 0$

$\Rightarrow N_x = 6 \text{V}$

*OR*

We know $N_{R_2}$.

**Loop:** purple loop

$-32 + 12 + 14 + N_x = 0$

$\Rightarrow N_x = 6 \text{V}$
3-4 Single-loop networks

![Circuit Diagram]

All of the elements in a circuit that carry the same current are said to be connected in series.

**KCL:** Same current $i$ flows clockwise through each element.

**KVL:** $v_1 + v_2 + v_{52} - v_3 - v_4 - v_{51} = 0$

Component (Ohm's law) equations:

\[
\begin{align*}
    v_1 &= R_1 i \\
    v_2 &= R_2 i \\
    v_3 &= -R_3 i \\
    v_4 &= -R_4 i
\end{align*}
\]

$v_{51}$ and $v_{52}$ are known and specified.

Substitute:

\[
R_1 i + R_2 i + v_{52} + R_3 i + R_4 i - v_{51} = 0
\]

\[
i = \frac{v_{51} - v_{52}}{R_1 + R_2 + R_3 + R_4}
\]
Example

\[ R_1 = 1 \Omega \quad R_2 = 2 \Omega \quad R_3 = 3 \Omega \quad R_4 = 4 \Omega \]

\[ V_{s1} = 10 V \]

Questions: \( i \) through loop? \( V_1, V_2, V_3, V_4 \)? Power delivered to each component?

\[ V_{s2} = \frac{18V}{i} \]

\[ V_1 - V_2 + V_3 - V_4 = 0 \]

\[ V_1 = -(i)i \quad V_3 = -3i \]

\[ V_2 = 2i \quad V_4 = 4i \]

\[ 18 + 2i + 4i + 3i - 10 + i = 0 \]

\[ 10i = 10 - 18 = -8 \]

\[ \rightarrow i = -0.8 A \]

Also:

\[ V_1 = -i = 0.8 V \quad V_2 = 2i = -1.6 V \]

\[ V_3 = -3i = 2.4 V \quad V_4 = 4i = -3.2 V \]

Power delivered to each component:

\[ P_1 = -V_1i = 0.64 W \]

\[ P_2 = V_2i = 1.28 W \]

\[ P_3 = -V_3i = 1.92 W \]

\[ P_4 = V_4i = 2.56 W \]

\[ P_{s1} = -V_{s1}i = 8.0 W \]

\[ P_{s2} = V_{s2}i = -14.4 W \]

Check: \( P_1 + P_2 + P_3 + P_4 + P_{s1} + P_{s2} = 0 \)
EXAMPLE

\[ R_1 = 10 \Omega \]
\[ R_2 = 20 \Omega \]
\[ V_1 = 5 \text{V} \]
\[ V_3 = 5 \text{V} \]
\[ i_s = 50 \text{mA} \]

Q: Power delivered to each component

Current is \( i_s = 50 \text{mA} \) throughout the loop.

\[ \begin{align*}
    v_1 &= -R_1i_s = -0.5 \text{V} \\
    v_2 &= R_2i_s = 1.0 \text{V} \\
    v_1 + 2v_2 + v_3 &= v_2 - v_1 - v_3 = 0 \\
    v_3 &= v_2 + v_3 - v_1 - 2v_2 = 4.5 \text{V} \\
    P_{R1} &= -v_1i_s = 25 \text{mW} \\
    P_{R2} &= v_2i_s = 50 \text{mW} \\
    P_{V3} &= v_3i_s = 250 \text{mW} \\
    P_{iS} &= -v_2i_s = -225 \text{mW} \\
    P_{2v_2} &= -2v_2i_s = -100 \text{mW} \\
    \text{Sum} &= 0 \text{J} \\
\end{align*} \]

Do practice problems 3.4 and 3.5.
Single node-pair networks (p. 49)

Network in which any number of simple elements are connected between the same pair of nodes.

KVL: The voltage across each branch is the same as that across any other branch.

KCL: 
\[-i_{s1} + i_1 - i_2 + i_{s2} + i_3 = 0\]

Elements in a circuit having a common voltage across them are said to be connected in parallel.

Component equations:
\[i_1 = \frac{v}{R_1}, \quad i_2 = \frac{-v}{R_2}, \quad i_3 = \frac{v}{R_3}\]

Substitute:
\[-i_{s1} + \frac{v}{R_1} + \frac{-v}{R_2} + i_{s2} + \frac{v}{R_3} = 0\]

\[\Rightarrow v = \frac{i_{s1} - i_{s2}}{1/R_1 + 1/R_2 + 1/R_3} = \frac{i_{s1} - i_{s2}}{G_1 + G_2 + G_3}\]

Find currents from component eqns, and
\[P_{R1} = v i_1\]
\[P_{is1} = -v i_{s1}, \text{ etc.}\]
EXAMPLE

\[ i_s = 10 \text{mA} \]

\[ R_1 = 50 \Omega \]

\[ R_2 = 100 \Omega \]

\[ i_1 \]

\[ i_2 \]

KCL:
\[-i_s + i_1 - 3i_2 - i_2 = 0\]

Ohm's law:
\[ i_1 = \frac{V}{R_1} = \frac{V}{50} \]
\[ i_2 = \frac{-V}{R_2} = \frac{-V}{100} \]

Subst:
\[-10 + \frac{V}{50} + \frac{3V}{100} + \frac{V}{100} = 0\]
\[ V \left( \frac{1}{50} + \frac{3}{100} + \frac{1}{100} \right) = 10 \]
\[ \rightarrow V = \left( \frac{50}{3} \right)10 = 167 \text{mV} \]

\[ i_1 = \frac{V}{R_1} = 3.33 \text{mA} \]
\[ i_2 = \frac{-V}{R_2} = -1.67 \text{mA} \]

Power delivered to each component:
\[ P_{R1} = VI_1 = 555 \mu W \]
\[ P_{R2} = -VI_2 = -1667 \mu W \]
\[ P_{i2} = -3V_i_2 = 833 \mu W \]

\[ \text{Sum Powers} = 0 \]

Do practice problems 3.6 and 3.7
3.4 Resistance and source combinations

**Series resistances**

\[ V = V_1 + V_2 + \cdots + V_n \]

\[ = R_1 i + R_2 i + \cdots + R_n i \]

\[ = (R_1 + R_2 + \cdots + R_n) i \]

\[ \rightarrow R_{eq} = R_1 + R_2 + \cdots + R_n \]

**Parallel resistances**

\[ V = \frac{V}{R_1} + \frac{V}{R_2} + \cdots + \frac{V}{R_n} \]

\[ = (\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}) V = \frac{1}{R_{eq}} V \]

\[ \rightarrow \frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \quad \text{(OR)} \quad G_{eq} = G_1 + G_2 + \cdots + G_n \]
EXAMPLE

Find current i

\[ \text{Re}_1 = \frac{1}{\frac{1}{20} + \frac{1}{5}} = \frac{1}{\frac{5 \times 20}{5 + 20}} = 4 \Omega \]

\[ \text{Re}_2 = 20 + \text{Re}_1 = 24 \Omega \]

\[ \text{Re}_3 = \frac{(\text{Re}_2)(10)}{\text{Re}_2 + 10} = 7.06 \Omega \]

\[ \text{Re}_4 = 5 + \text{Re}_3 = 12.06 \Omega \]

\[ i = \frac{5}{12.06} = 0.415 \text{ A} \]