EE Dept, IIT Bombay
Academic Year: 2025-2026, Semester I (Autumn)

Course: MS101 Makerspace

EE Lecture 1

Devices and Circuits I

Topics

1. Passive Devices: R, L, C, & Transformer
2. Active Devices: Independent and Dependent Sources
3. Circuit Analysis: Node, Path, Loop, Kirchoff's Voltage & Current Laws, Superposition Method

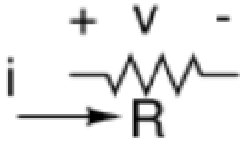
1. Passive Devices: Resistor (R), Inductor (L), Capacitor (C), & Transformer

- Passive devices cannot generate electrical energy, they can dissipate or store electrical energy.
- One-port devices have two terminals. They are described by voltage-current (V-I) relationship:

  (i) voltage as a function of current or (ii) current as a function of voltage.
- Two port devices have an input port with two terminals and an output port with two terminals. There are several ways of describing the relationship between the two voltages and two currents.

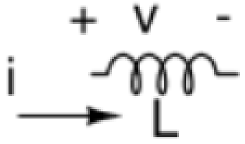
1.1 Two-terminal (single-port) devices described by their V-I characteristics

Resistor



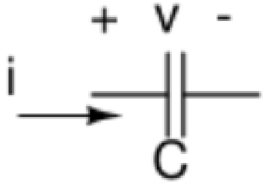
$$\boldsymbol{i = \frac{v}{R}} \quad \textbf{or} \quad \boldsymbol{v = iR}$$

Inductor



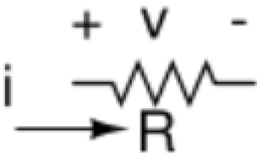
$$\boldsymbol{i = \frac{1}{L}\int v\,dt} \quad \textbf{or} \quad \boldsymbol{v = L\frac{di}{dt}}$$

Capacitor



$$\boldsymbol{i = C\frac{dv}{dt}} \quad \textbf{or} \quad \boldsymbol{v = \frac{1}{C}\int i\,dt}$$

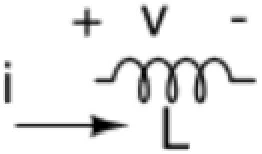
Let $v = V_m \cos(\omega t + \theta)$, where $\omega = 2\pi f$ is the angular frequency in rad/s, f is the frequency in Hz, and θ is an arbitrary phase angle.



- **Resistor**

$i = v/R = [V_m \cos(\omega t + \theta)]/R = (V_m/R) \cos(\omega t + \theta)$

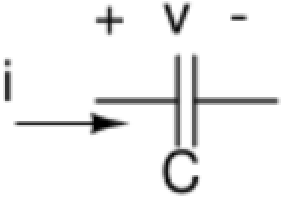
In a resistor, i and v are in phase. Unit of resistance R: ohm, Ω.



- **Inductor**

$i = (1/L) \int v\, dt = [V_m \sin(\omega t + \theta)]/(\omega L) = [V_m/(\omega L)] \cos(\omega t + \theta - \pi/2)$

In an inductor, i lags v by 90°. Unit of inductance L: henry, H.



- **Capacitor**

$i = C\, dv/dt = -\omega C V_m \sin(\omega t + \theta) = \omega C V_m \cos(\omega t + \theta + \pi/2)$

In a capacitor, i leads v by 90°. Unit of capacitance C: farad, F.

- Voltage-to-current ratio for a sinusoidal waveform is known as impedance Z. Unit: ohm, Ω.
- Impedance of R is independent of frequency, impedance of L is proportional to frequency, and impedance of C is inversely proportional to frequency.
- In R, current and voltage are in phase. In L, current lags voltage in phase by 90°. In C, current leads voltage in phase by 90°.

1.2 Resistors

Source: Chapter 2, Sec 2.4: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill, 2012.

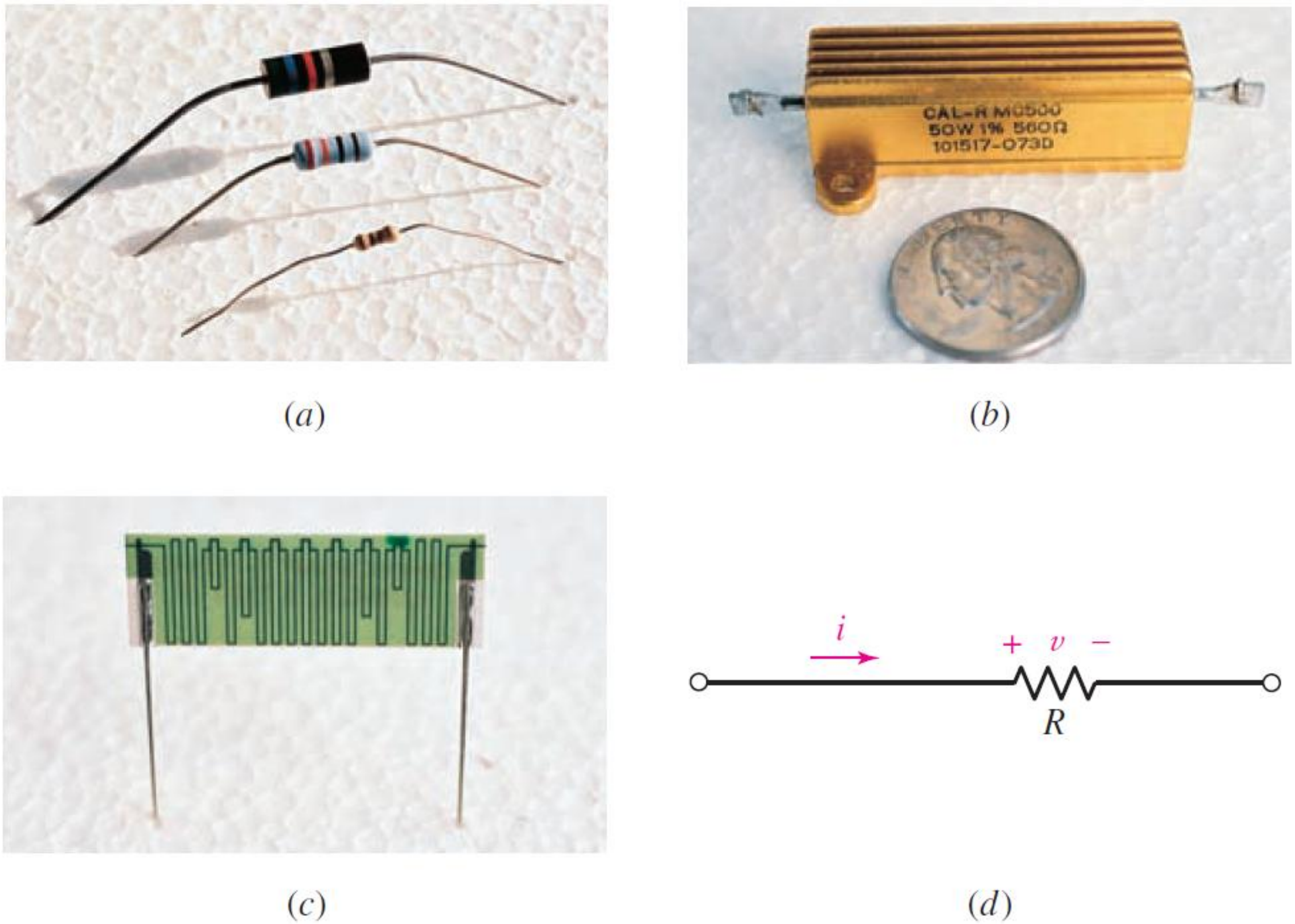
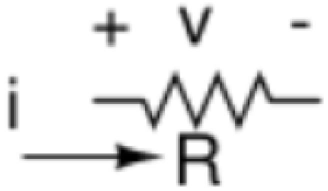


FIGURE 2.24 (*a*) Several common resistor packages. (*b*) A 560 Ω power resistor rated at up to 50 W. (*c*) A 5% tolerance 10-teraohm (10,000,000,000,000 Ω) resistor manufactured by Ohmcraft. (*d*) Circuit symbol for the resistor, applicable to all of the devices in (*a*) through (*c*).

1.3 Resistor property



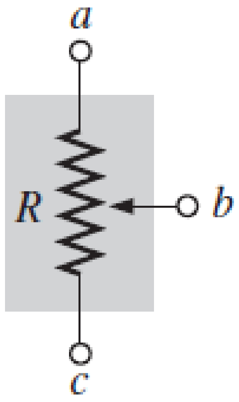
$$i = \frac{v}{R} \quad \textbf{or} \quad v = iR$$

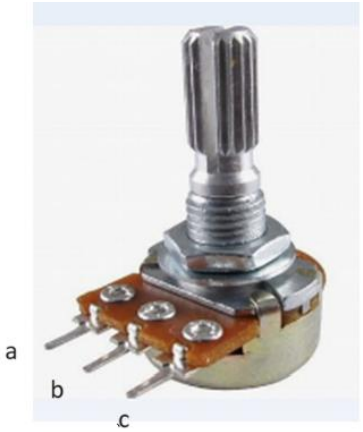
- Resistance unit: ohm, Ω.
- Instantaneous voltage & current are linearly related. For sinusoidal waveforms, current and voltage are in phase. Impedance is independent of frequency.
- Resistors are made using wire or film of a resistive material with two contact terminals. They are available with different values (ohm, Ω), tolerance (%), and power rating (power dissipation capability, watts, W). Power rating is related to size, value is generally not related to size.
- Value and tolerance are generally indicated through color codes.

1.4 Resistor applications

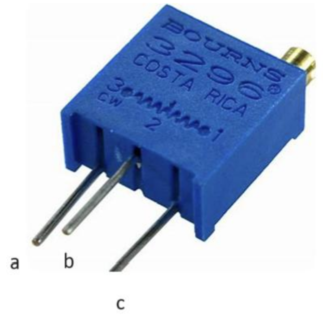
- Used for in-phase voltage-current relation & power dissipation.
- Potentiometer: 3-terminal resistor. Voltage is applied across the two outer terminals (a, c), & variable voltage is obtained between the central terminal (b) and an outer terminal (a or c).
- Variable resistor: Resistance between the central terminal (b) and an outer terminal (a or c). Unused terminal may be left unconnected, but better shorted to the central terminal.
- Variable resistor adjusted for a specific value using a screw is known as trimmable resistor.
- Resistors should be selected for proper power rating. The sliding central contact of variable & trimmable resistors can get damaged by a large current.

Potentiometers

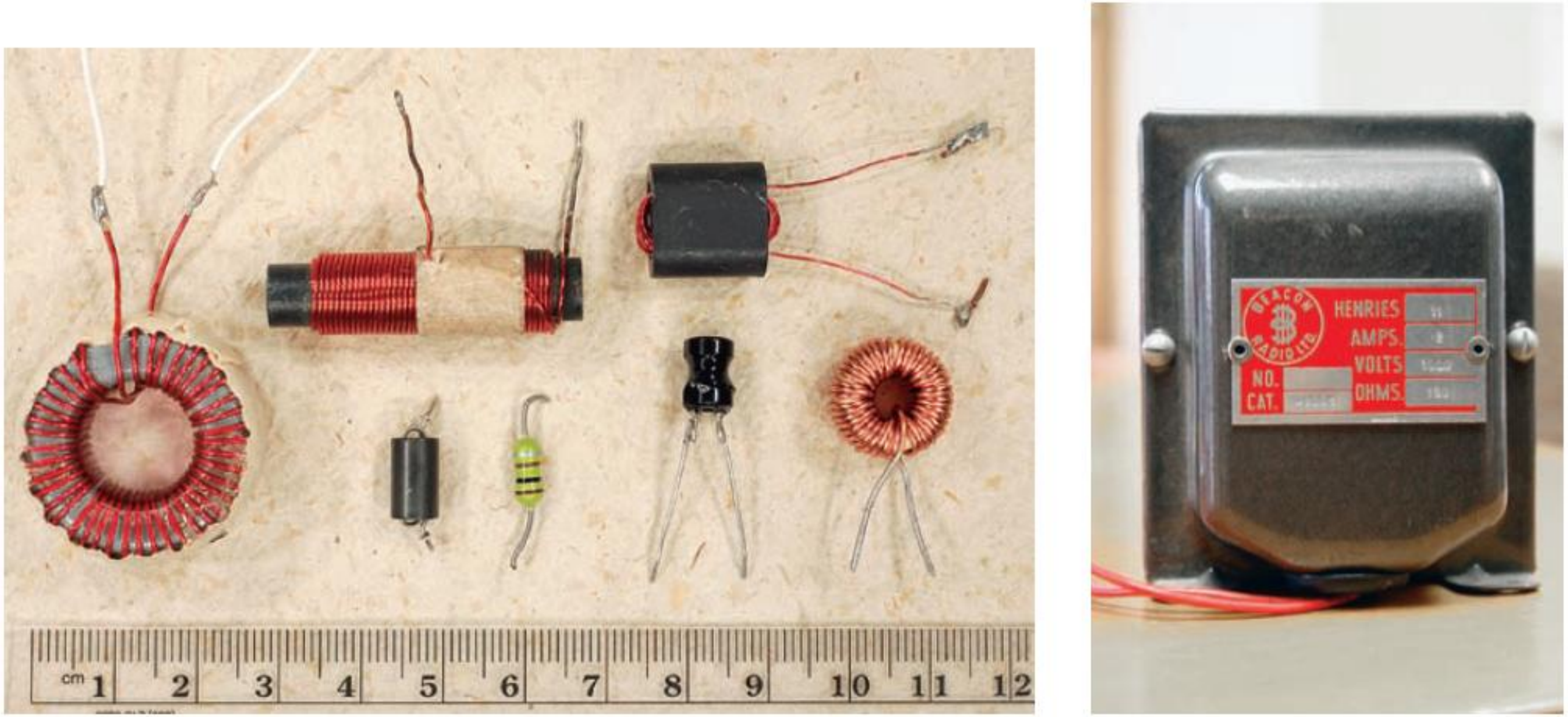




Rotating shaft (or screw) controls the sliding contact.



1.5 Inductors

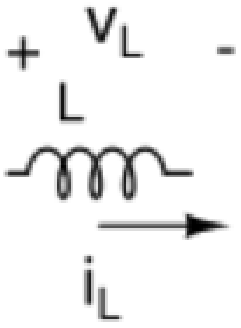


(*a*) (*b*)

FIGURE 7.11 (*a*) Several different types of commercially available inductors, sometimes also referred to as "chokes." Clockwise, starting from far left: 287 μH ferrite core toroidal inductor, 266 μH ferrite core cylindrical inductor, 215 μH ferrite core inductor designed for VHF frequencies, 85 μH iron powder core toroidal inductor, 10 μH bobbin-style inductor, 100 μH axial lead inductor, and 7 μH lossy-core inductor used for RF suppression. (*b*) An 11 H inductor, measuring 10 cm (tall) $\times$ 8 cm (wide) $\times$ 8 cm (deep).

Source: Chapter 7, Sec 7.2: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill, 2012

1.6 Inductor property



$$v_L = L\frac{di_L}{dt} \quad ; \quad i_L = \frac{1}{L}\int v_L dt$$

- Inductance unit: henry, H.
- Instantaneous voltage is linearly related to the derivative of the current.
- Current cannot change instantaneously, but the voltage can change instantaneously.
- For sinusoidal waveforms, current lags the voltage in phase by 90°. Impedance is proportional to frequency.
- Inductors are made by winding a conducting wire, usually around a magnetic core. They are available with different values (H), tolerance (%), and current rating (A). Value & current rating are related to size.

1.7 Inductor applications

Common applications

- In switched-mode power supplies (SMPS): μH to mH range.
- In RF circuits: nH to μH range.
- Compact fluorescent lamps (CFL) supply: μH to mH range.

Major disadvantages

- Large size and weight.
- Can create disturbance (electromagnetic interference, EMI) in sensitive circuits.

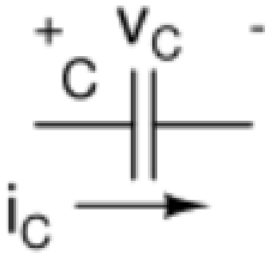
1.8. Capacitors

(a) (b) (c)

FIGURE 7.2 Several examples of commercially available capacitors. (*a*) Left to right: 270 pF ceramic, 20 μF tantalum, 15 nF polyester, 150 nF polyester. (*b*) Left: 2000 μF 40 VDC rated electrolytic, 25,000 μF 35 VDC rated electrolytic. (*c*) Clockwise from smallest: 100 μF 63 VDC rated electrolytic, 2200 μF 50 VDC rated electrolytic, 55 F 2.5 VDC rated electrolytic, and 4800 μF 50 VDC rated electrolytic. Note that generally speaking larger capacitance values require larger packages, with one notable exception above. What was the tradeoff in that case?

Source: Chapter 7, Sec 7.1: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., 2012.

1.9 Capacitor property



$$v_C = \frac{1}{C}\int i_C dt \quad ; \quad i_C = C\frac{dv_C}{dt}$$

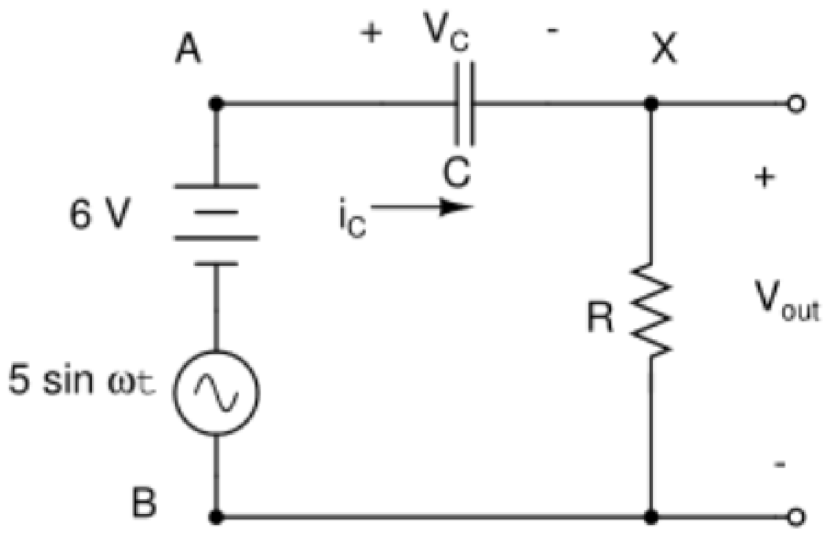
- Capacitance unit: farad, F.
- Instantaneous current is linearly related to the derivative of the voltage.
- Voltage cannot change instantaneously, but the current can change instantaneously.
- For sinusoidal waveforms, voltage lags the current in phase by 90°. Impedance is inversely proportional to frequency.
- Capacitors are made using two conducting plates separated by a thin dielectric. They are available with different values (F), tolerance (%), and voltage rating (V). Value & voltage rating are related to size.
- Capacitors known as "electrolytic capacitors" have much higher values than other types of comparable size. They have terminals with marked polarities (+/—) and must be connected with correct polarity.

1.10 Capacitor applications

• *"DC blocking" or "AC coupling" capacitor*

Capacitor connected in series with a resistor to block DC voltage and couple AC voltage, e.g. in amplifier circuits.

C is selected such that $R \gg 1/\omega C$.



Let C=0.1 µF , R= 1 MΩ, f= 1 kHz

V_{AB} = 6 + 5 sin(ωt) V .

Capacitive impedance = $1/(\omega C)$ = 1.6 kΩ

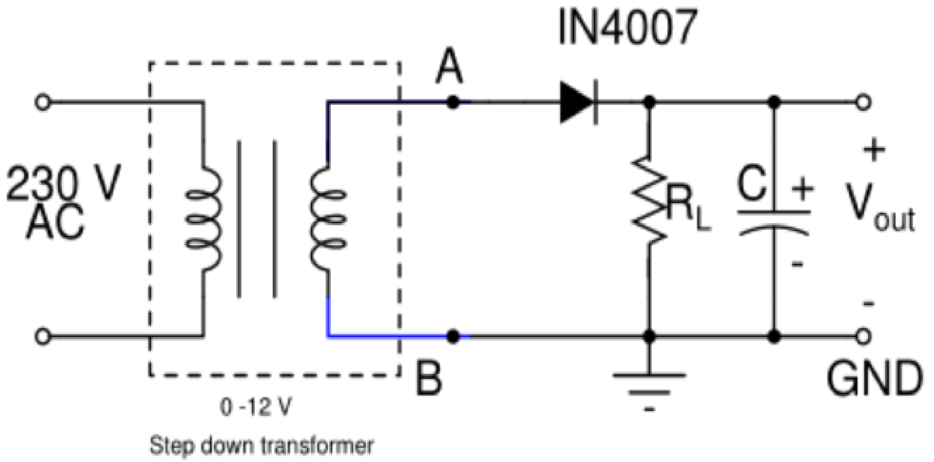
Hence, $R \gg 1/(\omega C)$.

C will block the DC but will couple AC across R.

Hence, $V_{out} \approx V_{XB}$ = 5 sin(ωt) V.

- *"Ripple filtering" capacitor*

Capacitor connected across a rectifier or DC supply output for reducing AC ripple in the output, without affecting the DC voltage. C is selected such that $R_L \gg 1/\omega C$. Typically 100–2000 μF electrolytic capacitor connected with correct polarity.



Electrolytic Capacitor C for ripple filtering in a half-wave rectifier

- *"Bypass" capacitor*

Capacitor connected across a resistor R_E carrying both AC and DC current. Select C such that $R_E \gg 1/\omega C$ so that only DC voltage appears across R_E

- *"Decoupling" capacitor*

Capacitors of 10–100 nF connected across the power supply pins of ICs to smoothen the power supply voltage.

- *Capacitor used for timing applications*

Capacitors used in oscillators, waveform generators, and filters circuits to set the timing and frequency response, typically 100 pF to 1 μF.

1.11 Transformer

- Device with two coils of wire coupled magnetically. Each coil has two terminals or a port.
- Primary coil: coil connected as the input port (left side coil in the figure to which the ac voltage source V_1 is connected). Secondary coil: coil connected as the output port (right side coil to which the load Z_L is connected).
- Turns ratio = N_2/N_1, = ratio of the number of secondary turns to the number of primary turns. For sinusoidal voltages, $V_2/V_1 = N_2/N_1$.

  $V_2/V_1 < 1$: step-down transformer.

  $V_2/V_1 > 1$: step-up transformer.
- Ideal transformer: output power = input power.

  $I_1/I_2 = N_2/N_1$

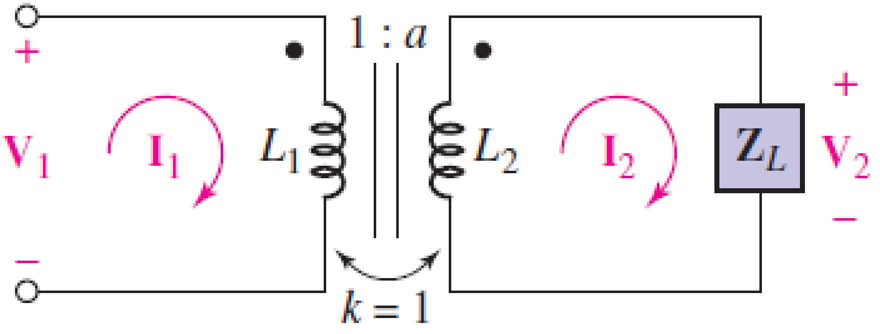


FIGURE 13.25 An ideal transformer is connected to a general load impedance.

Ref: Chapter 13, Sec 13.4: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill, 2012

1.12 Transformer applications

- Used for changing AC voltage and current.
- Also used for electrical isolation between the input and output ports.
- DC power supplies and common electronic applications powered from the AC mains use step-down transformers. For example: input V_1 is 230 V rms, and V_2 is typically 12 to 20 V rms.

FIGURE 13.15 A selection of small transformers for use in electronic applications; the AA battery is shown for scale only.

Source: Chapter 13, Sec 13.3: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill, 2012.

2. Active Devices: Independent & Dependent Sources

- Active devices generate electrical energy by using another form of energy. They serve as voltage or current sources.

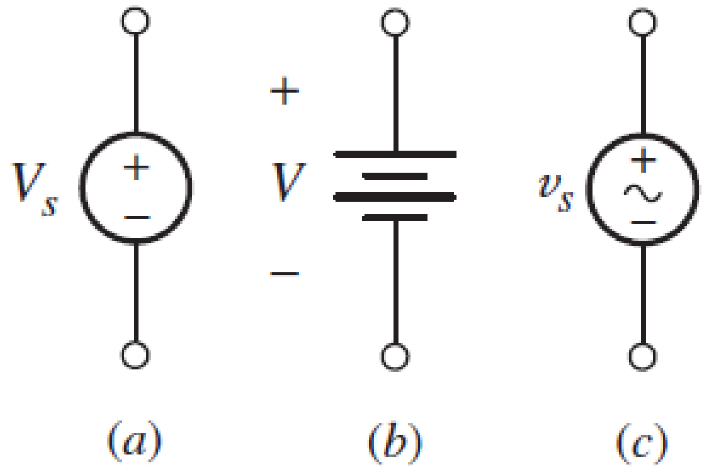
- Independent source: One-port (2 terminal) devices.
  - Independent voltage source: It generates a voltage and the current depends on the load,
  - Independent current source: It generates a current and the voltage depends on the load.

- Dependent source: Two-port devices. The output voltage and current depend on the input voltage or current.
  - Voltage-controlled voltage source,
  - Voltage-controlled current source,
  - Current-controlled voltage source,
  - Current-controlled current source.

2.1 Independent Voltage Source

- The voltage across the terminals is independent of the current.
- The current depends on the load connected across the terminals.
- No load: Terminals are left open. Zero current is drawn.

Circuit symbols for independent voltage source:
(a) DC voltage source,
(b) battery .
(c) AC voltage source (optional polarity signs to indicate polarity at an arbitrary time instant).



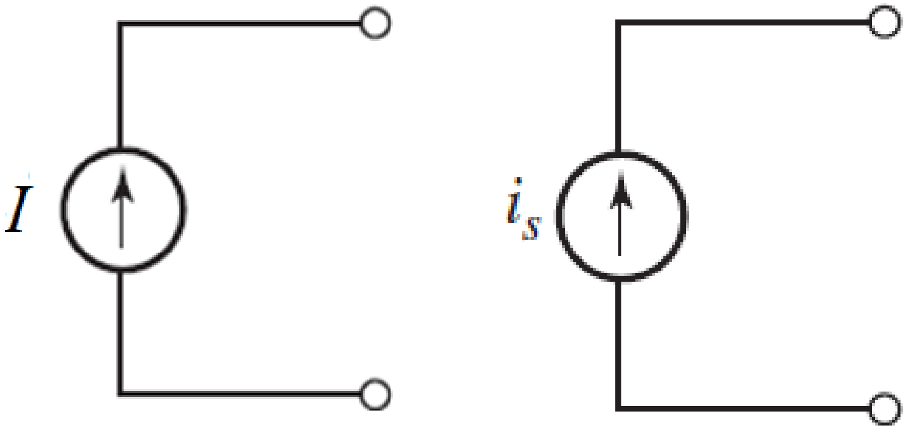
2.2 Independent Current Source

- The current is independent of the voltage across the terminals.
- The voltage depends on the load connected across the terminals.
- No load: Terminals are shorted. Zero voltage across the terminals.

Circuit symbols for independent current sources:

(a) DC current source,

(b) AC current source.

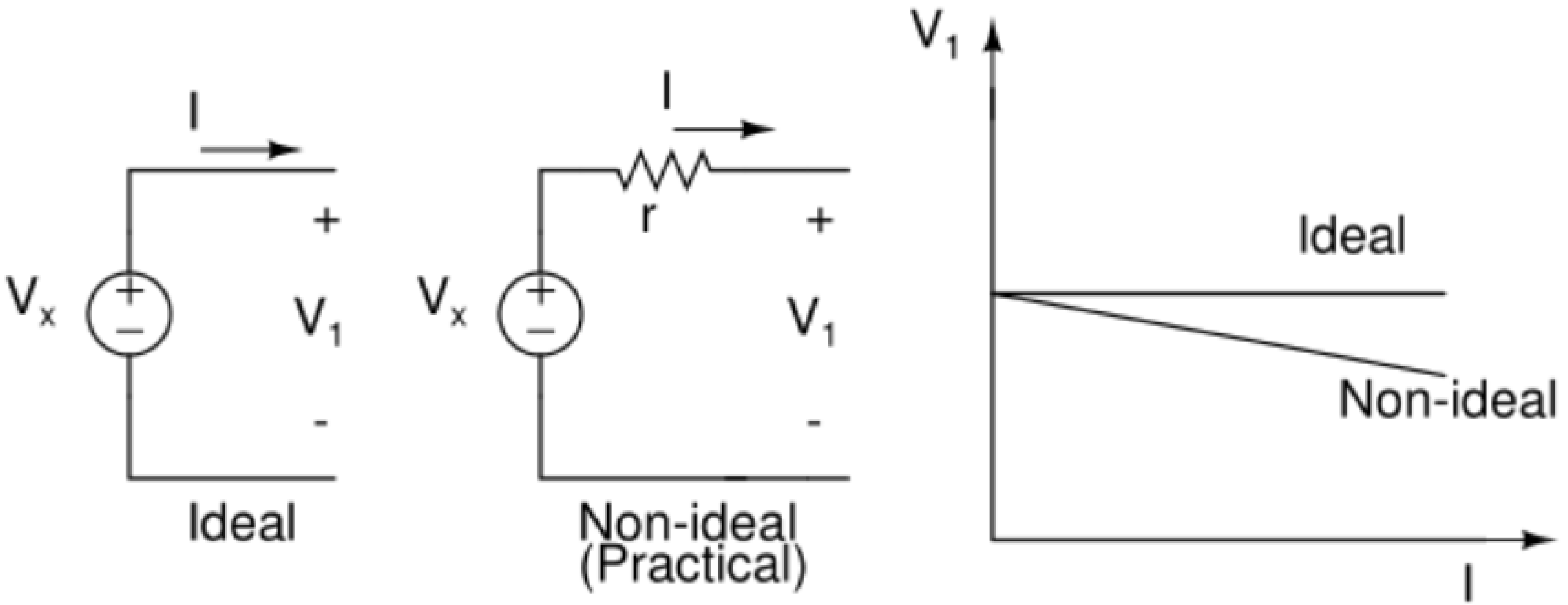


(a) (b)

2.3 Practical Voltage Source

Practical (non-ideal) voltage source:

As the current supplied to a load increases, the terminal voltage progressively decreases.



- Modelled as an ideal voltage source in series with a finite source resistance.

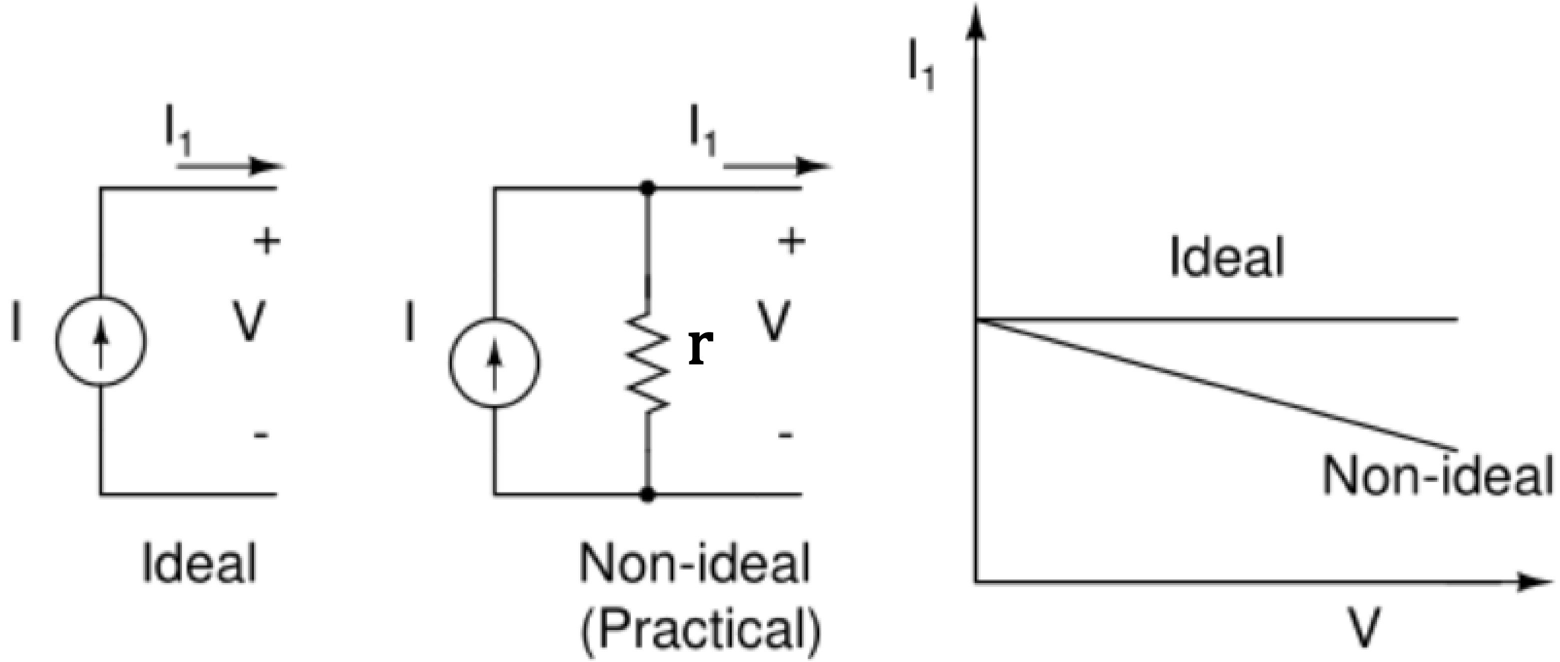
$$v_1 = v_x - i\,r$$

- The terminal voltage of the practical voltage source equals that of the ideal one when the current supplied is zero, i.e. the voltage source is open-circuited.

2.4 Practical Current Source

Practical (non-ideal) current source:

As the terminal voltage increases, the current supplied to the load progressively decreases.

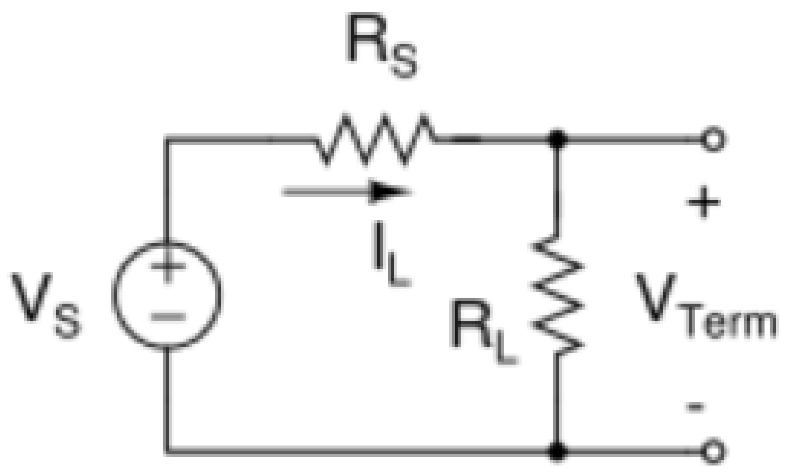


- Modelled as an ideal current source in parallel with a finite source resistance.

$$i_1 = i - V/r$$

- The current supplied by the practical current source equals that of the ideal one when the voltage across the terminals is zero, i.e. the current source is short-circuited.

2.5 Practical sources: Example 1



Problem

A practical voltage source is modelled as an ideal voltage source V_S of 15 V in series with a source resistance R_S. When a load resistance R_L was connected across this source, the current drawn from the source was 400 mA and its terminal voltage V_{Term} was 13 V.

A) Evaluate R_S in ohms.

B) If a 250 Ω resistance is connected across the voltage source what will be V_{Term} in V?

Solution

With reference to the figure,

A) $R_S = (V_S - V_{Term}) / I_L = (15\text{-}13)\ \text{V} / 0.4\text{A} = 5\ \Omega$

B) For load $R_L = 250\ \Omega$,

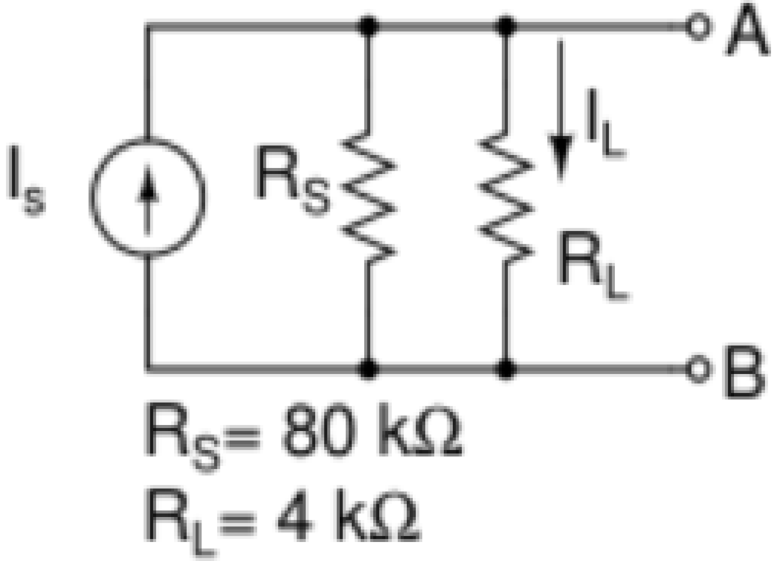
$$V_{Term} = V_S\ [R_L / (R_L + R_S)]$$
$$= 15\ [250/(250+5)] = 14.706\ \text{V}$$

2.6 Practical Sources: Example 2

Problem

A practical current source is modelled as an ideal current source of I_S in parallel with a source resistance R_S of 80 kΩ.

When a resistance R_L of 4 kΩ was connected across this source, the voltage across it was 20 V. What is the value of I_S in mA?



Solution

$V_{AB} = 20$ V; hence $I_L = 20\text{ V}/4\text{ k}\Omega = 5$ mA.

$I_L = I_S\,[R_S/(R_S+R_L)]$

or $I_S = I_L\,[(R_S+R_L)/R_S]$

$= 5\text{ mA}\,[(4+80)/80] = 5.25$ mA

2.7 Dependent (Controlled) Sources

Two-port device with the source quantity (voltage or current) at the output port controlled by a voltage or current at the input port.

- Used in the equivalent electrical models for many electronic devices, such as transistors, operational amplifiers, and integrated circuits.
- Four types:

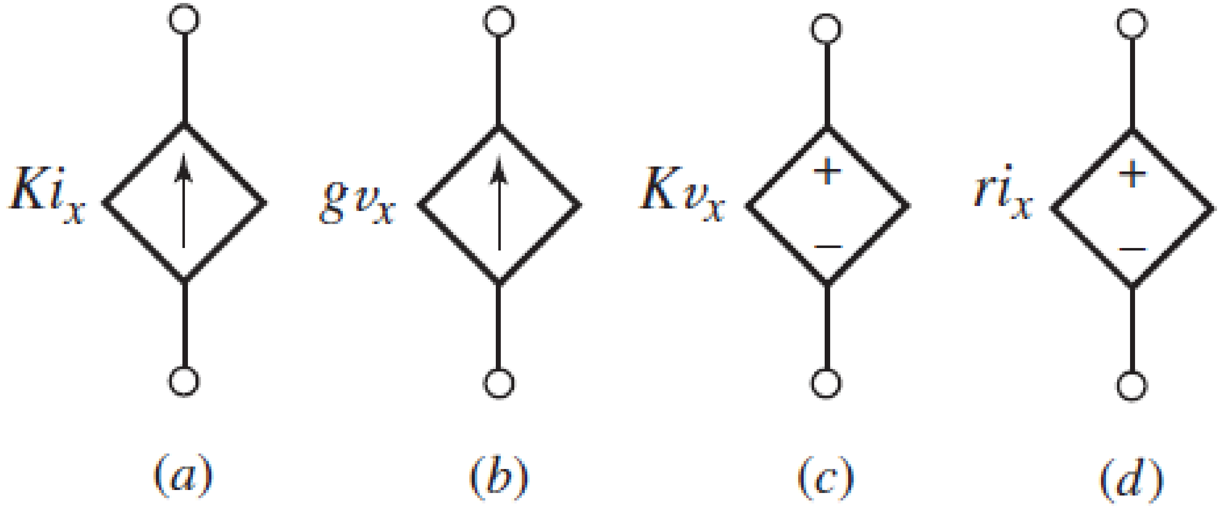
  - voltage-controlled voltage source
  - voltage-controlled current source
  - current-controlled voltage source
  - current-controlled current source

- Circuit symbol: Source at the output is shown with a diamond symbol (in place of circle for independent source). Input port may not be shown in the symbol.

2.8 Dependent Sources: Four Types

- Four types as shown.
- In (a) and (c), K is a dimensionless scaling constant.
- In (b), g is a scaling factor, known as trans-conductance. Unit: A/V.
- In (d), r is a scaling factor, known as trans-resistance. Unit: V/A (ohm, Ω).
- In these symbols, the controlling current i_x and the controlling voltage v_x are not shown. They must be defined in the circuit.

Circuit symbols for the dependent sources:
(a) current-controlled current source,
(b) voltage-controlled current source,
(c) voltage-controlled voltage source,
(d) current-controlled voltage source.



3. Circuit Analysis

Circuit: Connection of multiple electrical devices.

Circuit terms: nodes, paths, loops.

Circuit analysis: Finding voltages and currents for individual devices in the circuit, with the help of

- Kirchoff's voltage and current laws,
- Superposition method.

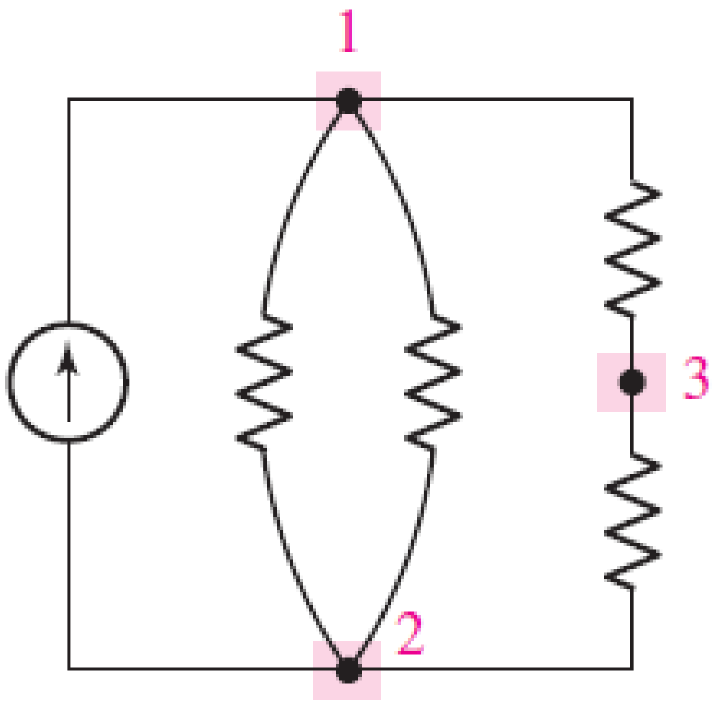
3.1 Node, Path, and Loop

- Node: Connection of two devices.

  Example: 1, 2, and 3 are nodes

- Path: moving from a node to another node in the circuit without encountering a node more than once. There may be multiple paths between a node pair.
- Example: Node 1 to node 3 to node 2 is a path
- Loop: Path starting and ending at the same node is a *closed path* or a *loop*.

  Example: Node 1 to node 3 to node 2 and then back to node 1 is a loop or a closed path. There may be multiple loops starting and ending at the same node.



3.2 Kirchhoff's Current Law (KCL)

- *Statement:* The algebraic sum of the currents entering a node is zero.
- Basis: charge cannot accumulate at a node.
- Example

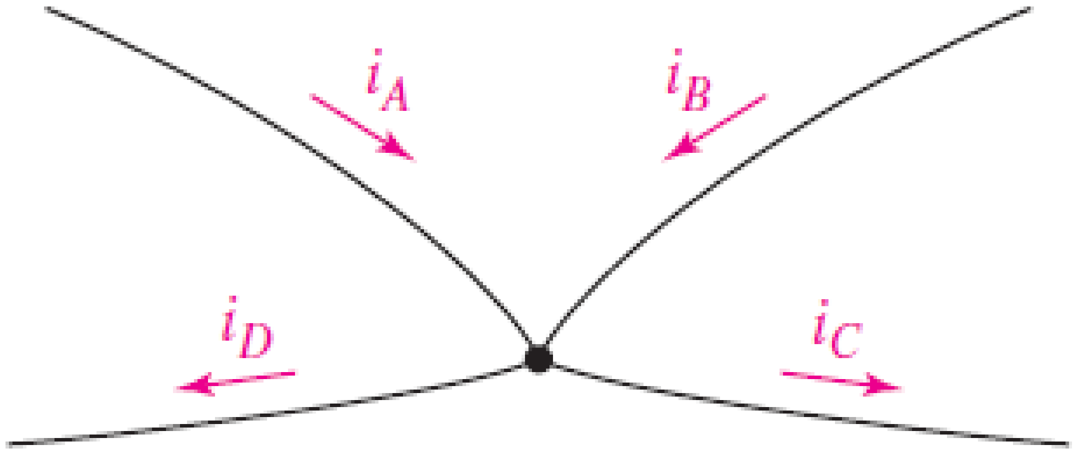
  $i_A + i_B + (-i_C) + (-i_D) = 0$

  Or $\quad i_A + i_B = i_C + i_D$

  i.e. sum of the currents entering a node must equal the sum of the currents leaving it.
- Compact expression for KCL:

$$\sum_{n=1}^{N} i_n = 0$$

Example node to illustrate the KCL application.



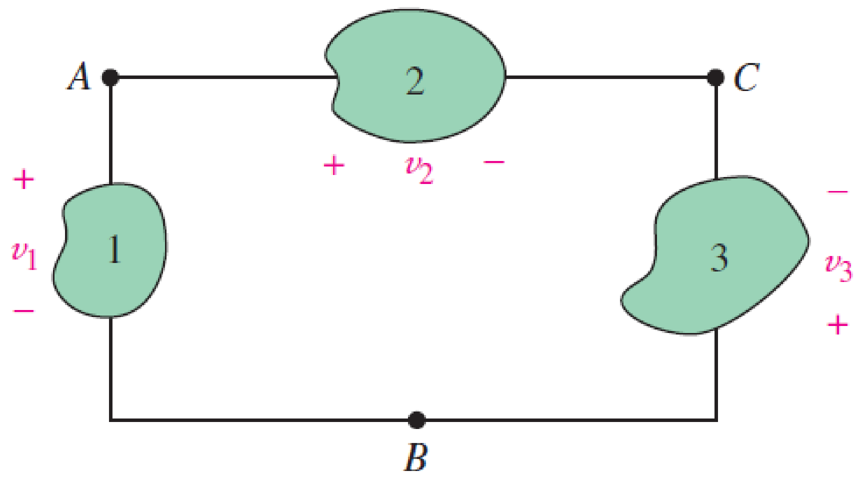
3.3 Kirchhoff's Voltage Law (KVL)

- *Statement:* The algebraic sum of the voltages around a loop (closed path) is zero.
- Basis: No change in potential energy in moving around a loop.
- Method: Move around the closed path in a clockwise direction and write down each voltage met at the +ve sign as positive and each voltage met at the –ve sign as negative.
- Example: $-v_1 + v_2 - v_3 = 0.$ Or $v_1 = v_2 - v_3$,

i.e. the voltage between a node pair is independent of the path selected.

- Compact expression of KVL: $$\sum_{n=1}^{N} v_n = 0$$

Voltage between nodes A and B is independent of the path selected.



3.4 Superposition Principle

- Superposition principle

  The output for a weighted sum of inputs is the same weighted sum of the outputs.

  Let the inputs x_1 and x_2 result in outputs y_1 and $y_{2,}$ respectively.

  The output for an input $x = ax_1 + bx_2$ is given as $y = ay_1 + by_2$.

  The inputs and outputs can be voltages or currents.

- Devices obeying the superposition principle are linear, those not obeying this principle are nonlinear.
- Circuits made of linear devices (e.g. resistors, capacitors, inductors, dependent sources) are called linear circuits.
- The superposition method uses the superposition principle to find a voltage or current due to multiple sources by considering one source at a time.

3.5 Superposition Method

- *Statement:*

  In a circuit with multiple independent sources, the current through (or voltage across) a device is equal to the algebraic sum of the currents (or voltages) produced in that device independently by each source.

- The method allows finding a solution for a current or voltage using only one source at a time.
- The term algebraic appears in the statement because the currents resulting from different sources can have different directions. Similarly, the voltages can have different polarities.

3.6 Application of Superposition Method

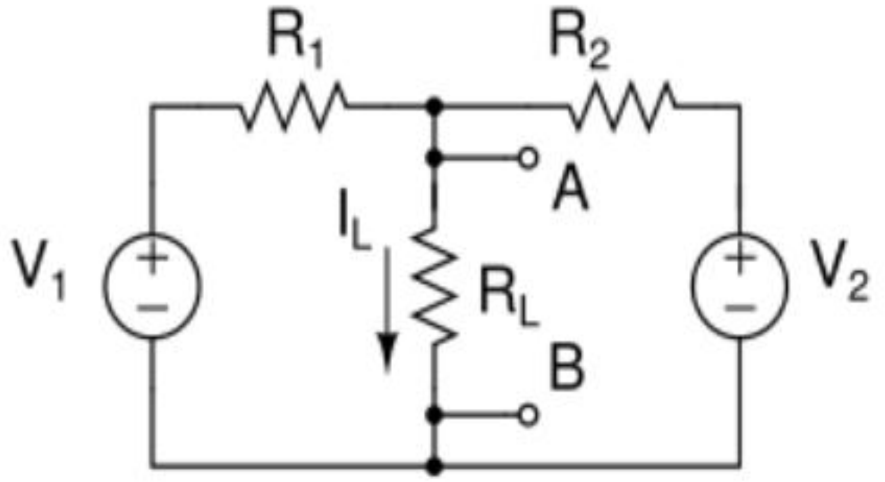
To consider the effects of each source, the other sources are removed.

- For removing an ideal voltage source, replace it by a short circuit. An internal resistance associated with a practical voltage source must remain in the circuit.
- For removing an ideal current source, replace it with an open circuit. An internal resistance associated with a practical current source must remain in the circuit.
- Since the effect of each source is determined independently, the number of times the circuit is analyzed is equal to the number of sources. Therefore, the method changes solving a complex problem to solving multiple simpler problems.

3.7 Superposition Method: Example 1

Problem: In the circuit shown, $R_1 = R_2 = R_L = 1200\ \Omega$. $V_1 = 9$ V, $V_2 = 12$ V. Evaluate I_L in mA.

Solution by applying Superposition Method



- Find I_L due to V_1 alone (say I_{L1}).

$V_1 = 9$ V. $V_2 = 0$ V.

Current through R_1 :

$I_{R1} = V_1 / (R_1 + R_2 || R_L) = 9/(1200+600)$ A $= 5$ mA.

Since $R_2 = R_L$, $I_{L1} = 0.5\ (I_{R1}) = 0.5\ (5)$ mA $= 2.5$ mA.

- Find I_L due to V_2 alone (say I_{L2}).

$V_1 = 0$ V. $V_2 = 12$ V.

Current through R_2:

$I_{R2} = V_2 / (R_2 + R_1 || R_L) = 12/(1200+600)$ A $= 20/3$ mA.

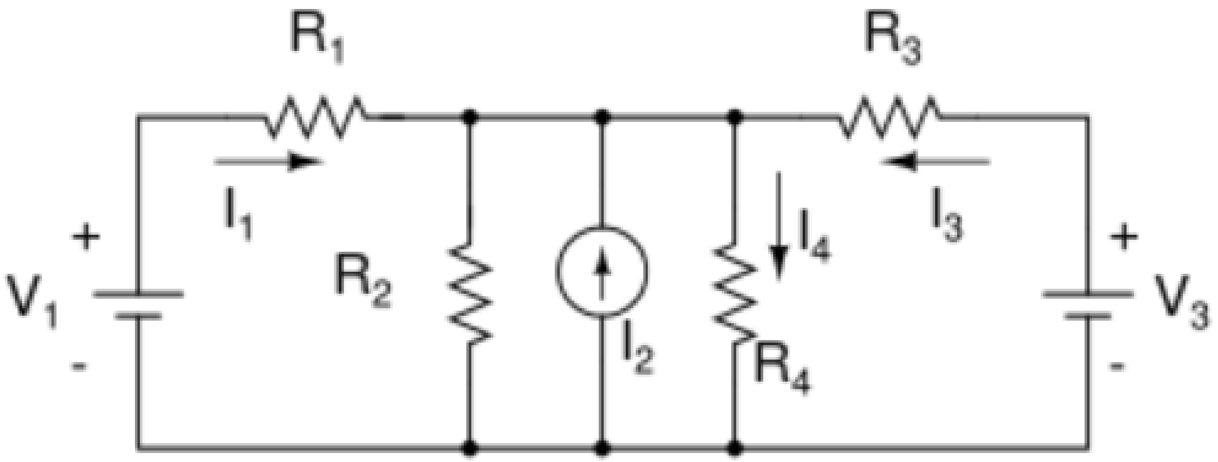
Since $R_1 = R_L$, $I_{L2} = 0.5(I_{R2}) = 0.5(20/3)$ mA $= 3.33$ mA.

- Hence, $I_L = I_{L1} + I_{L2} = 2.5 + 3.33 = 5.83$ mA.

3.7 Superposition Method: Example 2

Problem: In the circuit shown, $R_1 = R_2 = R_2 = R_4 = 250\ \Omega$. $V_1 = 10$ V, $I_2 = 8$ mA, $V_3 = -5$ V.

Evaluate I_4 in mA.



Solution by applying Superposition Method

- Find I_4 due to V_1 alone (say I_{41}).

$V_1 = 10$ V, $I_2 = 0$ mA, $V_3 = 0$ V.

$I_1 = V_1/[R_1 + (R_2 \| R_4 \| R_3)] = V_1/[R_1 + R_1/3]$
$= 3\ V_1/(4\ R_1)$.

Hence, $I_{41} = (1/3)I_1 = V_1/(4\ R_1) = 10$ mA.

- Find I_4 due to V_3 alone (say I_{43}).

$V_1 = 0$ V, $I_2 = 0$ mA, $V_3 = -5$ V.

$I_3 = V_3/(R_3 + [R_1 \| R_2 \| R_4]) = V_3/(R_1 + [R_1/3]) = 3\ V_3/(4\ R_1)$.

Hence, $I_{43} = (1/3)I_3 = V_3/(4\ R_1) = -5$ mA.

- Find I_4 due to I_2 alone (say I_{42}).

$V_1 = 0$ V, $I_2 = 8$ mA, $V_3 = 0$ V.

Since $R_1 = R_2 = R_3 = R_4$, $I_{42} = I_2/4 = 2$ mA.

- Hence, $I_4 = I_{41} + I_{42} + I_{43} = 10 + 2 - 5 = 7$ mA.

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