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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Brushing up the basics

By,

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Assistant Professor, SELECT

Charge The **unit of charge** is the coulomb (C) where one coulomb is one ampere second. (1 coulomb $= 6.24 \times 10^{18}$ electrons). The coulomb is defined as the quantity of electricity which flows past a given point in an electric circuit when a current of one ampere is maintained for one second. Thus,

charge, in coulombs $\boxed{Q = It}$

Problem 1. If a current of 5 A flows for 2 minutes, find the quantity of electricity transferred.

Quantity of electricity $Q = It$ coulombs

$I = 5$ A, $t = 2 \times 60 = 120$ s

Hence $Q = 5 \times 120 =$ **600 C**

Power The **unit of power** is the watt (W) where one watt is one joule per second. Power is defined as the rate of doing work or transferring energy. Thus,

power in watts, $\boxed{P = \dfrac{W}{t}}$

where W is the work done or energy transferred in joules and t is the time in seconds. Thus

energy, in joules, $\boxed{W = Pt}$

Electrical potential and e.m.f. The **unit of electric potential** is the volt (V) where one volt is one joule per coulomb. One volt is defined as the difference in potential between two points in a conductor which, when carrying a current of one ampere, dissipates a power of one watt, i.e.

$$\text{volts} = \frac{\text{watts}}{\text{amperes}} = \frac{\text{joules/second}}{\text{amperes}} = \frac{\text{joules}}{\text{ampere seconds}} = \frac{\text{joules}}{\text{coulombs}}$$

A change in electric potential between two points in an electric circuit is called a **potential difference**. The **electromotive force (e.m.f.)** provided by a source of energy such as a battery or a generator is measured in volts.

Resistance and conductance

The **unit of electric resistance** is the **ohm** (Ω) where one ohm is one volt per ampere. It is defined as the resistance between two points in a conductor when a constant electric potential of one volt applied at the two points produces a current flow of one ampere in the conductor. Thus,

resistance, in ohms $\boxed{R = \dfrac{V}{I}}$

where V is the potential difference across the two points in volts and I is the current flowing between the two points in amperes.

The reciprocal of resistance is called **conductance** and is measured in siemens (S). Thus,

conductance, in siemens $\boxed{G = \dfrac{1}{R}}$

where R is the resistance in ohms.

Electrical power and energy

When a direct current of I amperes is flowing in an electric circuit and the voltage across the circuit is V volts, then

power, in watts $\boxed{P = VI}$

Electrical energy = Power × time

$= VIt$ **Joules**

Although the unit of energy is the joule, when dealing with large amounts of energy, the unit used is the **kilowatt hour (kWh)** where

1 kWh = 1000 watt hour

= 1000 × 3600 watt seconds or joules

= 3 600 000 J

Problem . A source e.m.f. of 5 V supplies a current of 3 A for 10 minutes. How much energy is provided in this time?

Energy $= VIt = 5 \times 3 \times (10 \times 60) = 9000$ Ws or J

$=$ **9 kJ**

Problem . An electric heater consumes 1.8 MJ when connected to a 250 V supply for 30 minutes. Find the power rating of the heater and the current taken from the supply.

i.e. **Power rating of heater = 1 kW**

Power $P = VI$, thus $I = \dfrac{P}{V} = \dfrac{1000}{250} = 4$ A

Hence the current taken from the supply is 4 A

Problem . What current must flow if 0.24 coulombs is to be transferred in 15 ms?

Since the quantity of electricity, $Q = It$, then

$$I = \frac{Q}{t} = \frac{0.24}{15 \times 10^{-3}} = \frac{0.24 \times 10^3}{15} = \frac{240}{15} = \mathbf{16\ A}$$

Problem . If a current of 10 A flows for four minutes, find the quantity of electricity transferred.

Quantity of electricity, $Q = It$ coulombs

$I = 10$ A; $t = 4 \times 60 = 240$ s

Hence $Q = 10 \times 240 =$ **2400 C**

Ohm's law **Ohm's law** states that the current I flowing in a circuit is directly proportional to the applied voltage V and inversely proportional to the resistance R, provided the temperature remains constant. Thus,

$$\boxed{I = \frac{V}{R} \text{ or } V = IR \text{ or } R = \frac{V}{I}}$$

Problem. The current flowing through a resistor is 0.8 A when a p.d. of 20 V is applied. Determine the value of the resistance.

From Ohm's law, resistance $R = \frac{V}{I} = \frac{20}{0.8} = \frac{200}{8} = \mathbf{25\ \Omega}$

Problem. Determine the p.d. which must be applied to a 2 kΩ resistor in order that a current of 10 mA may flow.

Resistance $R = 2\ \text{k}\Omega = 2 \times 10^3 = 2000\ \Omega$

Current $I = 10\ \text{mA} = 10 \times 10^{-3}\ \text{A}$ or $\frac{10}{10^3}$ or $\frac{10}{1000}\ \text{A} = 0.01\ \text{A}$

From Ohm's law, potential difference, $V = IR = (0.01)(2000) = \mathbf{20\ V}$

Problem. A 100 V battery is connected across a resistor and causes a current of 5 mA to flow. Determine the resistance of the resistor. If the voltage is now reduced to 25 V, what will be the new value of the current flowing?

Resistance $R = \frac{V}{I} = \frac{100}{5 \times 10^{-3}} = \frac{100 \times 10^3}{5} = 20 \times 10^3 = \mathbf{20\ k\Omega}$

Current when voltage is reduced to 25 V,

$$I = \frac{V}{R} = \frac{25}{20 \times 10^3} = \frac{25}{20} \times 10^{-3} = \mathbf{1.25\ mA}$$

Electrical power and energy

Electrical power

Power P in an electrical circuit is given by the product of potential difference V and current I,

$$\boxed{P = V \times I \text{ watts}} \qquad (2.1)$$

From Ohm's law, $V = IR$

Substituting for V in equation (2.1) gives:

$$P = (IR) \times I$$

i.e. $\boxed{P = I^2 R \text{ watts}}$

Also, from Ohm's law, $I = \frac{V}{R}$

Substituting for I in equation (2.1) gives:

$$P = V \times \frac{V}{R}$$

i.e. $\boxed{P = \frac{V^2}{R} \text{ watts}}$

Problem. The hot resistance of a 240 V filament lamp is 960 Ω. Find the current taken by the lamp and its power rating.

From Ohm's law, current $I = \frac{V}{R} = \frac{240}{960} = \frac{24}{96} = \mathbf{\frac{1}{4}\ A \text{ or } 0.25\ A}$

Power rating $P = VI = (240)\left(\frac{1}{4}\right) = \mathbf{60\ W}$

Problem. Determine the power dissipated by the element of an electric fire of resistance 20 Ω when a current of 10 A flows through it. If the fire is on for 6 hours determine the energy used and the cost if 1 unit of electricity costs 7p.

Power $P = I^2R = 10^2 \times 20 = 100 \times 20 = \mathbf{2\,000\ W \text{ or } 2\ kW}$

(Alternatively, from Ohm's law, $V = IR = 10 \times 20 = 200$ V, hence power $P = V \times I = 200 \times 10 = 2000\ \text{W} = 2\ \text{kW}$)

Energy used in 6 hours = power × time = 2 kW × 6 h = **12 kWh**

1 unit of electricity = 1 kWh

Hence the number of units used is 12

Cost of energy = 12 × 7 = **84p**

Problem . If 5 A, 10 A and 13 A fuses are available, state which is most appropriate for the following appliances which are both connected to a 240 V supply (a) Electric toaster having a power rating of 1 kW (b) Electric fire having a power rating of 3 kW

Power $P = VI$, from which, current $I = \frac{P}{V}$

(a) For the toaster, current $I = \frac{P}{V} = \frac{1000}{240} = \frac{100}{24} = 4\frac{1}{6}$ A

Hence a **5 A fuse** is most appropriate

(b) For the fire, current $I = \frac{P}{V} = \frac{3000}{240} = \frac{300}{24} = 12\frac{1}{2}$ A

Hence a **13 A fuse** is most appropriate

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SCHOOL OF ELECTRICAL ENGINEERING
EEE 1001 : Basic Electrical and Electronics Engineering

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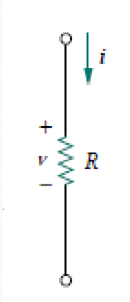
Module 1-DC circuits

Basic circuit elements and sources, Ohms law, Kirchhoff's laws, series and parallel connection of circuit elements, Node voltage analysis, Mesh current analysis, Thevenin's and Maximum power transfer theorem.

Ohm's law
(Georg Simon Ohm (1787–1854), a German physicist)

Ohm's law states that the voltage (v) across a resistor is directly proportional to the current (i) flowing through the resistor.

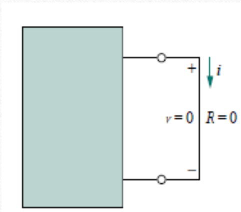
$$v \propto i$$
$$v = i\,R$$

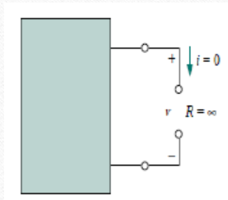


Ohm's law states that the current I flowing in a circuit is directly proportional to the applied voltage V and inversely proportional to the resistance R, provided the temperature remains constant.

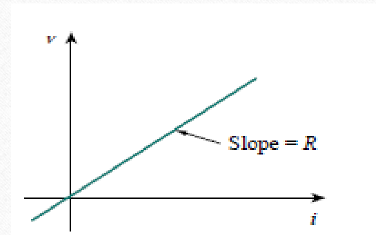
$$i = \frac{v}{R}$$

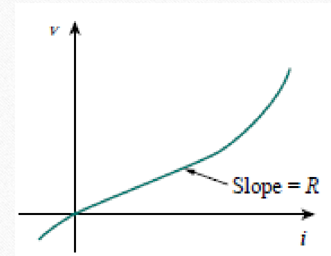
A short circuit is a circuit element with resistance approaching zero.
An open circuit is a circuit element with resistance approaching infinity.





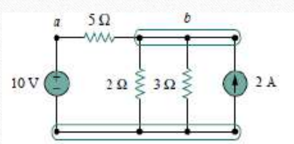
A resistor that obeys Ohm’s law is known as a *linear* resistor.
A *nonlinear* resistor does not obey Ohm’s law. Its resistance varies with current.

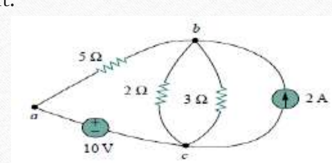




Nodes, Branches and Loops

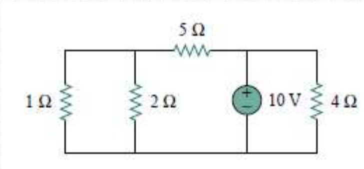
- A branch represents a single element such as a voltage source or a resistor.
- A node is the point of connection between two or more branches.
- A loop is any closed path in a circuit.

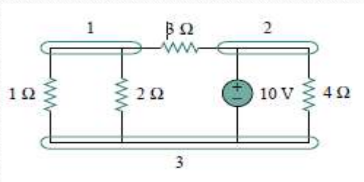




- A loop is a closed path formed by starting at a node, passing through a set of nodes, and returning to the starting node without passing through any node more than once.
- A **loop** is said to be ***independent*** if it contains a branch which is not in any other loop.
- A network with b branches, n nodes, and l independent loops will satisfy the fundamental theorem of network topology:

$$b = l + n - 1$$





KIRCHHOFF'S LAWS

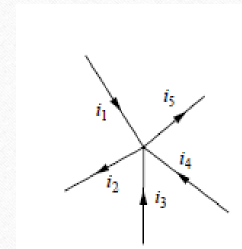
(Gustav Robert Kirchhoff (1847), German physicist)

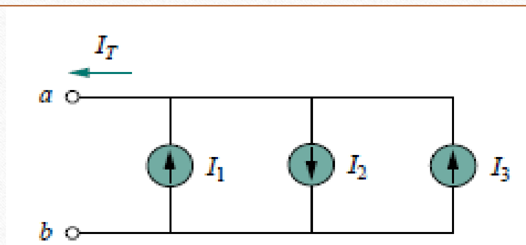
- Kirchhoff's current law (KCL) states that the algebraic sum of currents entering a node (or a closed boundary) is zero.

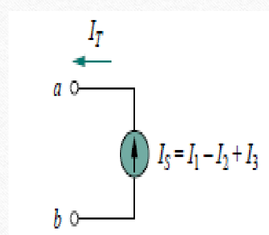
$$\sum_{n=1}^{N} i_n = 0$$

N – no. of branches

- The sum of the currents entering a node is equal to the sum of the currents leaving the node.





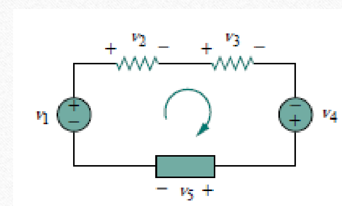


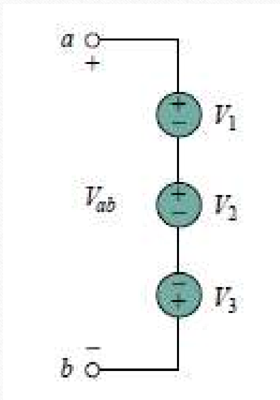
- Kirchhoff's voltage law (KVL) states that the algebraic sum of all voltages around a closed path(or loop) is zero.

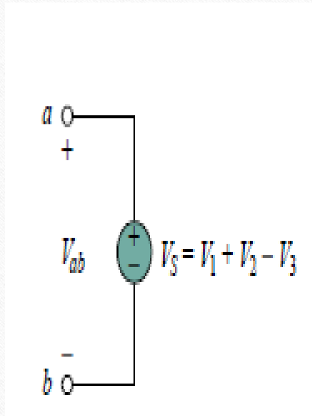
$$\sum_{m=1}^{M} v_m = 0$$

M is the number of the voltages (branches) in a loop.

Sum of voltage drops = Sum of voltage rises







Q1. 100V battery is connected across a resistor and causes a current of 5mA to flow. Determine the resistance of the resistor. If the voltage is now reduced to 25V, what will be the new value of the current flowing?

Resistance, $R = \frac{V}{I} = \frac{100}{5*10^{-3}} = 20 * 10^3 = 20k\Omega$

Current when the voltage is reduced to 25 V,

$$I = \frac{V}{R} = \frac{25}{20 * 10^3} = 1.25\ mA$$

Q21. A 60W electric light bulb is connected to a 240V supply. Determine (a) the current flowing in the bulb and (b) the resistance of the bulb.

Power , $P = 60\ W$; Voltage , $V = 240\ V$;

$$P = V * I = 60$$

$$I = \frac{P}{V} = \frac{60}{240} = 0.25\ A$$

$$R = \frac{V}{I} = \frac{240}{0.25} = 960\ \Omega$$

$$P = V * \frac{V}{R} = \frac{V^2}{R} = 60$$

$$R = \frac{240^2}{60} = 960\ \Omega$$

$$I = \frac{V}{R} = \frac{240}{960} = 0.25\ A$$

For the circuit in Figure, find voltages v_1 and v_2

By Ohm's law

$v_1 = 2i$ and $v_2 = -3i$

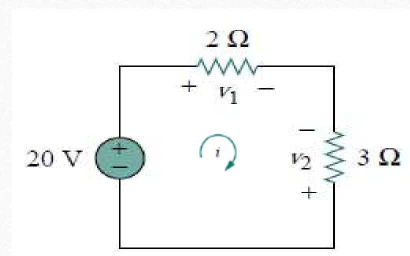
By KVL,

$$20 + v_2 = v_1$$

$$20 - 3i = 2i$$

$$i = 4A$$

$v_1 = 8\ V$; $v_2 = -6\ V$



Find the currents and voltages in the circuit shown.

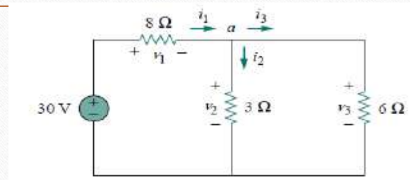
- By ohm's law,

$$v_1 = 8\,i_1$$
$$v_2 = 3\,i_2$$
$$v_3 = 6\,i_3$$

By KCL at node 'a',

$$i_1 = i_2 + i_3$$

i.e., $i_1 - i_2 - i_3 = 0$ ------------------ (1)



Applying KVL to loop 1,

Sum of the Voltage Rise = sum of the voltage drops

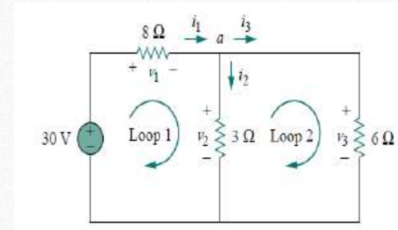
$$30 = v_1 + v_2$$

$8i_1 + 3i_2 = 30$ ---------------(2)

Applying KVL to loop 2,

$$v_2 = v_3$$

$3i_2 = 6\,i_3$ ------------------------(3)



From (2),

$i_1 = \frac{30 - 3i_2}{8}$ -----------------(4)

From (3),

$i_3 = \frac{i_2}{2}$ -----------------(5)

Substituting (4) and (5) in(1),

$$i_2 = 2\,A$$

$$i_1 = 3\,A$$
$$i_3 = 1\,A$$
$$v_1 = 24\,V$$
$$v_2 = 6\,V$$
$$v_3 = 6\,V$$

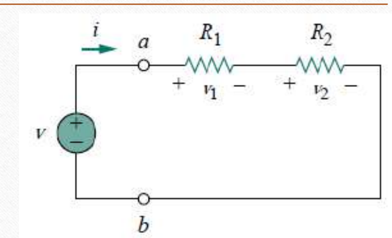
Series resistors and Voltage division

- By ohm's law,

$$v_1 = i\,R_1$$
$$v_2 = i\,R_2$$

By KVL,

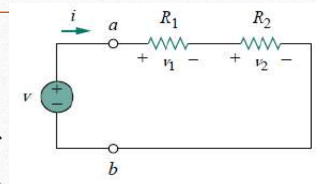
$$v = v_1 + v_2$$
$$v = i\,R_1 + i\,R_2 = i(R_1 + R_2)$$
$$i = \frac{v}{(R_1 + R_2)}$$

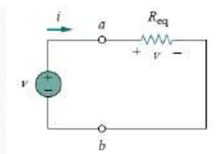


$$v = i\, R_{eq}$$
$$R_{eq} = R_1 + R_2$$

The equivalent resistance of any number of resistors connected in series is the sum of the individual resistances.

$$R_{eq} = R_1 + R_2 + \cdots + R_N = \sum_{n=1}^{N} R_n$$





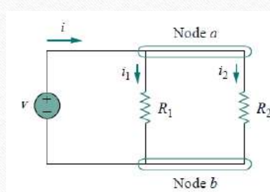
$$v_1 = i\, R_1 \,;\, v_2 = i\, R_2 \text{ and } i = \frac{v}{(R_1+R_2)}$$
$$v_1 = i\, R_1 = \frac{v}{(R_1 + R_2)} * R_1$$
$$v_2 = i\, R_2 = \frac{v}{(R_1 + R_2)} * R_2$$

$$\boldsymbol{v_1 = \frac{R_1}{(R_1 + R_2)} * v}$$
$$\boldsymbol{v_2 = \frac{R_2}{(R_1 + R_2)} * v}$$

Parallel resistors and current division

By ohm's law,

$$v = i_1 R_1 = i_2 R_2$$
$$i_1 = \frac{v}{R_1}$$
$$i_2 = \frac{v}{R_2}$$



At node 'a' by KCL,

$$i = i_1 + i_2$$

Substituting i_1 and i_2 from the previous equations,

$$i = \frac{v}{R_1} + \frac{v}{R_2} = v\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{v}{R_{eq}}$$
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{R_{eq}} = \frac{R_1 + R_2}{R_1 R_2}$$

$$\boldsymbol{R_{eq} = \frac{R_1 R_2}{R_1 + R_2}}$$

The equivalent resistance of two parallel resistors is equal to the product of their resistances divided by their sum.

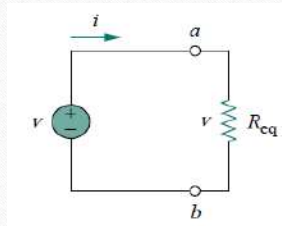
$$\boldsymbol{\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}}$$

$$v = iR_{eq}$$

$$v = i * \frac{R_1 R_2}{R_1 + R_2}$$

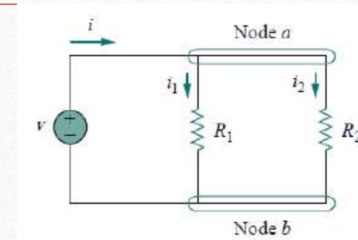
$$i_1 = \frac{v}{R_1} = \frac{i * \frac{R_1 R_2}{R_1 + R_2}}{R_1} = \frac{R_2}{R_1 + R_2} * i$$

$$i_2 = \frac{v}{R_2} = \frac{i * \frac{R_1 R_2}{R_1 + R_2}}{R_2} = \frac{R_1}{R_1 + R_2} * i$$



$$i_1 = \frac{R_2}{R_1 + R_2} * i$$

$$i_2 = \frac{R_1}{R_1 + R_2} * i$$



Thank you !

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

DC CIRCUITS

By,
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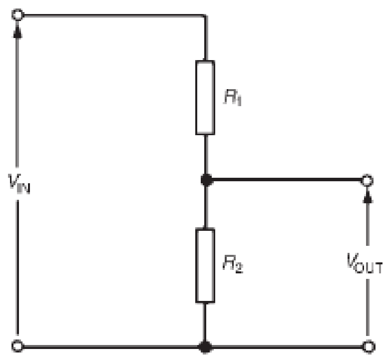
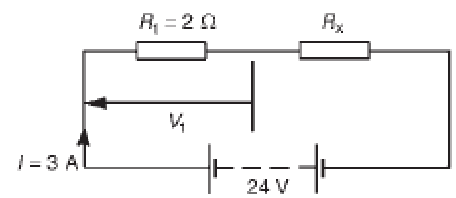
Potential divider



$$V_{OUT} = \left(\frac{R_2}{R_1 + R_2}\right) V_{IN}$$

Potential divider

Problem. Two resistors are connected in series across a 24 V supply and a current of 3 A flows in the circuit. If one of the resistors has a resistance of 2 Ω determine (a) the value of the other resistor, and (b) the p.d. across the 2 Ω resistor. If the circuit is connected for 50 hours, how much energy is used?



Total circuit resistance $R = \frac{V}{I} = \frac{24}{3} = 8\ \Omega$

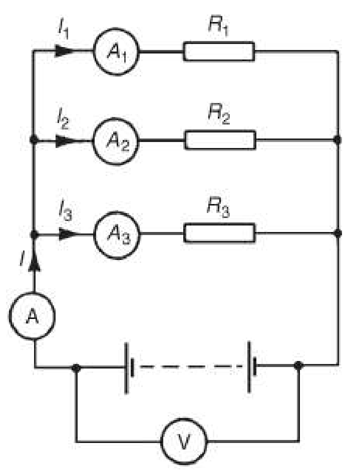
Value of unknown resistance, $R_x = 8 - 2 = \mathbf{6\ \Omega}$

P.d. across 2 Ω resistor, $V_1 = IR_1 = 3 \times 2 = \mathbf{6\ V}$

$$V_1 = \left(\frac{R_1}{R_1 + R_x}\right) \mathrm{V} = \left(\frac{2}{2+6}\right)(24) = 6\ \mathrm{V}$$

$$\begin{aligned}\text{Energy used} &= \text{power} \times \text{time} \\ &= V \times I \times t \\ &= (24 \times 3\ \mathrm{W})(50\ \mathrm{h}) \\ &= 3600\ \mathrm{Wh} = \mathbf{3.6\ kWh}\end{aligned}$$

Parallel Networks



From Ohm's law:

$$I_1 = \frac{V}{R_1},\ I_2 = \frac{V}{R_2},\ I_3 = \frac{V}{R_3} \text{ and } I = \frac{V}{R}$$

Since $I = I_1 + I_2 + I_3$

then, $\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$

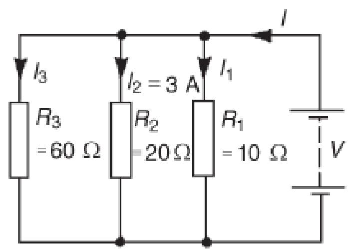
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

For the special case of **two resistors in parallel**

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

Parallel Networks

Problem • For the circuit shown in Figure 5.12, find (a) the value of the supply voltage V and (b) the value of current I.



P.d. across 20 Ω resistor $= I_2R_2 = 3 \times 20 = 60$ V,

$$\boldsymbol{V = 60\ \mathrm{V}}$$

Current $I_1 = \dfrac{V}{R_1} = \dfrac{60}{10} = 6$ A;

$$I_3 = \frac{V}{R_3} = \frac{60}{60} = 1 \text{ A}$$

Current $I = I_1 + I_2 + I_3$ $\quad$ $\boldsymbol{I = 6 + 3 + 1 = 10\ \mathrm{A}}$

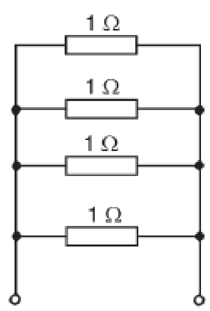
Alternatively, $\dfrac{1}{R} = \dfrac{1}{60} + \dfrac{1}{20} + \dfrac{1}{10} = \dfrac{1+3+6}{60} = \dfrac{10}{60}$

Hence total resistance $R = \dfrac{60}{10} = 6\ \Omega$

Current $I = \dfrac{V}{R} = \dfrac{60}{6} = \mathbf{10\ A}$

Problem • Given four 1 Ω resistors, state how they must be connected to give an overall resistance of (a) $\frac{1}{4}\Omega$ (b) 1 Ω (c) $1\frac{1}{3}$ Ω (d) $2\frac{1}{2}$ Ω, all four resistors being connected in each case.

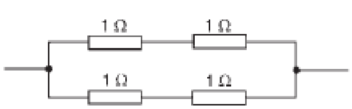
(a) **All four in parallel**



since $\dfrac{1}{R} = \dfrac{1}{1} + \dfrac{1}{1} + \dfrac{1}{1} + \dfrac{1}{1} = \dfrac{4}{1}$, i.e., $R = \dfrac{1}{4}\Omega$

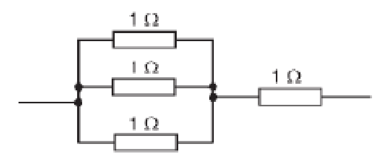
(b) **Two in series, in parallel with another two in series**

$$\frac{2 \times 2}{2+2} = \frac{4}{4} = 1\ \Omega$$



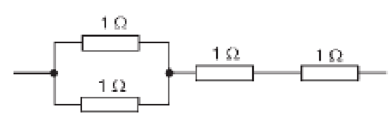
(c) **Three in parallel, in series with one**

$\dfrac{1}{R} = \dfrac{1}{1} + \dfrac{1}{1} + \dfrac{1}{1} = \dfrac{3}{1}$, i.e., $R = \dfrac{1}{3}$ Ω and $\dfrac{1}{3}$ Ω in series with 1 Ω gives $1\frac{1}{3}$ Ω

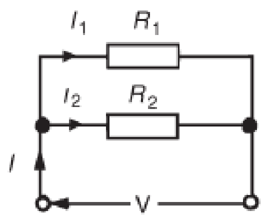


(d) **Two in parallel, in series with two in series**

$R = \dfrac{1 \times 1}{1+1} = \dfrac{1}{2}$ Ω, and $\dfrac{1}{2}$ Ω, 1 Ω and 1 Ω in series gives $2\dfrac{1}{2}$ Ω



Current division



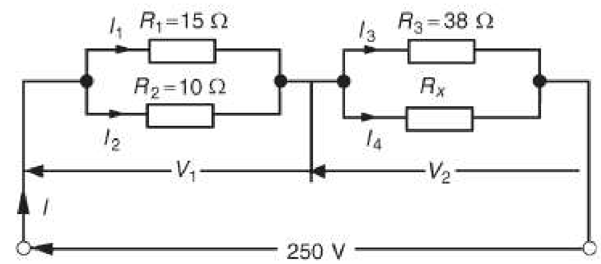
$$R_T = \frac{R_1R_2}{R_1+R_2} \qquad \text{and} \quad V = IR_T = I\left(\frac{R_1R_2}{R_1+R_2}\right)$$

$$\text{Current } I_1 = \frac{V}{R_1} = \frac{I}{R_1}\left(\frac{R_1R_2}{R_1+R_2}\right) = \left(\frac{R_2}{R_1+R_2}\right)(I)$$

$$\text{current } I_2 = \frac{V}{R_2} = \frac{I}{R_2}\left(\frac{R_1R_2}{R_1+R_2}\right) = \left(\frac{R_1}{R_1+R_2}\right)(I)$$

$$\boxed{I_1 = \left(\frac{R_2}{R_1+R_2}\right)(I)} \quad \text{and} \quad \boxed{I_2 = \left(\frac{R_1}{R_1+R_2}\right)(I)}$$

Problem For the circuit shown in Figure calculate (a) the value of resistor R_x such that the total power dissipated in the circuit is 2.5 kW, and (b) the current flowing in each of the four resistors.



(a) Power dissipated $P = VI$ watts, hence $2500 = (250)(I)$

$$I = \frac{2500}{250} = 10 \text{ A}$$

The equivalent resistance of R_1 and R_2 in parallel is $\dfrac{15 \times 10}{15+10} = \dfrac{150}{25} = 6\ \Omega$

The equivalent resistance of resistors R_3 and R_x in parallel is equal to $25\ \Omega - 6\ \Omega$, i.e., $19\ \Omega$

$$19 = \frac{38R_x}{38+R_x}$$

$$19(38+R_x) = 38R_x$$

$$722 + 19R_x = 38R_x$$

$$722 = 38R_x - 19R_x = 19R_x$$

Thus $R_x = \dfrac{722}{19} = \mathbf{38\ \Omega}$

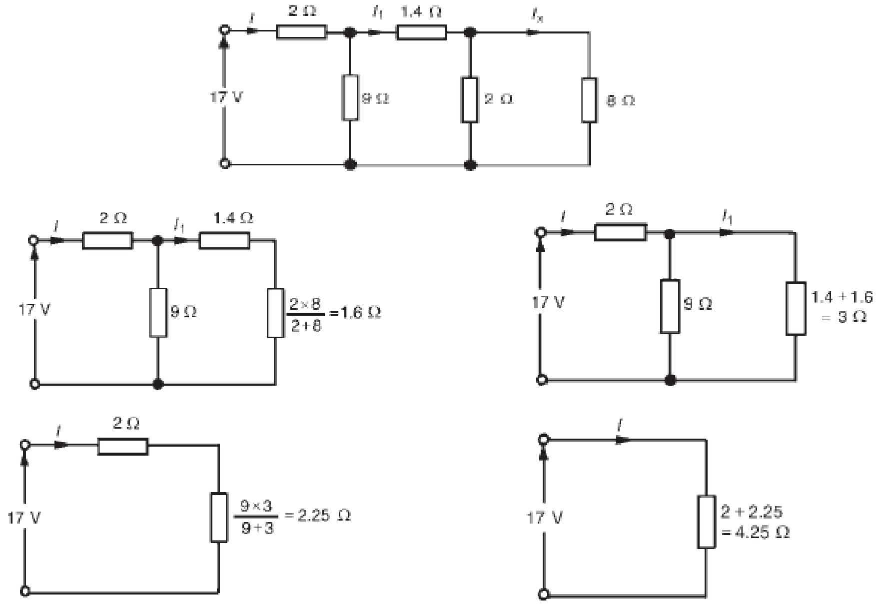
(b) Current $I_1 = \left(\dfrac{R_2}{R_1+R_2}\right) I = \left(\dfrac{10}{15+10}\right)(10)$

$$= \left(\frac{2}{5}\right)(10) = \mathbf{4\ A}$$

$$\text{Current } I_2 = \left(\frac{R_1}{R_1+R_2}\right) I = \left(\frac{15}{15+10}\right)(10)$$

$$= \left(\frac{3}{5}\right)(10) = \mathbf{6\ A}$$

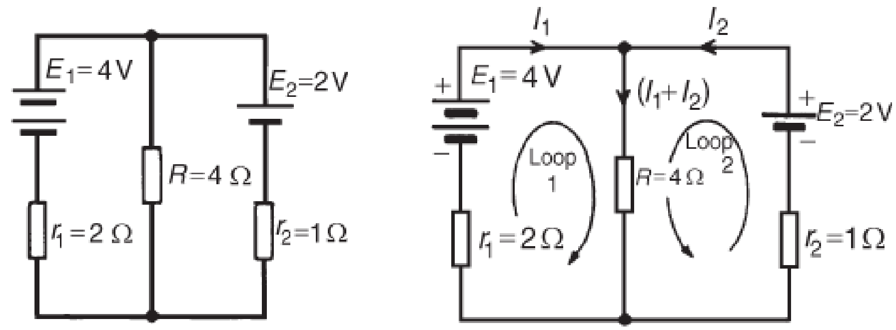
$$\mathbf{I_3 = I_4 = 5\ A}$$



$$I_x = \left(\frac{2}{2+8}\right)(I_1) = \left(\frac{2}{10}\right)(3) = \mathbf{0.6\ A}$$

Kirchhoff's law

Problem : Use Kirchhoff's laws to determine the currents flowing in each branch of the network shown in Figure



$$E_1 = I_1 r_1 + (I_1 + I_2)R, \text{ i.e. } 4 = 2I_1 + 4(I_1 + I_2),$$

$$\text{i.e. } 6I_1 + 4I_2 = 4$$

$$E_2 = I_2 r_2 + (I_1 + I_2)R, \text{ i.e. } 2 = I_2 + 4(I_1 + I_2),$$

$$\text{i.e. } 4I_1 + 5I_2 = 2$$

$$12I_1 + 8I_2 = 8$$

$$12I_1 + 15I_2 = 6$$

$$I_2 = -\frac{2}{7} = \mathbf{-0.286\ A}$$

$$6I_1 + 4(-0.286) = 4$$

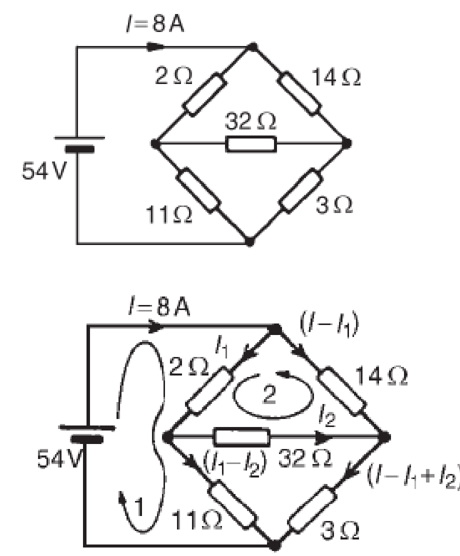
$$6I_1 = 4 + 1.144$$

$$I_1 = \frac{5.144}{6} = \mathbf{0.857\ A}$$

Current flowing through resistance R is

$$I_1 + I_2 = 0.857 + (-0.286) = \mathbf{0.571\ A}$$

Problem . For the bridge network shown in Figure , determine the currents in each of the resistors.



$$54 = 2I_1 + 11(I_1 - I_2)$$

i.e. $13I_1 - 11I_2 = 54$

$$0 = 2I_1 + 32I_2 - 14(I - I_1)$$

$I = 8$ A

$$0 = 2I_1 + 32I_2 - 14(8 - I_1)$$

$$16I_1 + 32I_2 = 112$$

$$208I_1 - 176I_2 = 864$$

$$208I_1 + 416I_2 = 1456$$

$$592I_2 = 592$$

$$I_2 = 1 \text{ A}$$

$$13I_1 - 11 = 54$$

$$I_1 = \frac{65}{13} = 5\ A$$

the current flowing in the 2 Ω resistor $= I_1 = \mathbf{5\ A}$

the current flowing in the 14 Ω resistor $= I - I_1 = 8 - 5 = \mathbf{3\ A}$

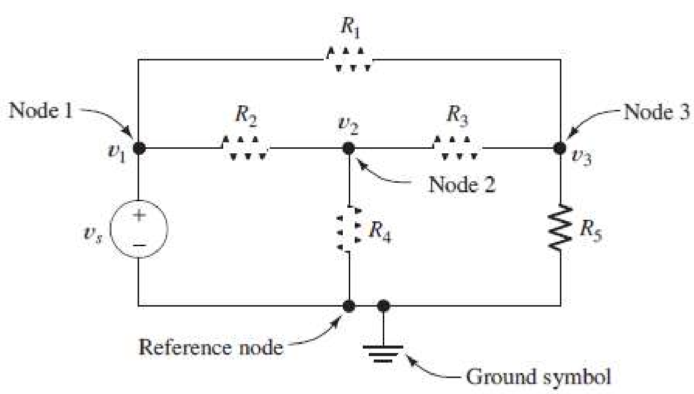
the current flowing in the 32 Ω resistor $= I_2 = \mathbf{1\ A}$

the current flowing in the 11 Ω resistor $= I_1 - I_2 = 5 - 1 = \mathbf{4\ A}$ and

the current flowing in the 3 Ω resistor $= I - I_1 + I_2 = 8 - 5 + 1$

$= \mathbf{4\ A}$

NODE VOLTAGE ANALYSIS



The first step in node analysis is to select a reference node and label the voltages at each of the other nodes.

Selecting the Reference Node

A **node** is a point at which two or more circuit elements are joined together. In node-voltage analysis, we first select one of the nodes as the **reference node**. In principle, any node can be picked to be the reference node. However, the solution is usually facilitated by selecting one end of a voltage source as the reference node.

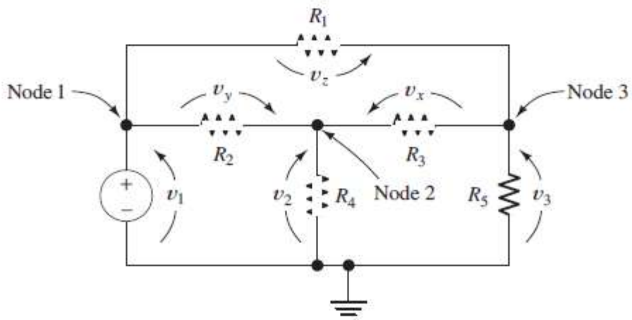
Assigning Node Voltages

Next, we label the voltages at each of the other nodes.

The negative reference polarity for each of the node voltages is at the reference node.

Finding Element Voltages in Terms of the Node Voltages

In node-voltage analysis, we write equations and eventually solve for the node voltages. Once the node voltages have been found, it is relatively easy to find the current, voltage, and power for each element in the circuit.



Assuming that we can determine the node voltages v_1, v_2, and v_3, we can use KVL to determine v_x, v_y, and v_z. Then using Ohm's law, we can find the current in each of the resistances. Thus, the key problem is in determining the node voltages.

$$-v_2 + v_x + v_3 = 0$$

Solving for v_x, we obtain

$$v_x = v_2 - v_3$$

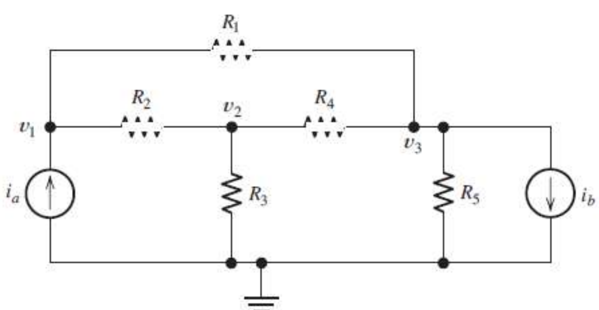
Writing KCL Equations in Terms of the Node Voltages

$$v_1 = v_s$$

$$\frac{v_2 - v_1}{R_2} + \frac{v_2}{R_4} + \frac{v_2 - v_3}{R_3} = 0$$

$$\frac{v_3 - v_1}{R_1} + \frac{v_3}{R_5} + \frac{v_3 - v_2}{R_3} = 0$$

$$\mathbf{GV} = \mathbf{I} \qquad\qquad \mathbf{V} = \mathbf{G}^{-1}\mathbf{I}$$



Node 1: $\quad \dfrac{v_1 - v_3}{R_1} + \dfrac{v_1 - v_2}{R_2} = i_a$

Node 2: $\quad \dfrac{v_2 - v_1}{R_2} + \dfrac{v_2}{R_3} + \dfrac{v_2 - v_3}{R_4} = 0$

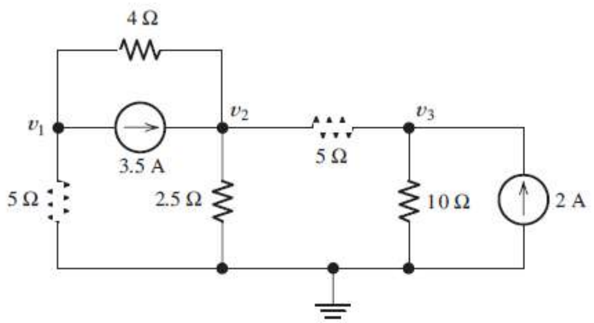
Node 3: $\quad \dfrac{v_3}{R_5} + \dfrac{v_3 - v_2}{R_4} + \dfrac{v_3 - v_1}{R_1} + i_b = 0$

$$\begin{bmatrix} \frac{1}{R_1} + \frac{1}{R_2} & -\frac{1}{R_2} & -\frac{1}{R_1} \\ -\frac{1}{R_2} & \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} & -\frac{1}{R_4} \\ -\frac{1}{R_1} & -\frac{1}{R_4} & \frac{1}{R_1} + \frac{1}{R_4} + \frac{1}{R_5} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} i_a \\ 0 \\ -i_b \end{bmatrix}$$

Thus, if a circuit consists of resistances and independent current sources, we can use the following steps to rapidly write the node equations directly in matrix form.

1. Make sure that the circuit contains only resistances and independent current sources.
2. The diagonal terms of **G** are the sums of the conductances connected to the corresponding nodes.
3. The off diagonal terms of **G** are the negatives of the conductances connected between the corresponding nodes.
4. The elements of **I** are the currents pushed into the corresponding nodes by the current sources.

Write the node-voltage equations in matrix form for the circuit of Figure



Writing KCL at each node, we have

$$\frac{v_1}{5} + \frac{v_1 - v_2}{4} + 3.5 = 0 \qquad \frac{v_2 - v_1}{4} + \frac{v_2}{2.5} + \frac{v_2 - v_3}{5} = 3.5$$

$$\frac{v_3 - v_2}{5} + \frac{v_3}{10} = 2$$

Manipulating the equations into standard form, we have

$$0.45v_1 - 0.25v_2 = -3.5$$
$$-0.25v_1 + 0.85v_2 - 0.2v_3 = 3.5$$
$$-0.2v_2 + 0.35v_3 = 2$$

Then, in matrix form, we obtain

$$\begin{bmatrix} 0.45 & -0.25 & 0 \\ -0.25 & 0.85 & -0.20 \\ 0 & -0.20 & 0.30 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} -3.5 \\ 3.5 \\ 2 \end{bmatrix}$$

Answer $v_1 = -5\,\text{V},\ v_2 = 5\,\text{V},\ v_3 = 10\,\text{V}.$

Vellore Institute of Technology

(Deemed to be University under section 3 of UGC Act, 1956)

SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Nodal and Mesh Analysis

By,

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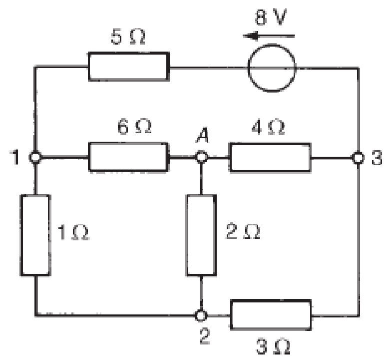
Assistant Professor, SELECT

NODAL ANALYSIS

Problem 9. Use nodal analysis to determine the voltages at nodes 2 and 3 in Figure 31.13 and hence determine the current flowing in the 2 Ω resistor and the power dissipated in the 3 Ω resistor.



At node 1, $$\frac{V_1-V_2}{1}+\frac{V_1}{6}+\frac{V_1-8-V_3}{5}=0$$

At node 2, $$\frac{V_2}{2}+\frac{V_2-V_1}{1}+\frac{V_2-V_3}{3}=0$$

At node 3, $$\frac{V_3}{4}+\frac{V_3-V_2}{3}+\frac{V_3+8-V_1}{5}=0$$

$$1.367V_1-V_2-0.2V_3-1.6=0$$

$$-V_1+1.833V_2-0.333V_3+0=0$$

$$-0.2V_1-0.333V_2+0.783V_3+1.6=0$$

$$\frac{V_1}{\begin{vmatrix}-1 & -0.2 & -1.6\\ 1.833 & -0.333 & 0\\ -0.333 & 0.783 & 1.6\end{vmatrix}}=\frac{-V_2}{\begin{vmatrix}1.367 & -0.2 & -1.6\\ -1 & -0.333 & 0\\ -0.2 & 0.783 & 1.6\end{vmatrix}}$$

$$=\frac{V_3}{\begin{vmatrix}1.367 & -1 & -1.6\\ -1 & 1.833 & 0\\ -0.2 & -0.333 & 1.6\end{vmatrix}}=\frac{-1}{\begin{vmatrix}1.367 & -1 & -0.2\\ -1 & 1.833 & -0.333\\ -0.2 & -0.333 & 0.783\end{vmatrix}}$$

$$V_2=\frac{0.31104}{0.82093}$$

$$=\mathbf{0.3789\ V}$$

Thus the current in the 2 Ω resistor $=\frac{V_2}{2}=\frac{0.3789}{2}=\mathbf{0.19\ A}$,

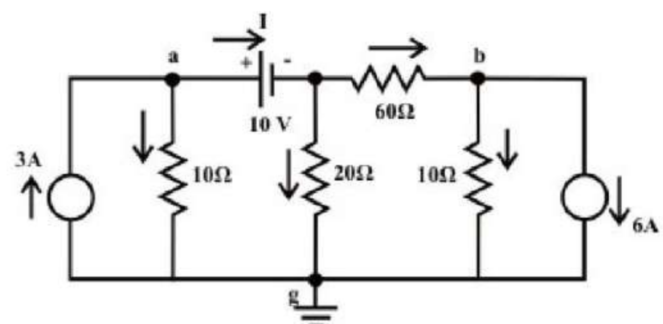
$$\text{voltage}, V_3=\frac{-1.2898}{0.82093}$$

$$=\mathbf{-1.571\ V}$$

Power in the 3 Ω resistor $=(I_3)^2(3)=\left(\frac{V_2-V_3}{3}\right)^2(3)$

$$=\frac{(0.3789-(-1.571))^2}{3}=\mathbf{1.27\ W}$$

Find the value of the current I flowing through the battery using 'Node voltage' method.



KCL equation at node-a:

$$3=\frac{V_a-0}{10}+I\rightarrow 10I+V_a=30$$

KCL equation at node-b:

$$\frac{(V_a-10)-V_b}{60}=6+\frac{V_b-0}{10}\rightarrow V_a-7V_b=370$$

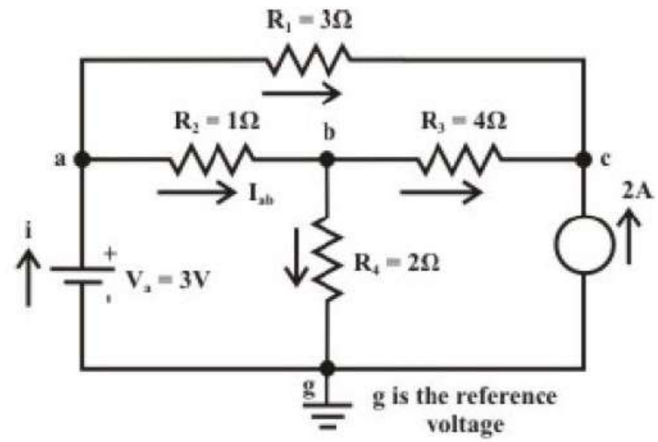
KCL at the central node (note central node voltage is (V_a-10))

$$I=\frac{V_a-10}{20}+\frac{(V_a-10)-V_b}{60}\rightarrow 60I=4V_a-V_b-40\rightarrow I=\frac{(4V_a-V_b-40)}{60}$$

$$V_b=-50.43V \text{ and } V_a=16.99V.$$

$$I=1.307A.$$

Find the **current** through 'ab-branch' (I_{ab}) and **voltage** (V_{cg}) across the current source using Node-voltage method.



KCL at node-a: (note $V_a=3V$)

$$i=\frac{V_a-V_b}{R_2}+\frac{V_a-V_c}{R_1}\rightarrow i=\left(\frac{1}{R_1}+\frac{1}{R_2}\right)V_a-\frac{1}{R_2}V_b-\frac{1}{R_1}V_c\rightarrow i=1.33V_a-V_b-\frac{1}{3}V_c$$

KCL at node-b: (note $V_g=0V$)

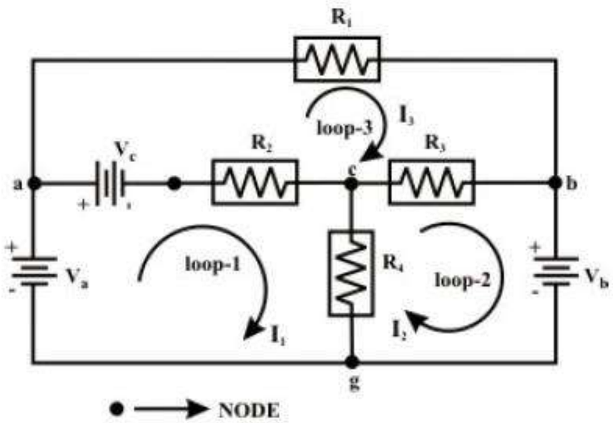
$$\frac{V_a-V_b}{R_2}=\frac{V_b-V_c}{R_3}+\frac{V_b-V_g}{R_4}\rightarrow\left(1+\frac{1}{4}+\frac{1}{2}\right)V_b-V_a-\frac{1}{4}V_c=0$$

KCL at node-c:

$$2+\frac{V_b-V_c}{R_3}+\frac{V_a-V_c}{R_1}=0\quad\rightarrow\left(\frac{1}{4}+\frac{1}{3}\right)V_c-\frac{1}{3}V_a-\frac{1}{4}V_b=2$$

$$V_c=6.26V,\ V_b=2.61V \qquad I_{ab}=\frac{V_a-V_b}{R_2}=\frac{3-2.61}{1}=0.39A$$

MESH ANALYSIS

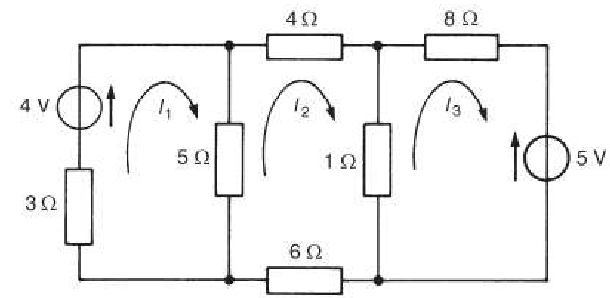


$$V_a - V_c - (I_1 - I_3)R_2 - (I_1 - I_2)R_4 = 0$$

$$-V_b - (I_2 - I_3)R_3 - (I_2 - I_1)R_4 = 0$$

$$V_c - I_3R_1 - (I_3 - I_2)R_3 - (I_3 - I_1)R_2 = 0$$

Problem 1. Use mesh-current analysis to determine the current flowing in (a) the 5 Ω resistance, and (b) the 1 Ω resistance of the d.c. circuit shown in Figure



For loop 1, $(3+5)I_1 - 5I_2 = 4$

For loop 2, $(4+1+6+5)I_2 - (5)I_1 - (1)I_3 = 0$

For loop 3, $(1+8)I_3 - (1)I_2 = -5$

Thus

$$\begin{aligned} 8I_1 - 5I_2 \qquad\quad & - 4 = 0 \\ -5I_1 + 16I_2 - I_3 \quad & = 0 \\ -I_2 \quad + 9I_3 \quad & + 5 = 0 \end{aligned}$$

$$\frac{I_1}{\begin{vmatrix} -5 & 0 & -4 \\ 16 & -1 & 0 \\ -1 & 9 & 5 \end{vmatrix}} = \frac{-I_2}{\begin{vmatrix} 8 & 0 & -4 \\ -5 & -1 & 0 \\ 0 & 9 & 5 \end{vmatrix}} = \frac{I_3}{\begin{vmatrix} 8 & -5 & -4 \\ -5 & 16 & 0 \\ 0 & -1 & 5 \end{vmatrix}}$$

$$= \frac{-1}{\begin{vmatrix} 8 & -5 & 0 \\ -5 & 16 & -1 \\ 0 & -1 & 9 \end{vmatrix}}$$

$$\frac{I_1}{-547} = \frac{-I_2}{140} = \frac{I_3}{495} = \frac{-1}{919}$$

$$I_1 = \frac{547}{919} = 0.595 \text{ A}, \qquad I_2 = \frac{140}{919} = 0.152 \text{ A},$$

$$I_3 = \frac{-495}{919} = -0.539 \text{ A}$$

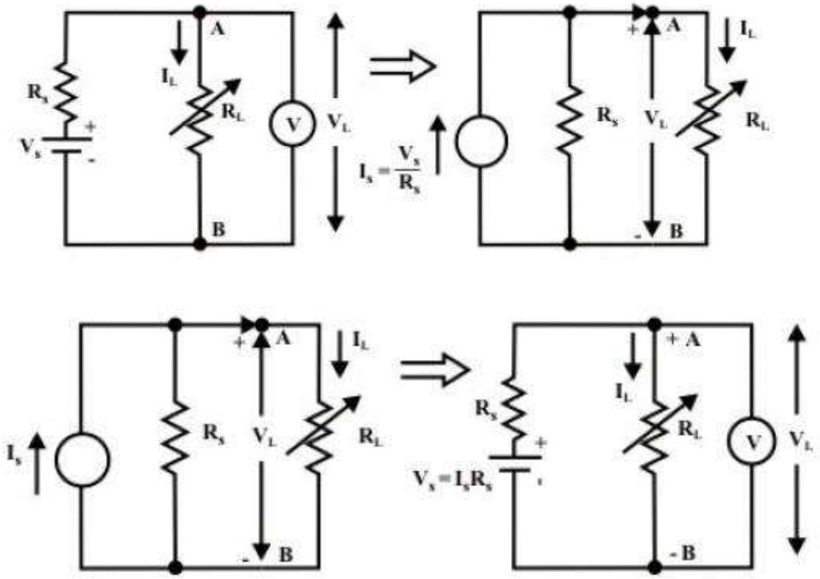
Thus current in the 5 Ω resistance $= I_1 - I_2 = 0.595 - 0.152$

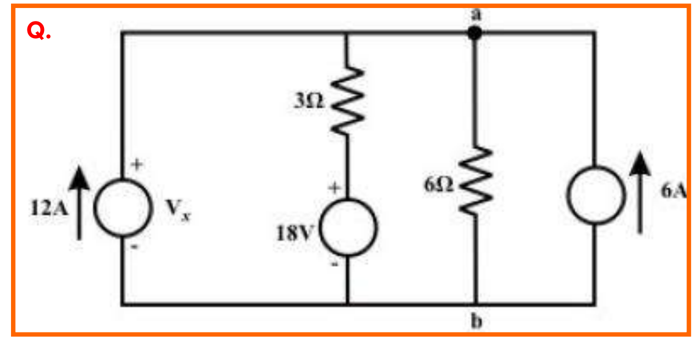
$= \mathbf{0.44\ A}$,

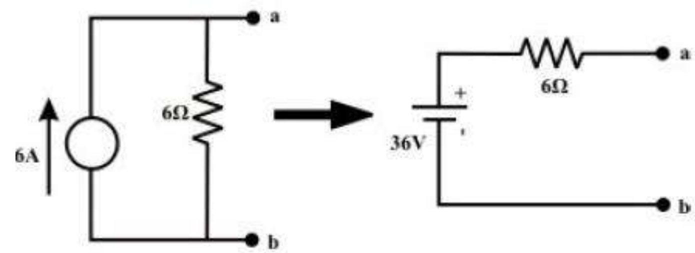
and current in the 1 Ω resistance $= I_2 - I_3 = 0.152 - (-0.539)$

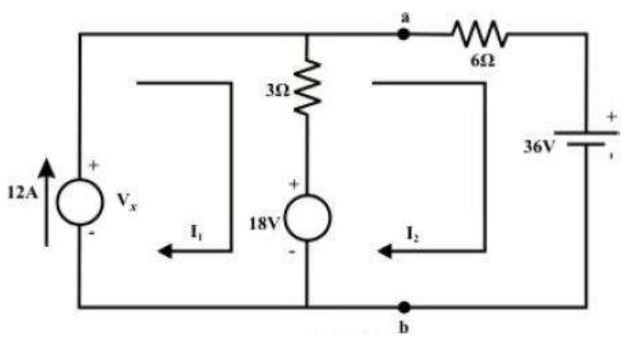
$= \mathbf{0.69\ A}$

Source conversions









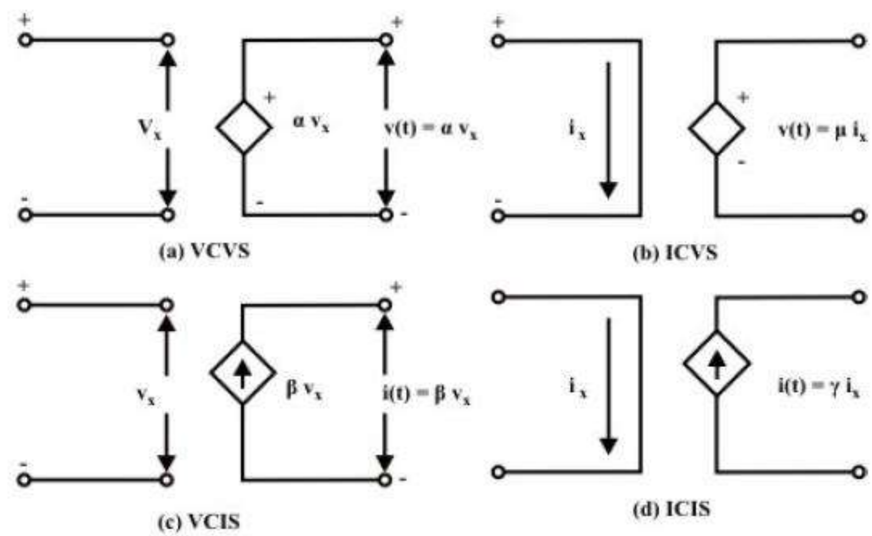
Loop-1: (Write KVL, note $I_1 = 12A$)

$V_x - (I_1 - I_2)\times 3 - 18 = 0 \Rightarrow V_x + 3I_2 = 54$

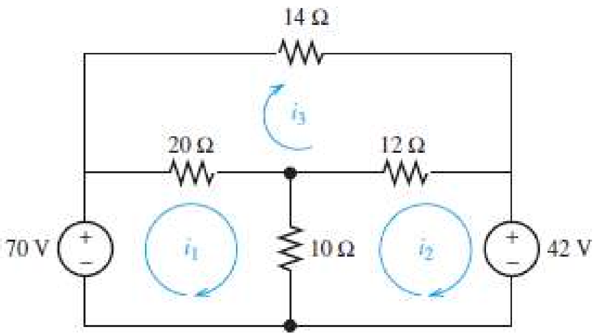
Loop-2: (write KVL)

$18 - (I_2 - I_1)\times 3 - I_2 \times 6 - 36 = 0 \Rightarrow 9I_2 = 18 \Rightarrow I_2 = 2A$

Dependent sources



Q.



$$20(i_1 - i_3) + 10(i_1 - i_2) - 70 = 0$$

For meshes 2 and 3, we have:

$$10(i_2 - i_1) + 12(i_2 - i_3) + 42 = 0$$
$$20(i_3 - i_1) + 14i_3 + 12(i_3 - i_2) = 0$$

In matrix form, the equations become:

$$\begin{bmatrix} 30 & -10 & -20 \\ -10 & 22 & -12 \\ -20 & -12 & 46 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} 70 \\ -42 \\ 0 \end{bmatrix}$$

```
I =

    4.0000
    1.0000
    2.0000
```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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Nodal and Mesh Analysis

By,

Meera P. S.

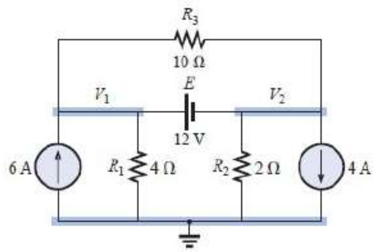
Assistant Professor, SELECT

SUPERNODE

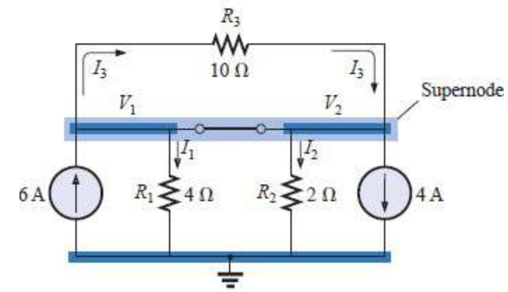
On occasion there will be independent voltage sources in the network to which nodal analysis is to be applied. In such cases we can convert the voltage source to a current source (if a series resistor is present) and proceed as before, or we can introduce the concept of a ***supernode*** and proceed.

Any node including the effect of elements tied only to other nodes is referred to as a supernode.

EXAMPLE :- Determine the nodal voltages V_1 and V_2 of Fig. using the concept of a supernode.



Replacing the independent voltage source of 12 V with a short-circuit equivalent will result in the network of Fig. The result is a single supernode for which Kirchhoff's current law must be applied. Be sure to leave the other defined nodes in place and use them to define the currents from that region of the network.



$\Sigma I_i = \Sigma I_o$ $\qquad$ $6\text{ A} + I_3 = I_1 + I_2 + 4\text{ A} + I_3$ $\qquad$ $I_1 + I_2 = 6\text{ A} - 4\text{ A} = 2\text{ A}$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = 2\text{ A} \qquad \frac{V_1}{4\,\Omega} + \frac{V_2}{2\,\Omega} = 2\text{ A}$$

$$V_1 - V_2 = E = 12\text{ V}$$

$$V_2 = \frac{-1}{0.75} = \mathbf{-1.333\text{ V}}$$

$$V_1 = V_2 + 12\text{ V} = -1.333\text{ V} + 12\text{ V} = \mathbf{+10.667\text{ V}}$$

The current of the network can then be determined as follows:

$$I_1\downarrow = \frac{V}{R_1} = \frac{10.667\text{ V}}{4\,\Omega} = \mathbf{2.667\text{ A}}$$

$$I_2\uparrow = \frac{V_2}{R_2} = \frac{1.333\text{ V}}{2\,\Omega} = \mathbf{0.667\text{ A}}$$

$$\underset{\rightarrow}{I_3} = \frac{V_1 - V_2}{10\,\Omega} = \frac{10.667\text{ V} - (-1.333\text{ V})}{10\,\Omega} = \frac{12\text{ V}}{10\,\Omega} = \mathbf{1.2\text{ A}}$$

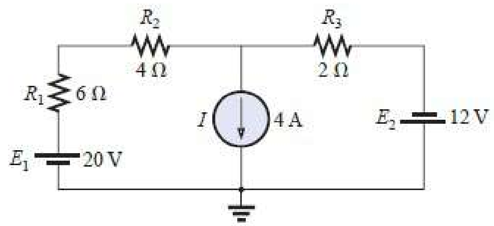
SUPERMESH

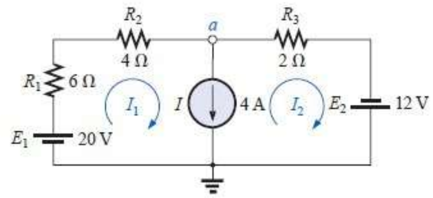
On occasion there will be current sources in the network to which mesh analysis is to be applied. In such cases one can convert the current source to a voltage source (if a parallel resistor is present) and proceed as before or utilize a **supermesh** current and proceed.

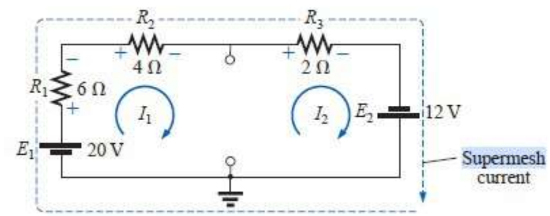
Any resulting path,

including two or more mesh currents, is said to be the path of a supermesh current.

EXAMPLE Using mesh analysis, determine the currents of the network of Fig.







Applying Kirchhoff's law:

$$20\ \text{V} - I_1(6\ \Omega) - I_1(4\ \Omega) - I_2(2\ \Omega) + 12\ \text{V} = 0$$

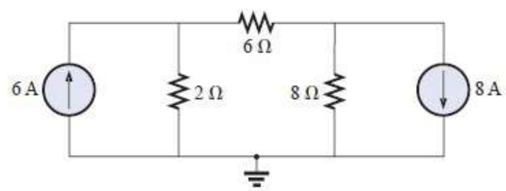
$$I_1 = I + I_2$$

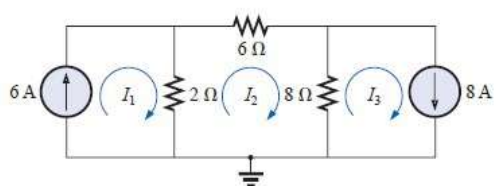
$$\begin{aligned} 10I_1 + 2I_2 &= 32 \\ I_1 - I_2 &= 4 \end{aligned}$$

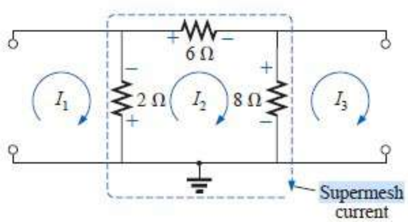
$$I_1 = \frac{\begin{vmatrix} 32 & 2 \\ 4 & -1 \end{vmatrix}}{\begin{vmatrix} 10 & 2 \\ 1 & -1 \end{vmatrix}} = \frac{(32)(-1) - (2)(4)}{(10)(-1) - (2)(1)} = \frac{40}{12} = \mathbf{3.33\ A}$$

$$I_2 = I_1 - I = 3.33\ \text{A} - 4\ \text{A} = \mathbf{-0.67\ A}$$

EXAMPLE Using mesh analysis, determine the currents for the network of Fig.







Applying Kirchhoff's voltage law around the supermesh path:

$$\begin{aligned} &-V_{2\Omega} - V_{6\Omega} - V_{8\Omega} = 0 \\ &-(I_2 - I_1)2\ \Omega - I_2(6\ \Omega) - (I_2 - I_3)8\ \Omega = 0 \\ &-2I_2 + 2I_1 - 6I_2 - 8I_2 + 8I_3 = 0 \\ &\ \ 2I_1 - 16I_2 + 8I_3 = 0 \end{aligned}$$

$$I_1 = 6\ \text{A} \qquad 2I_1 - 16I_2 + 8I_3 = 0$$

$$I_3 = 8\ \text{A} \qquad 2(6\ \text{A}) - 16I_2 + 8(8\ \text{A}) = 0$$

$$I_2 = \frac{76\ \text{A}}{16} = \mathbf{4.75\ A}$$

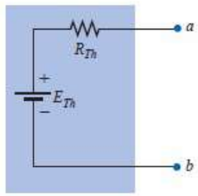
Then $\quad I_{2\Omega}\downarrow = I_1 - I_2 = 6\ \text{A} - 4.75\ \text{A} = \mathbf{1.25\ A}$

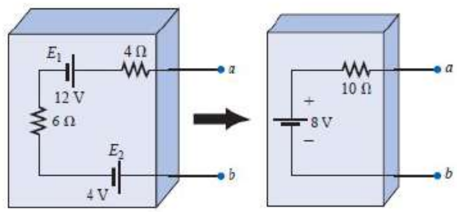
and $\quad I_{8\Omega}\uparrow = I_3 - I_2 = 8\ \text{A} - 4.75\ \text{A} = \mathbf{3.25\ A}$

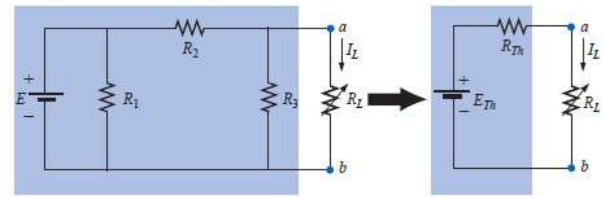
THEVENIN'S THEOREM

Thévenin's theorem states the following:

Any two-terminal, linear bilateral dc network can be replaced by an equivalent circuit consisting of a voltage source and a series resistor, as shown in Fig.







STEPS TO OBTAIN THE THEVENIN EQUIVALENT CIRCUIT

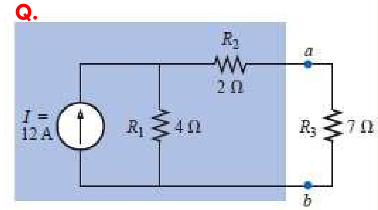
1. Remove that portion of the network across which the Thevenin equivalent circuit is to be found. The load resistor R_L has to be temporarily removed from the network.
2. Mark the terminals of the remaining two-terminal network.

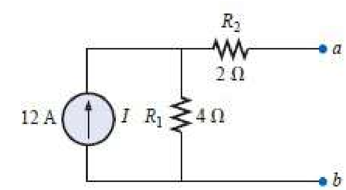
3. Calculate R_{Th} by first setting all sources to zero (voltage sources are replaced by short circuits, and current sources by open circuits) and then finding the resultant resistance between the two marked terminals. (If the internal resistance of the voltage and/or current sources is included in the original network, it must remain when the sources are set to zero.)

4. Calculate E_{Th} by first returning all sources to their original position and finding the open-circuit voltage between the marked terminals.

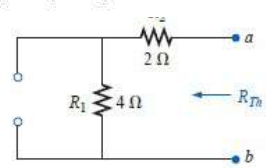
5. Draw the Thevenin equivalent circuit with the portion of the circuit previously removed replaced between the terminals of the equivalent circuit. This step is indicated by the placement of the resistor R_L between the terminals of the Thevenin equivalent circuit.

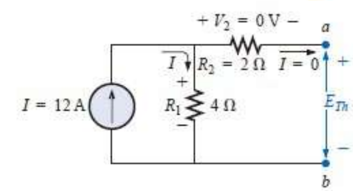
Q.



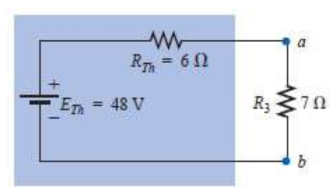


$$R_{Th} = R_1 + R_2 = 4\ \Omega + 2\ \Omega = 6\ \Omega$$





$$E_{Th} = V_1 = I_1R_1 = IR_1 = (12\ \text{A})(4\ \Omega) = \mathbf{48\ V}$$



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Basic Electrical & Electronics Engineering

Thevenin's theorem
&
Maximum Power Transfer theorem

By,
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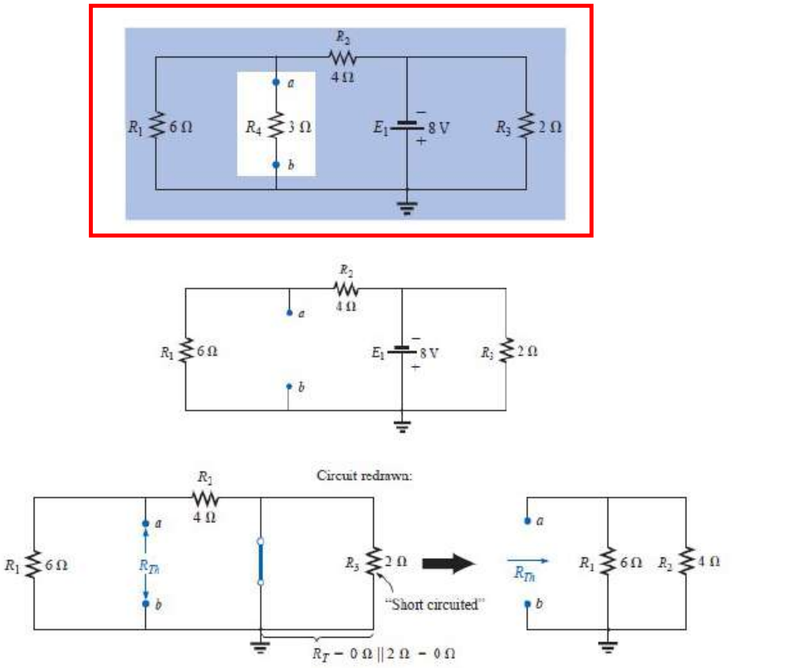
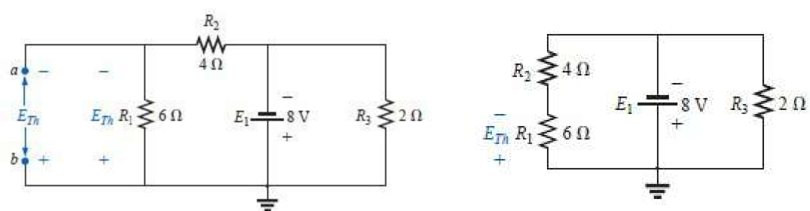
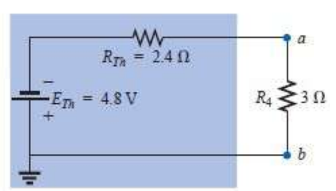
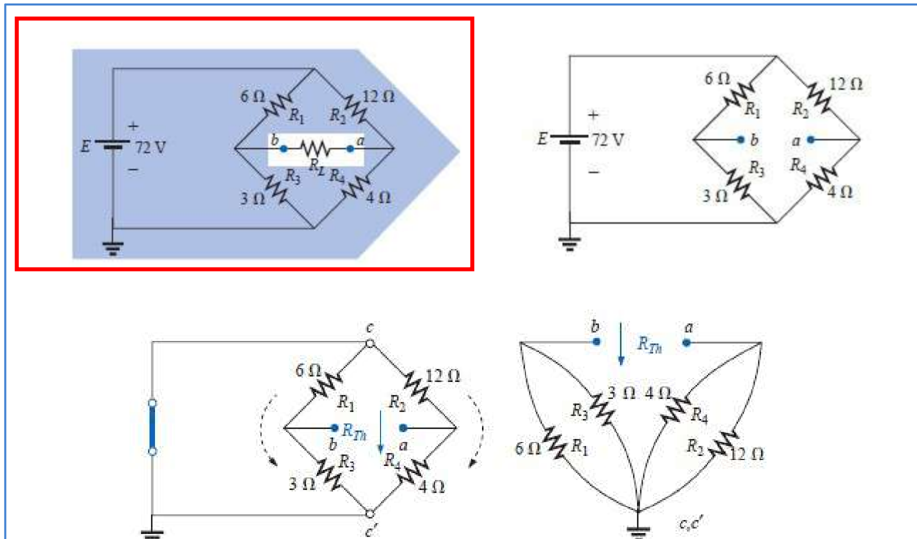
Assistant Professor, SELECT



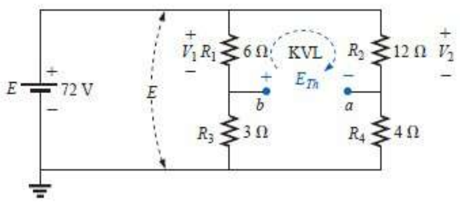


$$E_{Th} = \frac{R_1E_1}{R_1+R_2} = \frac{(6\,\Omega)(8\,V)}{6\,\Omega + 4\,\Omega} = \frac{48\,V}{10} = \mathbf{4.8\,V}$$





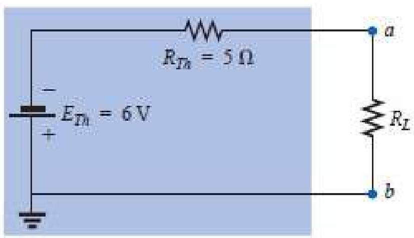
$$\begin{aligned} R_{Th} = R_{a\text{-}b} &= R_1 \| R_3 + R_2 \| R_4 \\ &= 6\,\Omega \| 3\,\Omega + 4\,\Omega \| 12\,\Omega \\ &= 2\,\Omega + 3\,\Omega = 5\,\Omega \end{aligned}$$



$$V_1 = \frac{R_1 E}{R_1 + R_3} = \frac{(6\ \Omega)(72\ \text{V})}{6\ \Omega + 3\ \Omega} = \frac{432\ \text{V}}{9} = 48\ \text{V}$$

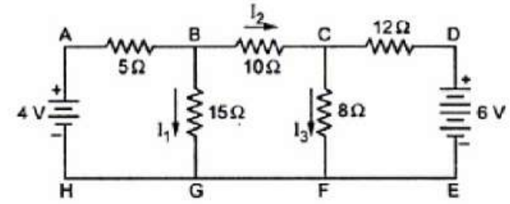
$$V_2 = \frac{R_2 E}{R_2 + R_4} = \frac{(12\ \Omega)(72\ \text{V})}{12\ \Omega + 4\ \Omega} = \frac{864\ \text{V}}{16} = 54\ \text{V}$$

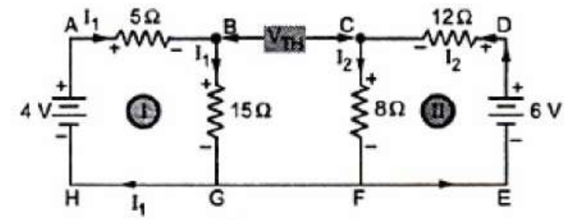
$$\Sigma_{\circlearrowleft} V = +E_{Th} + V_1 - V_2 = 0$$



$$E_{Th} = V_2 - V_1 = 54\ \text{V} - 48\ \text{V} = 6\ \text{V}$$

Find the current I_2, in Fig. ___ by application of Thevenin's theorem.





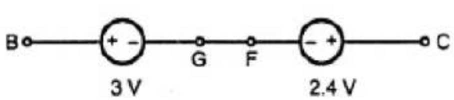
Applying KVL to the two loops,

$$-5\,I_1 - 15\,I_1 + 4 = 0 \qquad I_1 = \frac{4}{20} = 0.2\ \text{A}$$

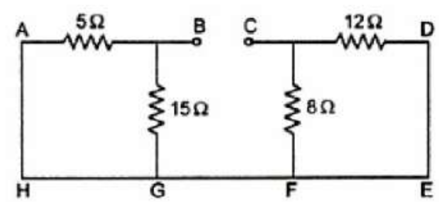
$$\text{Drop } V_{BG} = 15 \times 0.2 = 3\ \text{V}$$

$$-12\,I_2 - 8\,I_2 + 6 = 0 \qquad I_2 = \frac{6}{20} = 0.3\ \text{A}$$

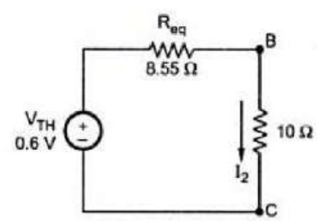
$$\text{Drop } V_{CF} = 8 \times 0.3 = 2.4\ \text{V}$$



$$V_{TH} = V_{BC} = 3 - 2.4 = 0.6\ \text{V with B positive}$$



$$R_{BC} = (5 \parallel 15) + (8 \parallel 12) = 8.55\ \Omega = R_{eq}$$



$$I_2 = \frac{V_{TH}}{R_{eq} + 10} = \frac{0.6}{8.55 + 10}$$

$$= 32.345\ \text{mA}$$

MAXIMUM POWER TRANSFER THEOREM

The **maximum power transfer theorem** states the following:

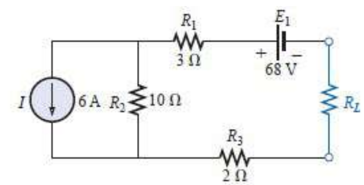
A load will receive maximum power from a linear bilateral dc network when its total resistive value is exactly equal to the Thévenin resistance of the network as "seen" by the load.

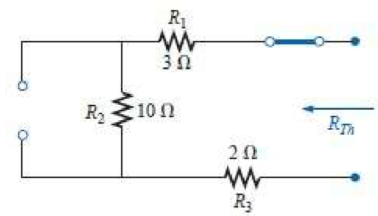
$$I = \frac{E_{Th}}{R_{Th} + R_L} = \frac{E_{Th}}{2R_{Th}}$$

$$P_L = I^2 R_L = \left(\frac{E_{Th}}{2R_{Th}}\right)^2 R_{Th} = \frac{E_{Th}^2 R_{Th}}{4R_{Th}^2}$$

$$\boxed{P_{L_{max}} = \frac{E_{Th}^2}{4R_{Th}}} \quad \text{(watts, W)}$$

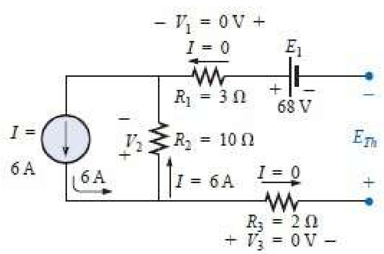
EXAMPLE — Find the value of R_L in Fig. ___ for maximum power to R_L, and determine the maximum power.





$$R_{Th} = R_1 + R_2 + R_3 = 3\ \Omega + 10\ \Omega + 2\ \Omega = 15\ \Omega$$

$$R_L = R_{Th} = \mathbf{15\ \Omega}$$



$$V_1 = V_3 = 0\ \text{V}$$

$$V_2 = I_2R_2 = IR_2 = (6\ \text{A})(10\ \Omega) = 60\ \text{V}$$

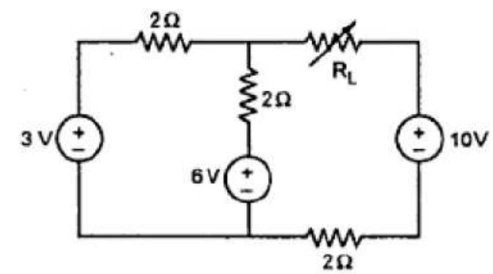
Applying Kirchhoff's voltage law,

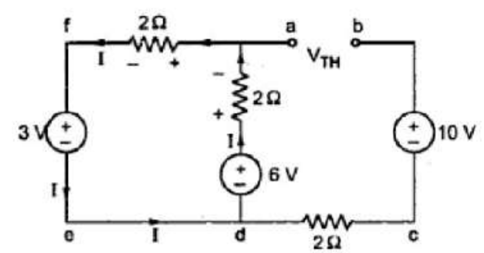
$$\Sigma_C\ V = -V_2 - E_1 + E_{Th} = 0$$

$$E_{Th} = V_2 + E_1 = 60\ \text{V} + 68\ \text{V} = 128\ \text{V}$$

$$P_{L_{max}} = \frac{E_{Th}^2}{4R_{Th}} = \frac{(128\ \text{V})^2}{4(15\ \Omega)} = \mathbf{273.07\ W}$$

Example — *Find the value of R_L for maximum power transfer and the magnitude of maximum power dissipated in the resistor R_L in the circuit shown in the Fig.*





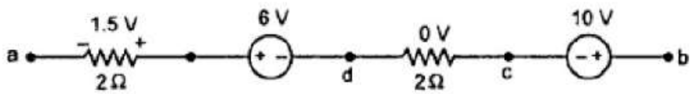
Applying KVL to the loop,

$$-2I - 2I - 3 + 6 = 0$$

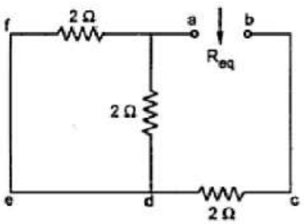
$$4I = 3$$

$$I = 0.75\ \text{A}$$

Drop across 2 Ω = 2×0.75 = 1.5 V



V_{TH} = 11.5 − 6 = 5.5 V with b positive with respect to a.



$$R_{eq} = [2 \parallel 2] + 2 = 1 + 2 = 3\ \Omega$$

Thus for maximum power transfer to load,

$$R_L = R_{eq} = 3\ \Omega$$

$$P_{max} = \frac{V_{TH}^2}{4\,R_{eq}} = \frac{(5.5)^2}{4 \times 3} = 2.5208\ \text{W}$$

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

AC circuits

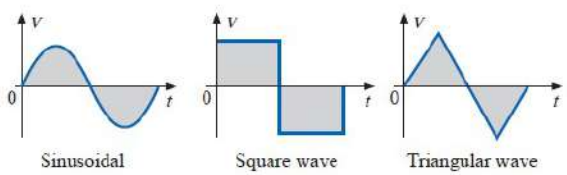
By,

Meera P. S.

Assistant Professor, SELECT

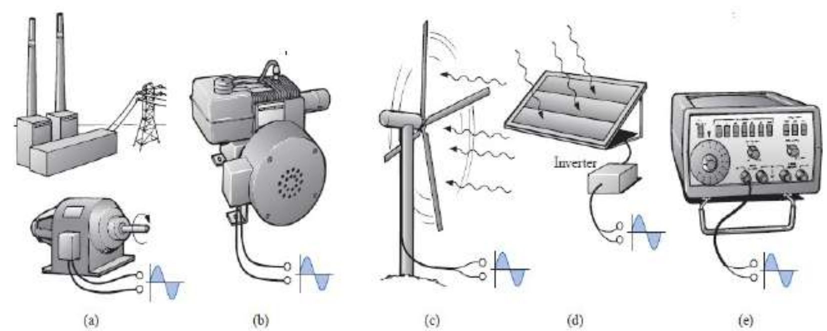
Alternating waveforms

❖ The term **alternating** indicates only that the waveform alternates between two prescribed levels in a set time sequence.



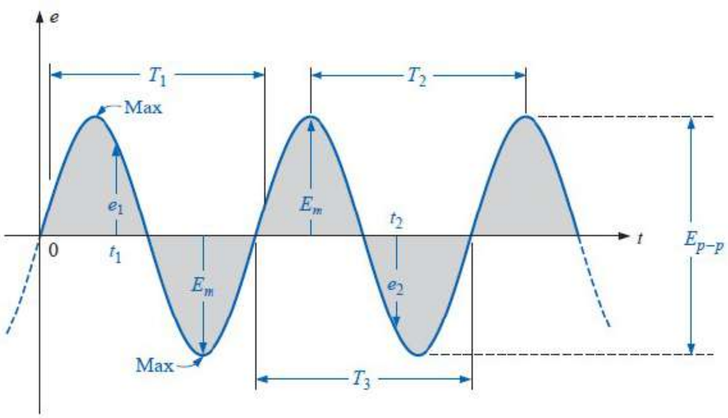
❖ One of the important reasons for concentrating on the sinusoidal ac voltage is that it is the voltage generated by utilities throughout the world. Other reasons include its application throughout electrical, electronic, communication, and industrial systems.

SINUSOIDAL AC VOLTAGE



Various sources of ac power: (a) generating plant; (b) portable ac generator; (c) wind-power station; (d) solar panel; (e) function generator.

Definitions

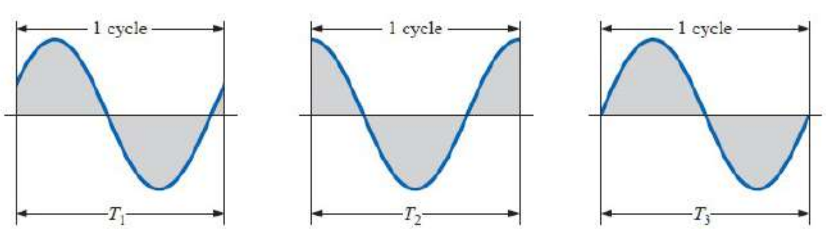


Definitions

- **Instantaneous value:** The magnitude of a waveform at any instant of time; denoted by lowercase letters (e_1, e_2)
- **Peak amplitude:** The maximum value of a waveform.
- **Peak-to-peak value:** Denoted by E_{p-p}, the full voltage between positive and negative peaks of the waveform, that is, the sum of the magnitude of the positive and negative peaks.
- **Periodic waveform:** A waveform that continually repeats itself after the same time interval.

Definitions

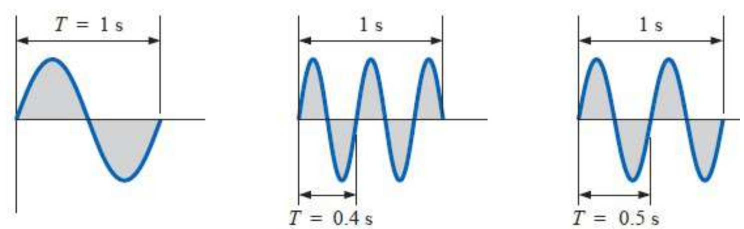
- **Period (T):** The time interval between successive repetitions of a periodic waveform.
- **Cycle:** The portion of a waveform contained in one period of time.



Definitions

- **Frequency (f):** The number of cycles that occur in 1 s. The unit of measure for frequency is the hertz (Hz), where

$$\boxed{1 \text{ hertz (Hz)} = 1 \text{ cycle per second (c/s)}}$$

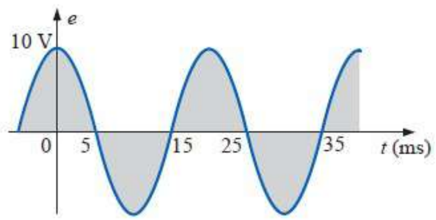


Definitions

$$\boxed{f = \frac{1}{T}}$$

$f = \text{Hz}$
$T = \text{seconds (s)}$

Determine the frequency of the waveform of Fig.



Sine Wave

***The sinusoidal waveform** is the only alternating waveform whose shape is unaffected by the response characteristics of R, L, and C elements.*

$$\boxed{2\pi \text{ rad} = 360°}$$

$$\boxed{1 \text{ rad} = 57.296° \cong 57.3°}$$

$$\boxed{\text{Radians} = \left(\frac{\pi}{180°}\right) \times (\text{degrees})}$$

$$\boxed{\text{Degrees} = \left(\frac{180°}{\pi}\right) \times (\text{radians})}$$

Sine Wave

$$90°\text{:} \quad \text{Radians} = \frac{\pi}{180°}(90°) = \frac{\pi}{2}\ \textbf{rad}$$

$$30°\text{:} \quad \text{Radians} = \frac{\pi}{180°}(30°) = \frac{\pi}{6}\ \textbf{rad}$$

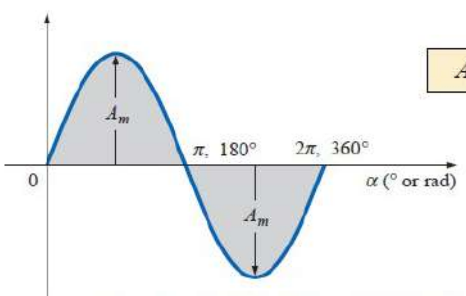
$$\frac{\pi}{3}\ \textbf{rad:} \quad \text{Degrees} = \frac{180°}{\pi}\left(\frac{\pi}{3}\right) = \mathbf{60°}$$

$$\frac{3\pi}{2}\ \textbf{rad:} \quad \text{Degrees} = \frac{180°}{\pi}\left(\frac{3\pi}{2}\right) = \mathbf{270°}$$

$$\boxed{\omega = \frac{2\pi}{T}} \quad (\text{rad/s}) \qquad \boxed{\omega = 2\pi f} \quad (\text{rad/s})$$

Given $\omega = 200$ rad/s, determine how long it will take the sinusoidal waveform to pass through an angle of 90°.

$$t = \frac{\alpha}{\omega} \qquad t = \frac{\alpha}{\omega} = \frac{\pi/2 \text{ rad}}{200 \text{ rad/s}} = \frac{\pi}{400}\text{ s} = \mathbf{7.85\ ms}$$



$$\boxed{A_m \sin \alpha} \qquad \boxed{A_m \sin \omega t}$$

$$e = E_m \sin \alpha$$

$$\boxed{\alpha = \sin^{-1}\frac{e}{E_m}}$$

For electrical quantities such as current and voltage, the general format is

$$i = I_m \sin \omega t = I_m \sin \alpha$$
$$e = E_m \sin \omega t = E_m \sin \alpha$$

EXAMPLE

a. Determine the angle at which the magnitude of the sinusoidal function $v = 10 \sin 377t$ is 4 V.

b. Determine the time at which the magnitude is attained.

$$\alpha_1 = \sin^{-1}\frac{v}{E_m} = \sin^{-1}\frac{4\text{ V}}{10\text{ V}} = \sin^{-1} 0.4 = \mathbf{23.578^\circ}$$

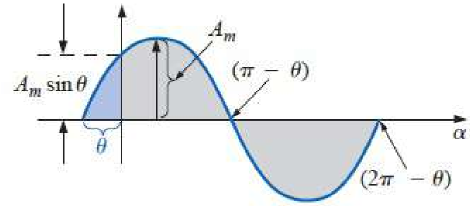
$$\alpha_2 = 180^\circ - 23.578^\circ = \mathbf{156.422^\circ}$$

$$\alpha\ (\text{rad}) = \frac{\pi}{180^\circ}(23.578^\circ) = 0.411\text{ rad}$$

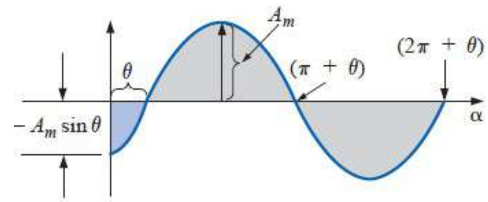
$$t_1 = \frac{\alpha}{\omega} = \frac{0.411\text{ rad}}{377\text{ rad/s}} = \mathbf{1.09\ ms}$$

$$\alpha\ (\text{rad}) = \frac{\pi}{180^\circ}(156.422^\circ) = 2.73\text{ rad}$$

$$t_2 = \frac{\alpha}{\omega} = \frac{2.73\text{ rad}}{377\text{ rad/s}} = \mathbf{7.24\ ms}$$

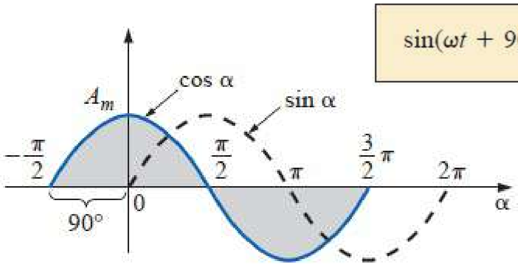


$$A_m \sin(\omega t + \theta)$$



$$A_m \sin(\omega t - \theta)$$

$$\sin(\omega t + 90^\circ) = \sin\left(\omega t + \frac{\pi}{2}\right) = \cos \omega t$$

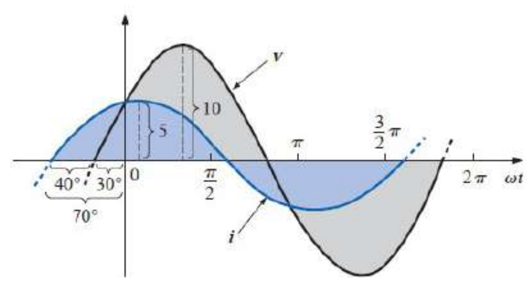


$$\sin \omega t = \cos(\omega t - 90^\circ) = \cos\left(\omega t - \frac{\pi}{2}\right)$$

The terms *lead* and *lag* are used to indicate the relationship between two sinusoidal waveforms of the *same frequency* plotted on the same set of axes. In Fig., the cosine curve is said to *lead* the sine curve by 90°, and the sine curve is said to *lag* the cosine curve by 90°. Note that the phase angle between the two waveforms is measured between those two points on the horizontal axis through which each passes with the *same slope*. If both waveforms cross the axis at the same point with the same slope, they are *in phase*.

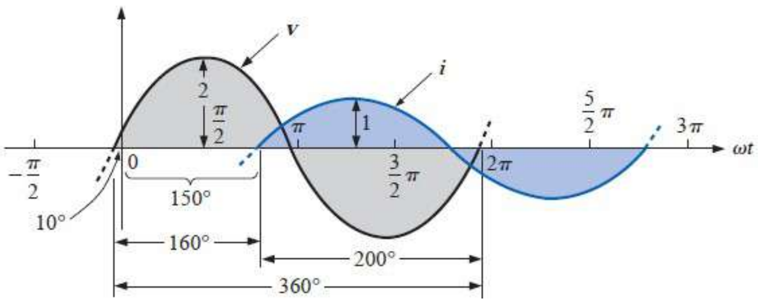
$$\begin{aligned} \cos\alpha &= \sin(\alpha + 90^\circ) \\ \sin\alpha &= \cos(\alpha - 90^\circ) \\ -\sin\alpha &= \sin(\alpha \pm 180^\circ) \\ -\cos\alpha &= \sin(\alpha + 270^\circ) = \sin(\alpha - 90^\circ) \\ &\text{etc.} \end{aligned}$$

$$\begin{aligned} \sin(-\alpha) &= -\sin\alpha \\ \cos(-\alpha) &= \cos\alpha \end{aligned}$$



$$\begin{aligned} v &= 10 \sin(\omega t + 30^\circ) \\ i &= 5 \sin(\omega t + 70^\circ) \end{aligned}$$

***i* leads *v* by 40°, or *v* lags *i* by 40°.**



v leads i by 160°, or i lags v by 160°.

$$i = -\sin(\omega t + 30°)$$
$$v = 2\sin(\omega t + 10°)$$

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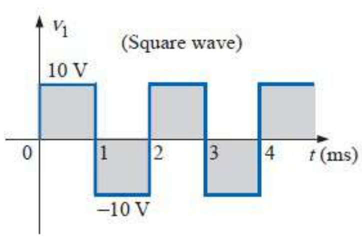
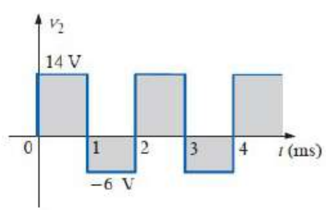
AVERAGE VALUE

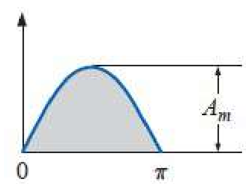
$$\boxed{G \text{ (average value)} = \frac{\text{algebraic sum of areas}}{\text{length of curve}}}$$



$$G = \frac{(10\text{ V})(1\text{ ms}) - (10\text{ V})(1\text{ ms})}{2\text{ ms}}$$
$$= \frac{0}{2\text{ ms}} = \mathbf{0\ V}$$



$$G = \frac{(14\text{ V})(1\text{ ms}) - (6\text{ V})(1\text{ ms})}{2\text{ ms}}$$
$$= \frac{14\text{ V} - 6\text{ V}}{2} = \frac{8\text{ V}}{2} = \mathbf{4\ V}$$

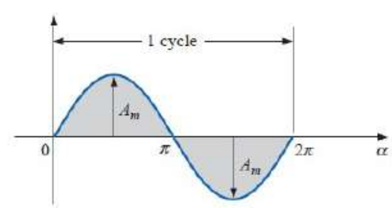


$$\text{Area} = \int_0^{\pi} A_m \sin\alpha\, d\alpha$$

$$\begin{aligned}\text{Area} &= A_m[-\cos\alpha]_0^{\pi}\\ &= -A_m(\cos\pi - \cos 0°)\\ &= -A_m[-1 - (+1)] = -A_m(-2)\end{aligned}$$

$$G = \frac{2A_m}{\pi}$$

$$\boxed{G = 0.637 A_m}$$



$$G = \frac{+2A_m - 2A_m}{2\pi} = \mathbf{0\ V}$$

EFFECTIVE (rms) VALUES

- The amplitude of a sinusoidal ac current required to deliver the same power as a particular dc current.

The power delivered by the ac supply at any instant of time is

$$P_{ac} = (i_{ac})^2 R = (I_m \sin \omega t)^2 R = (I_m^2 \sin^2 \omega t) R$$

$$\sin^2 \omega t = \frac{1}{2}(1 - \cos 2\omega t)$$

$$\boxed{P_{ac} = \frac{I_m^2 R}{2} - \frac{I_m^2 R}{2} \cos 2\omega t}$$

EFFECTIVE (rms) VALUES

$$P_{av(ac)} = P_{dc}$$

$$\frac{I_m^2 R}{2} = I_{dc}^2 R \quad \text{and} \quad I_m = \sqrt{2} I_{dc}$$

$$I_{dc} = \frac{I_m}{\sqrt{2}} = 0.707 I_m$$

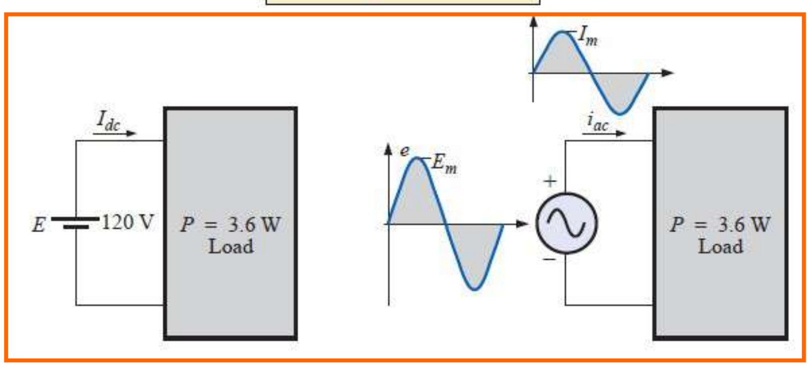
the equivalent dc value of a sinusoidal current or voltage is $1/\sqrt{2}$ or 0.707 of its maximum value.

$$\boxed{I_{eq(dc)} = I_{eff} = 0.707 I_m}$$

$$\boxed{I_m = \sqrt{2} I_{eff} = 1.414 I_{eff}}$$

$$\boxed{I_{eff} = \sqrt{\frac{\int_0^T i^2(t)\, dt}{T}}}$$

$$\boxed{I_{eff} = \sqrt{\frac{\text{area } (i^2(t))}{T}}}$$

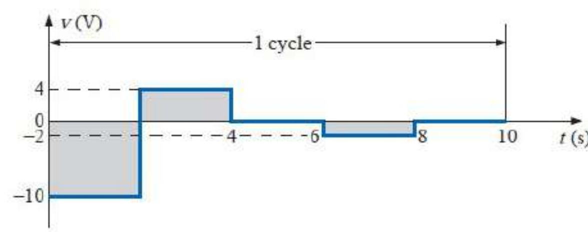


$$P_{dc} = V_{dc} I_{dc}$$

$$I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{3.6\text{ W}}{120\text{ V}} = 30\text{ mA}$$

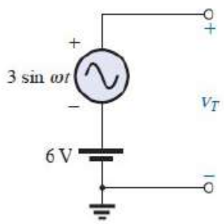
$$I_m = \sqrt{2} I_{dc} = (1.414)(30\text{ mA}) = \mathbf{42.42\text{ mA}}$$

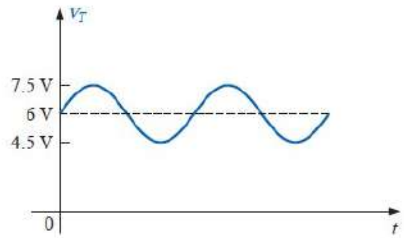
$$E_m = \sqrt{2} E_{dc} = (1.414)(120\text{ V}) = \mathbf{169.68\text{ V}}$$



$$V_{rms} = \sqrt{\frac{(100)(2) + (16)(2) + (4)(2)}{10}} = \sqrt{\frac{240}{10}}$$

$$= \mathbf{4.899\text{ V}}$$

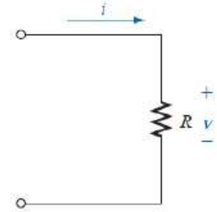




$$V_{\text{rms}} = \sqrt{V_{\text{dc}}^2 + V_{\text{ac(rms)}}^2}$$

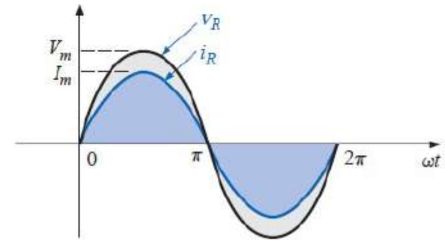
$$\begin{aligned} V_{\text{rms}} &= \sqrt{(6\text{ V})^2 + (1.06\text{ V})^2} \\ &= \sqrt{37.124}\text{ V} \\ &\cong \mathbf{6.1\ V} \end{aligned}$$

Resistor



$$i = \frac{v}{R} = \frac{V_m \sin \omega t}{R} = \frac{V_m}{R} \sin \omega t = I_m \sin \omega t$$

$$\boxed{I_m = \frac{V_m}{R}}$$



for a purely resistive element, the voltage across and the current through the element are in phase, with their peak values related by Ohm's law.

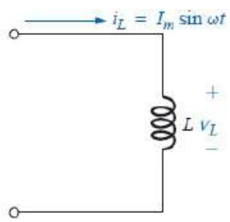
Inductor

$$v_L = L\,\frac{di_L}{dt}$$

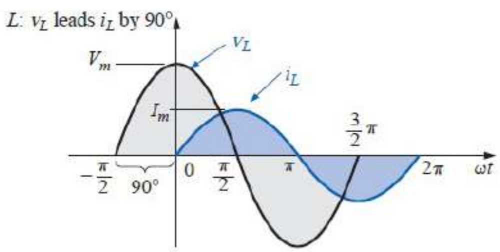
$$\frac{di_L}{dt} = \frac{d}{dt}(I_m \sin \omega t) = \omega I_m \cos \omega t$$

$$v_L = V_m \sin(\omega t + 90°)$$

$$V_m = \omega L I_m$$



for an inductor, v_L leads i_L by 90°, or i_L lags v_L by 90°.



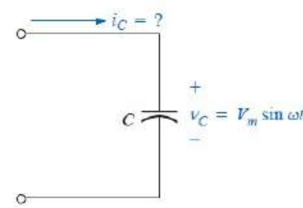
$$\boxed{X_L = \omega L} \quad \text{(ohms, } \Omega\text{)}$$

$$\boxed{X_L = \frac{V_m}{I_m}}$$

Capacitor

$$i_C = C\,\frac{dv_C}{dt}$$

$$\frac{dv_C}{dt} = \frac{d}{dt}(V_m \sin \omega t) = \omega V_m \cos \omega t$$

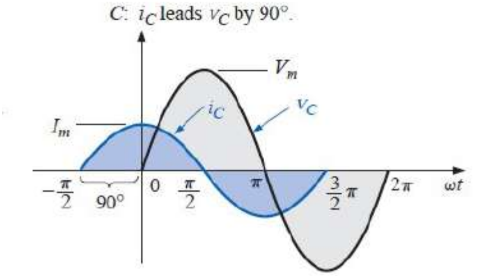


$$i_C = C\,\frac{dv_C}{dt} = C(\omega V_m \cos \omega t) = \omega C V_m \cos \omega t$$

$$i_C = I_m \sin(\omega t + 90°)$$

$$I_m = \omega C V_m$$

for a capacitor, i_C leads v_C by 90°, or v_C lags i_C by 90°.



$$\boxed{X_C = \frac{1}{\omega C}} \quad \text{(ohms, } \Omega\text{)}$$

$$\boxed{X_C = \frac{V_m}{I_m}}$$

$$\boxed{i_L = \frac{1}{L}\int v_L\, dt}$$

$$\boxed{v_C = \frac{1}{C}\int i_C\, dt}$$

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AVERAGE POWER AND POWER FACTOR

$$v = V_m \sin(\omega t + \theta_v)$$

$$i = I_m \sin(\omega t + \theta_i)$$

$$p = vi = V_m \sin(\omega t + \theta_v) I_m \sin(\omega t + \theta_i)$$
$$= V_m I_m \sin(\omega t + \theta_v)\sin(\omega t + \theta_i)$$

$$\sin A \sin B = \frac{\cos(A - B) - \cos(A + B)}{2}$$

$$\sin(\omega t + \theta_v)\sin(\omega t + \theta_i)$$
$$= \frac{\cos[(\omega t + \theta_v) - (\omega t + \theta_i)] - \cos[(\omega t + \theta_v) + (\omega t + \theta_i)]}{2}$$
$$= \frac{\cos(\theta_v - \theta_i) - \cos(2\omega t + \theta_v + \theta_i)}{2}$$

so that

$$p = \overbrace{\left[\frac{V_m I_m}{2}\cos(\theta_v - \theta_i)\right]}^{\text{Fixed value}} - \overbrace{\left[\frac{V_m I_m}{2}\cos(2\omega t + \theta_v + \theta_i)\right]}^{\text{Time-varying (function of } t\text{)}}$$

The first term in the preceding equation, however, has a constant magnitude (no time dependence) and therefore provides some net transfer of energy. This term is referred to as the average power. The average power, or real power as it is sometimes called, is the power delivered to and dissipated by the load. It corresponds to the power calculations performed for dc networks.

$$\boxed{P = \frac{V_m I_m}{2}\cos\theta} \quad \text{(watts, W)}$$

$$P = \left(\frac{V_m}{\sqrt{2}}\right)\left(\frac{I_m}{\sqrt{2}}\right)\cos\theta$$

$$V_{\text{eff}} = \frac{V_m}{\sqrt{2}} \quad \text{and} \quad I_{\text{eff}} = \frac{I_m}{\sqrt{2}}$$

$$\boxed{P = V_{\text{eff}} I_{\text{eff}} \cos\theta}$$

$$\boxed{P = \frac{V_m I_m}{2} = V_{\text{eff}} I_{\text{eff}}}$$

$$I_{\text{eff}} = \frac{V_{\text{eff}}}{R}$$

$$\boxed{P = \frac{V_{\text{eff}}^2}{R} = I_{\text{eff}}^2 R}$$

Inductor

In a purely inductive circuit, since v leads i by 90°, $|\theta_v - \theta_i| = \theta = |-90°| = 90°$. Therefore,

$$P = \frac{V_m I_m}{2}\cos 90° = \frac{V_m I_m}{2}(0) = \mathbf{0\ W}$$

The average power or power dissipated by the ideal inductor (no associated resistance) is zero watts.

Capacitor

In a purely capacitive circuit, since i leads v by 90°, $|\theta_v - \theta_i| = \theta = |-90°| = 90°$. Therefore,

$$P = \frac{V_m I_m}{2}\cos(90°) = \frac{V_m I_m}{2}(0) = \mathbf{0\ W}$$

The average power or power dissipated by the ideal capacitor (no associated resistance) is zero watts.

EXAMPLE Determine the average power delivered to networks having the following input voltage and current:

a. $v = 100 \sin(\omega t + 40°)$
   $i = 20 \sin(\omega t + 70°)$
b. $v = 150 \sin(\omega t - 70°)$
   $i = 3 \sin(\omega t - 50°)$

$$P = \frac{V_m I_m}{2}\cos\theta = \frac{(100\text{ V})(20\text{ A})}{2}\cos(30°) = (1000\text{ W})(0.866)$$

$$= \mathbf{866\ W}$$

$$P = \frac{V_m I_m}{2}\cos\theta = \frac{(150\text{ V})(3\text{ A})}{2}\cos(20°) = (225\text{ W})(0.9397)$$

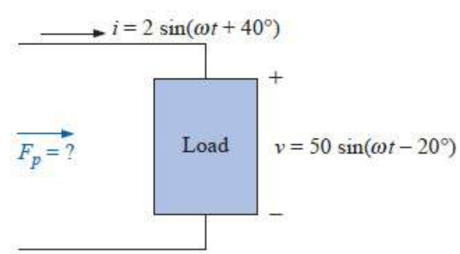
$$= \mathbf{211.43\ W}$$

Power Factor

$$\boxed{\text{Power factor} = F_p = \cos\theta}$$

$$\boxed{F_p = \cos\theta = \frac{P}{V_{\text{eff}} I_{\text{eff}}}}$$

capacitive networks have leading power factors, and inductive networks have lagging power factors.



$$F_p = \cos\theta = \cos|40° - (-20°)| = \cos 60° = \mathbf{0.5\ leading}$$

COMPLEX NUMBERS

RECTANGULAR FORM

The format for the **rectangular form** is

$$\boxed{\mathbf{C} = X + jY}$$

POLAR FORM

The format for the **polar form** is

$$\boxed{\mathbf{C} = Z \angle \theta}$$

Rectangular to Polar

$$\boxed{Z = \sqrt{X^2 + Y^2}}$$

$$\boxed{j = \sqrt{-1}}$$

$$\boxed{\theta = \tan^{-1} \frac{Y}{X}}$$

$$\boxed{j^2 = -1}$$

Polar to Rectangular

$$\boxed{X = Z \cos \theta}$$

$$\boxed{Y = Z \sin \theta}$$

$$\boxed{\frac{1}{j} = -j}$$

Complex Conjugate

$\mathbf{C} = 2 + j3$

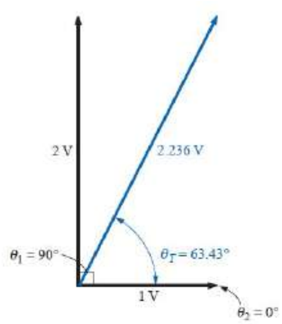
$2 - j3$

$\mathbf{C} = 2 \angle 30°$

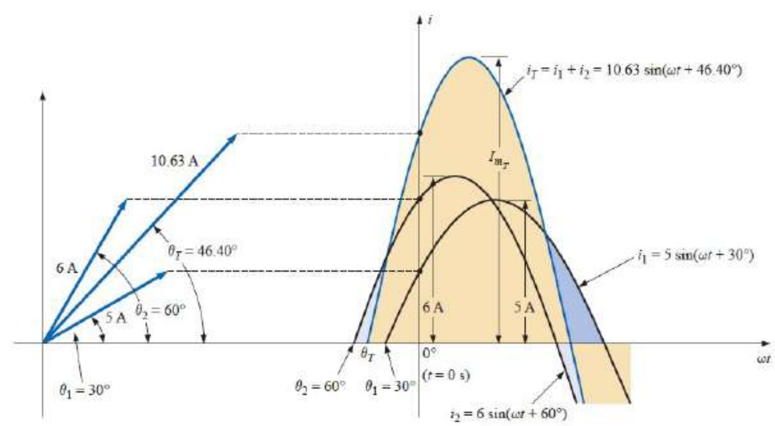
$2 \angle -30°$

PHASORS

The *radius vector,* having a *constant magnitude* (length) with *one end fixed at the origin,* is called a phasor when applied to electric circuits.



$2.236 \sin(\omega t + 63.43°)$



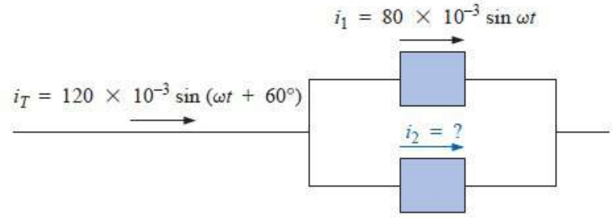
In general, for all of the analyses to follow, the phasor form of a sinusoidal voltage or current will be

$$\mathbf{V} = V\angle\theta \quad \text{and} \quad \mathbf{I} = I\angle\theta$$

where V and I are rms values and θ is the phase angle. It should be pointed out that in phasor notation, the sine wave is always the reference, and the frequency is not represented.

Phasor algebra for sinusoidal quantities is applicable only for waveforms having the same frequency.

Determine the current i_2 for the network of Fig.



$$i_2 = i_T - i_1$$

$$i_T = 120 \times 10^{-3} \sin(\omega t + 60°) \Rightarrow 84.84 \text{ mA} \angle 60°$$

$$i_1 = 80 \times 10^{-3} \sin \omega t \Rightarrow 56.56 \text{ mA} \angle 0°$$

$$\mathbf{I}_T = 84.84 \text{ mA} \angle 60° = 42.42 \text{ mA} + j\,73.47 \text{ mA}$$

$$\mathbf{I}_1 = 56.56 \text{ mA} \angle 0° = 56.56 \text{ mA} + j\,0$$

$$\mathbf{I}_2 = \mathbf{I}_T - \mathbf{I}_1$$
$$= (42.42 \text{ mA} + j\,73.47 \text{ mA}) - (56.56 \text{ mA} + j\,0)$$

$$\mathbf{I}_2 = -14.14 \text{ mA} + j\,73.47 \text{ mA}$$

$$\mathbf{I}_2 = 74.82 \text{ mA} \angle 100.89°$$

$$\mathbf{I}_2 = 74.82 \text{ mA} \angle 100.89° \Rightarrow$$
$$i_2 = \sqrt{2}(74.82 \times 10^{-3}) \sin(\omega t + 100.89°)$$
$$i_2 = \mathbf{105.8 \times 10^{-3} \sin(\omega t + 100.89°)}$$

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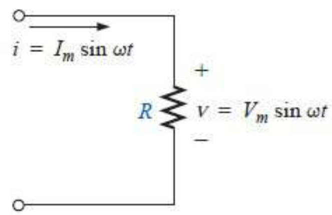
SERIES ac CIRCUITS

Resistive Elements

$$I_m = \frac{V_m}{R} \quad \text{or} \quad V_m = I_m R$$



In phasor form,

$$v = V_m \sin \omega t \Rightarrow \mathbf{V} = V \angle 0^\circ$$

where $V = 0.707V_m$.

Applying Ohm's law and using phasor algebra, we have

$$\mathbf{I} = \frac{V \angle 0^\circ}{R \angle \theta_R} = \frac{V}{R} \underline{/0^\circ - \theta_R}$$

$$\mathbf{I} = \frac{V \angle 0^\circ}{R \angle 0^\circ} = \frac{V}{R} \underline{/0^\circ - 0^\circ} = \frac{V}{R} \angle 0^\circ \qquad i = \sqrt{2}\left(\frac{V}{R}\right) \sin \omega t$$

$$\boxed{\mathbf{Z}_R = R \angle 0^\circ}$$

Inductive Reactance

$$v = V_m \sin \omega t \Rightarrow \text{phasor form } \mathbf{V} = V \angle 0^\circ$$

$$\mathbf{I} = \frac{V \angle 0^\circ}{X_L \angle \theta_L} = \frac{V}{X_L} \underline{/0^\circ - \theta_L}$$

$$\mathbf{I} = \frac{V \angle 0^\circ}{X_L \angle 90^\circ} = \frac{V}{X_L} \underline{/0^\circ - 90^\circ} = \frac{V}{X_L} \angle -90^\circ$$

$$i = \sqrt{2}\left(\frac{V}{X_L}\right) \sin(\omega t - 90^\circ) \qquad \boxed{\mathbf{Z}_L = X_L \angle 90^\circ}$$

Capacitive Reactance

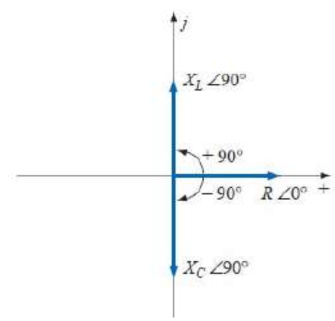
$$\mathbf{I} = \frac{V \angle 0^\circ}{X_C \angle \theta_C} = \frac{V}{X_C} \underline{/0^\circ - \theta_C}$$

$$\mathrm{I} = \frac{V \angle 0^\circ}{X_C \angle -90^\circ} = \frac{V}{X_C} \underline{/0^\circ - (-90^\circ)} = \frac{V}{X_C} \angle 90^\circ$$

$$i = \sqrt{2}\left(\frac{V}{X_C}\right) \sin(\omega t + 90^\circ)$$

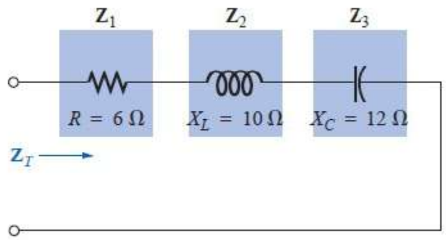
$$\boxed{\mathbf{Z}_C = X_C \angle -90^\circ}$$

Impedance Diagram



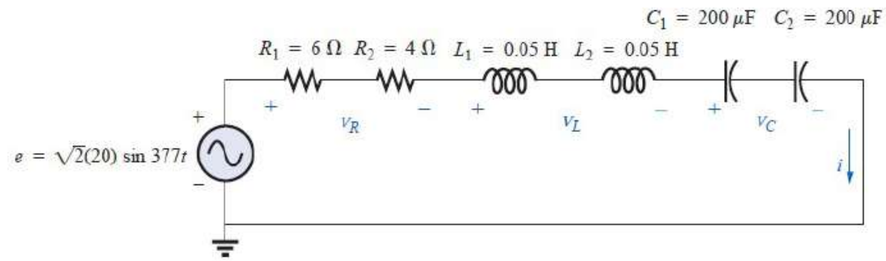
For any configuration (series, parallel, series-parallel, etc.), the angle associated with the total impedance is the angle by which the applied voltage leads the source current. For inductive networks, θ_T will be positive, whereas for capacitive networks, θ_T will be negative.

Determine the input impedance to the series network



$$\begin{aligned}
\mathbf{Z}_T &= \mathbf{Z}_1 + \mathbf{Z}_2 + \mathbf{Z}_3 \\
&= R\angle 0^\circ + X_L\angle 90^\circ + X_C\angle -90^\circ \\
&= R + jX_L - jX_C \\
&= R + j(X_L - X_C) = 6\ \Omega + j(10\ \Omega - 12\ \Omega) = 6\ \Omega - j2\ \Omega
\end{aligned}$$

$$\mathbf{Z}_T = \mathbf{6.325\ \Omega \angle -18.43^\circ}$$



a. Calculate $\mathbf{I}$, $\mathbf{V}_R$, $\mathbf{V}_L$, and $\mathbf{V}_C$ in phasor form.
b. Calculate the total power factor.
c. Calculate the average power delivered to the circuit.
d. Draw the phasor diagram.
e. Obtain the phasor sum of $\mathbf{V}_R$, $\mathbf{V}_L$, and $\mathbf{V}_C$, and show that it equals the input voltage $\mathbf{E}$.
f. Find $\mathbf{V}_R$ and $\mathbf{V}_C$ using the voltage divider rule.

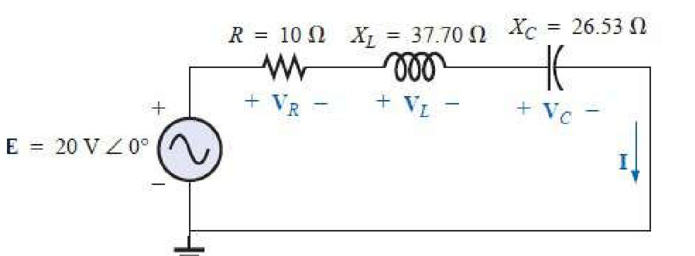
$$R_T = 6\ \Omega + 4\ \Omega = 10\ \Omega$$

$$L_T = 0.05\text{ H} + 0.05\text{ H} = 0.1\text{ H}$$

$$C_T = \frac{200\ \mu\text{F}}{2} = 100\ \mu\text{F}$$

$$X_L = \omega L = (377\text{ rad/s})(0.1\text{ H}) = 37.70\ \Omega$$

$$X_C = \frac{1}{\omega C} = \frac{1}{(377\text{ rad/s})(100 \times 10^{-6}\text{ F})} = \frac{10^6\ \Omega}{37{,}700} = 26.53\ \Omega$$



$$\begin{aligned}
\mathbf{Z}_T &= R\angle 0^\circ + X_L\angle 90^\circ + X_C\angle -90^\circ \\
&= 10\ \Omega + j\,37.70\ \Omega - j\,26.53\ \Omega \\
&= 10\ \Omega + j\,11.17\ \Omega = \mathbf{15\ \Omega \angle 48.16^\circ}
\end{aligned}$$

The current $\mathbf{I}$ is

$$\mathbf{I} = \frac{\mathbf{E}}{\mathbf{Z}_T} = \frac{20\text{ V}\angle 0^\circ}{15\ \Omega\angle 48.16^\circ} = \mathbf{1.33\ A \angle -48.16^\circ}$$

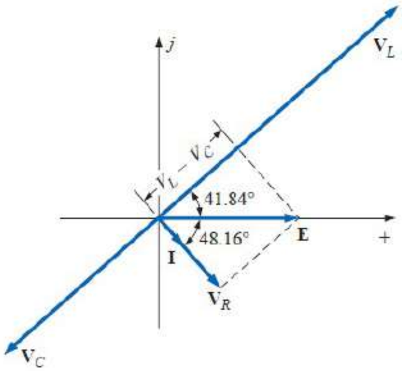
$$\begin{aligned}
\mathbf{V}_R = \mathbf{I}\mathbf{Z}_R &= (I\angle\theta)(R\angle 0^\circ) = (1.33\text{ A}\angle -48.16^\circ)(10\ \Omega\angle 0^\circ) \\
&= \mathbf{13.30\ V \angle -48.16^\circ}
\end{aligned}$$

$$\begin{aligned}
\mathbf{V}_L = \mathbf{I}\mathbf{Z}_L &= (I\angle\theta)(X_L\angle 90^\circ) = (1.33\text{ A}\angle -48.16^\circ)(37.70\ \Omega\angle 90^\circ) \\
&= \mathbf{50.14\ V \angle 41.84^\circ}
\end{aligned}$$

$$\begin{aligned}
\mathbf{V}_C = \mathbf{I}\mathbf{Z}_C &= (I\angle\theta)(X_C\angle -90^\circ) = (1.33\text{ A}\angle -48.16^\circ)(26.53\ \Omega\angle -90^\circ) \\
&= \mathbf{35.28\ V \angle -138.16^\circ}
\end{aligned}$$

$F_p = \cos\theta = \cos 48.16° = \mathbf{0.667\ lagging}$

$P_T = EI\cos\theta = (20\text{ V})(1.33\text{ A})(0.667) = \mathbf{17.74\ W}$



$$\mathbf{E} = \mathbf{V}_R + \mathbf{V}_L + \mathbf{V}_C$$
$$= 13.30\text{ V}\angle -48.16° + 50.14\text{ V}\angle 41.84° + 35.28\text{ V}\angle -138.16°$$
$$\mathbf{E} = 13.30\text{ V}\angle -48.16° + 14.86\text{ V}\angle 41.84°$$

Therefore,

$$E = \sqrt{(13.30\text{ V})^2 + (14.86\text{ V})^2} = \mathbf{20\ V}$$

$$\mathbf{E} = 20\angle 0°$$

$$\mathbf{V}_R = \frac{\mathbf{Z}_R\mathbf{E}}{\mathbf{Z}_T} = \frac{(10\ \Omega\angle 0°)(20\text{ V}\angle 0°)}{15\ \Omega\angle 48.16°} = \frac{200\text{ V}\angle 0°}{15\angle 48.16°}$$

$$= \mathbf{13.3\ V\angle -48.16°}$$

$$\mathbf{V}_C = \frac{\mathbf{Z}_C\mathbf{E}}{\mathbf{Z}_T} = \frac{(26.5\ \Omega\angle -90°)(20\text{ V}\angle 0°)}{15\ \Omega\angle 48.16°} = \frac{530.6\text{ V}\angle -90°}{15\angle 48.16°}$$

$$= \mathbf{35.37\ V\angle -138.16°}$$

EEE 1001 : Basic Electrical and Electronics Engineering

Module 2- AC Circuits
Series AC circuits

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Complex power

- The complex power S absorbed by the ac load is the product of the voltage and the complex conjugate of the current,

$$\mathbf{S} = \frac{1}{2}\mathbf{V}\mathbf{I}^* \qquad \mathbf{S} = \mathbf{V}_{\text{rms}}\mathbf{I}^*_{\text{rms}} \qquad \mathbf{V}_{\text{rms}} = \frac{\mathbf{V}}{\sqrt{2}} = V_{\text{rms}}\underline{/\theta_v} \qquad \mathbf{I}_{\text{rms}} = \frac{\mathbf{I}}{\sqrt{2}} = I_{\text{rms}}\underline{/\theta_i}$$

$$\mathbf{S} = V_{\text{rms}}I_{\text{rms}}\underline{/\theta_v - \theta_i}$$
$$= V_{\text{rms}}I_{\text{rms}}\cos(\theta_v - \theta_i) + jV_{\text{rms}}I_{\text{rms}}\sin(\theta_v - \theta_i)$$

$$\mathbf{Z} = \frac{\mathbf{V}}{\mathbf{I}} = \frac{\mathbf{V}_{\text{rms}}}{\mathbf{I}_{\text{rms}}} = \frac{V_{\text{rms}}}{I_{\text{rms}}}\underline{/\theta_v - \theta_i}$$

$$\mathbf{S} = I^2_{\text{rms}}(R + jX) = P + jQ$$

$$\boxed{\mathbf{S} = I^2_{\text{rms}}\mathbf{Z} = \frac{V^2_{\text{rms}}}{\mathbf{Z}^*}}$$

$$P = \text{Re}(\mathbf{S}) = I^2_{\text{rms}}R$$
$$Q = \text{Im}(\mathbf{S}) = I^2_{\text{rms}}X$$

$$P = V_{\text{rms}}I_{\text{rms}}\cos(\theta_v - \theta_i), \qquad Q = V_{\text{rms}}I_{\text{rms}}\sin(\theta_v - \theta_i)$$

- The real power P is the average power in watts delivered to a load; it is the only useful power. It is the actual power dissipated by the load.
- The reactive power Q is a measure of the energy exchange between the source and the reactive part of the load. The unit of Q is the volt-ampere reactive(VAR) to distinguish it from the real power.
- The reactive power is being transferred back and forth between the load and the source.

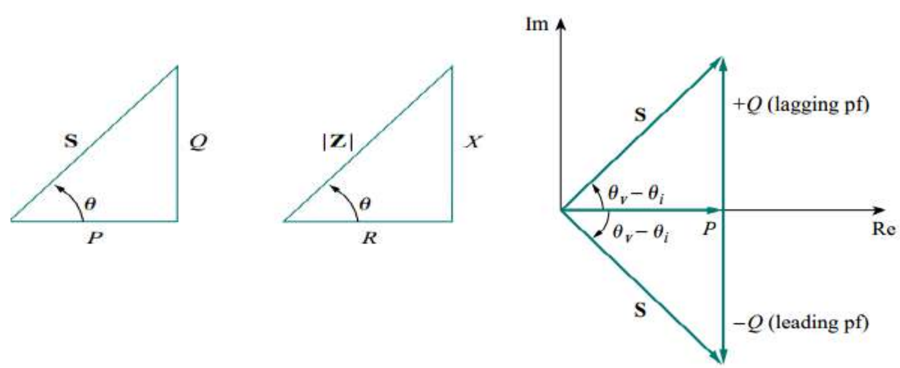
1. Q=0 for resistive loads (unity pf).
2. Q<0 for capacitive loads (leading pf).
3. Q>0 for inductive loads (lagging pf).

- Complex power (in VA) is the product of the rms voltage phasor and the complex conjugate of the rms current phasor. As a complex quantity, its real part is real power P and its imaginary part is reactive power Q.

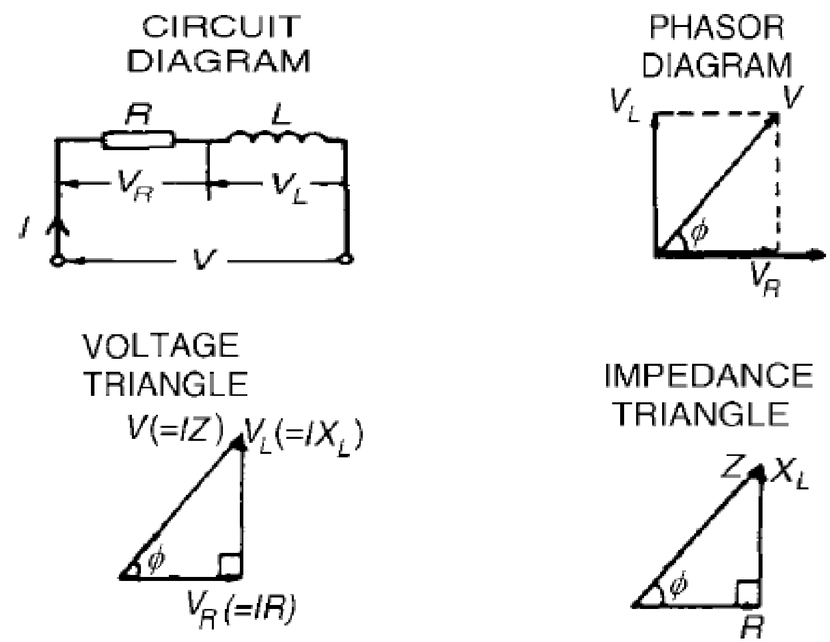
$$\text{Complex Power} = \mathbf{S} = P + jQ = \frac{1}{2}\mathbf{V}\mathbf{I}^*$$
$$= V_{\text{rms}} I_{\text{rms}} \underline{/\theta_v - \theta_i}$$
$$\text{Apparent Power} = S = |\mathbf{S}| = V_{\text{rms}} I_{\text{rms}} = \sqrt{P^2 + Q^2}$$
$$\text{Real Power} = P = \text{Re}(\mathbf{S}) = S\cos(\theta_v - \theta_i)$$
$$\text{Reactive Power} = Q = \text{Im}(\mathbf{S}) = S\sin(\theta_v - \theta_i)$$
$$\text{Power Factor} = \frac{P}{S} = \cos(\theta_v - \theta_i)$$

Power Triangle

- It is a standard practice to represent S, P, and Q in the form of a triangle, known as the power triangle.
- The power triangle has four items—the apparent/complex power, real power, reactive power, and the power factor angle.



RL Series ac circuit



For the R–L circuit:

$$V = \sqrt{(V_R^2 + V_L^2)} \quad \text{(by Pythagoras' theorem)}$$

$$\text{and } \tan\phi = \frac{V_L}{V_R} \quad \text{(by trigonometric ratios)}$$

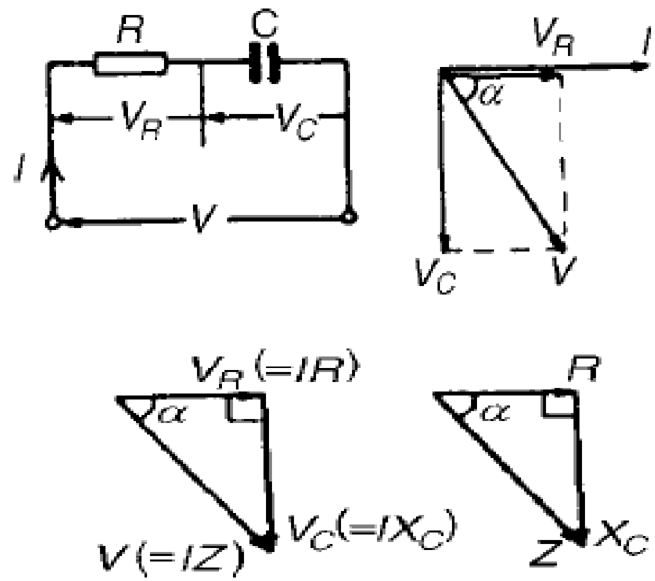
In an a.c. circuit, the ratio $\dfrac{\text{applied voltage } V}{\text{current } I}$ is called the **impedance** Z, i.e.

$$\boxed{Z = \frac{V}{I}\ \Omega}$$

For the R–L circuit: $Z = \sqrt{(R^2 + X_L^2)}$

$$\tan\phi = \frac{X_L}{R}, \ \sin\phi = \frac{X_L}{Z} \ \text{and} \ \cos\phi = \frac{R}{Z}$$

RC series ac circuit



$$V = \sqrt{(V_R^2 + V_C^2)} \quad \text{(by Pythagoras' theorem)}$$

$$\text{and } \tan\alpha = \frac{V_C}{V_R} \quad \text{(by trigonometric ratios)}$$

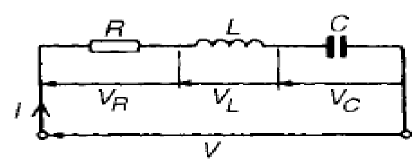
For the R–C circuit: $Z = \sqrt{(R^2 + X_C^2)}$

$$\tan\alpha = \frac{X_C}{R}, \quad \sin\alpha = \frac{X_C}{Z} \quad \text{and} \quad \cos\alpha = \frac{R}{Z}$$

RLC series ac circuit

In an a.c. series circuit containing resistance R, inductance L and capacitance C, the applied voltage V is the phasor sum of V_R, V_L and V_C

V_L and V_C are anti-phase, i.e. displaced by 180°

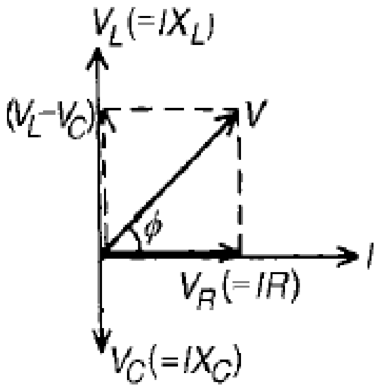


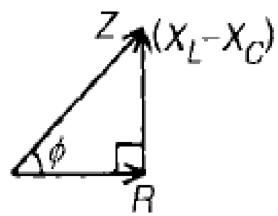
there are three phasor diagrams possible — each depending on the relative values of V_L and V_C.

When $X_L > X_C$

$$Z = \sqrt{[R^2 + (X_L - X_C)^2]}$$

$$\text{and } \tan\phi = \frac{(X_L - X_C)}{R}$$



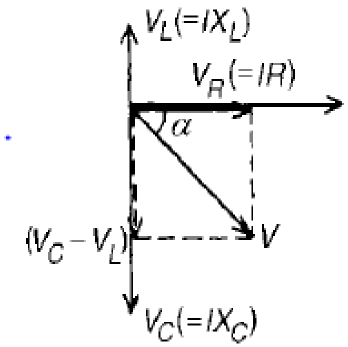


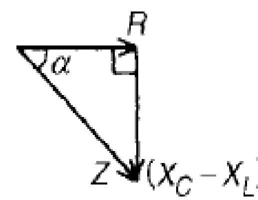
IMPEDANCE TRIANGLE

When $X_C > X_L$

$$Z = \sqrt{[R^2 + (X_C - X_L)^2]}$$

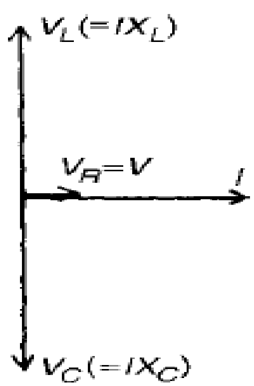
$$\text{and } \tan\alpha = \frac{(X_C - X_L)}{R}$$





IMPEDANCE TRIANGLE

When $X_L = X_C$ the applied voltage V and the current I are in phase. This effect is called **series resonance**



Problem In a series R–L circuit the p.d. across the resistance R is 12 V and the p.d. across the inductance L is 5 V. Find the supply voltage and the phase angle between current and voltage.

$$V = \sqrt{(12^2 + 5^2)} \text{ i.e. } \mathbf{V = 13\,V}$$

$$\tan\phi = \frac{V_L}{V_R} = \frac{5}{12}, \text{ from which } \phi = \tan^{-1}\left(\frac{5}{12}\right)$$

$$= 22.62^\circ$$

$$= \mathbf{22^\circ 37' \text{ lagging}}$$

Problem A coil consists of a resistance of 100 Ω and an inductance of 200 mH. If an alternating voltage, v, given by $v = 200 \sin 500t$ volts is applied across the coil, calculate (a) the circuit impedance, (b) the current flowing, (c) the p.d. across the resistance, (d) the p.d. across the inductance and (e) the phase angle between voltage and current.

Since $v = 200 \sin 500t$ volts then $V_m = 200\,\text{V}$ and

$$\omega = 2\pi f = 500\,\text{rad/s}$$

Hence rms voltage $V = 0.707 \times 200 = 141.4\,\text{V}$

Inductive reactance, $X_L = 2\pi f L = \omega L$
$= 500 \times 200 \times 10^{-3} = 100\,\Omega$

(a) Impedance $Z = \sqrt{(R^2 + X_L^2)}$
$= \sqrt{(100^2 + 100^2)} = \mathbf{141.4\,\Omega}$

(b) Current $I = \dfrac{V}{Z} = \dfrac{141.4}{141.4} = \mathbf{1\,A}$

(c) p.d. across the resistance $V_R = IR = 1 \times 100 = \mathbf{100\,V}$
p.d. across the inductance $V_L = IX_L = 1 \times 100 = \mathbf{100\,V}$

(e) Phase angle between voltage and current is given by:
$\tan \phi = \left(\dfrac{X_L}{R}\right)$
from which, $\phi = \tan^{-1}(100/100)$, hence $\boldsymbol{\phi = 45°}$ **or** $\boldsymbol{\dfrac{\pi}{4}}$ **rads**

Problem A capacitor C is connected in series with a 40 Ω resistor across a supply of frequency 60 Hz. A current of 3 A flows and the circuit impedance is 50 Ω. Calculate: (a) the value of capacitance, C, (b) the supply voltage, (c) the phase angle between the supply voltage and current, (d) the p.d. across the resistor, and (e) the p.d. across the capacitor. Draw the phasor diagram.

(a) Impedance $Z = \sqrt{(R^2 + X_C^2)}$

Hence $X_C = \sqrt{(Z^2 - R^2)} = \sqrt{(50^2 - 40^2)} = 30\,\Omega$

$$X_C = \frac{1}{2\pi f C} \text{ hence } C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi(60)30}\text{F}$$

$$= \mathbf{88.42\,\mu F}$$

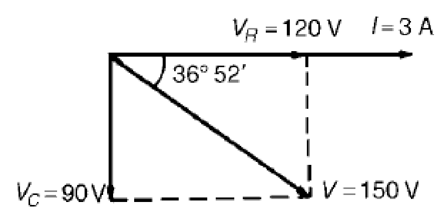
(b) Since $Z = \dfrac{V}{I}$ then $V = IZ = (3)(50) = \mathbf{150\,V}$

(c) Phase angle, $\alpha = \tan^{-1}\dfrac{X_C}{R} = \tan^{-1}\left(\dfrac{30}{40}\right) = 36.87°$

$$= \mathbf{36°52'\ leading}$$

(d) P.d. across resistor, $V_R = IR = (3)(40) = \mathbf{120\,V}$

(e) P.d. across capacitor, $V_C = IX_C = (3)(30) = \mathbf{90\,V}$

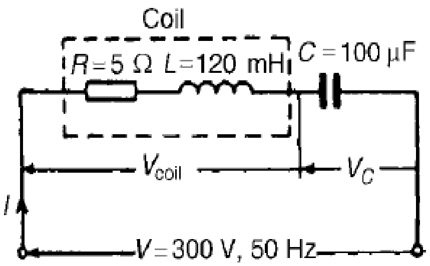


Phasor diagram

Problem A coil of resistance 5 Ω and inductance 120 mH in series with a 100 μF capacitor, is connected to a 300 V, 50 Hz supply. Calculate (a) the current flowing, (b) the phase difference between the supply voltage and current, (c) the voltage across the coil and (d) the voltage across the capacitor.

$$X_L = 2\pi f L = 2\pi(50)(120 \times 10^{-3}) = \mathbf{37.70\ \Omega}$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(50)(100 \times 10^{-6})} = \mathbf{31.83\ \Omega}$$



Since X_L is greater than X_C the circuit is inductive.

$X_L - X_C = 37.70 - 31.83 = 5.87\ \Omega$

$$\text{Impedance } Z = \sqrt{[R^2 + (X_L - X_C)^2]} = \sqrt{[(5)^2 + (5.87)^2]} = 7.71\ \Omega$$

(a) Current $I = \dfrac{V}{Z} = \dfrac{300}{7.71} = \mathbf{38.91\ A}$

(b) Phase angle $\phi = \tan^{-1}\left(\dfrac{X_L - X_C}{R}\right) = \tan^{-1}\dfrac{5.87}{5}$

$= 49.58°$

$= \mathbf{49°35'}$

(c) Impedance of coil, Z_{COIL}

$= \sqrt{(R^2 + X_L^2)} = \sqrt{[(5)^2 + (37.70)^2]} = 38.03\ \Omega$

Voltage across coil $V_{COIL} = IZ_{COIL} = (38.91)(38.03)$

$= \mathbf{1480\ V}$

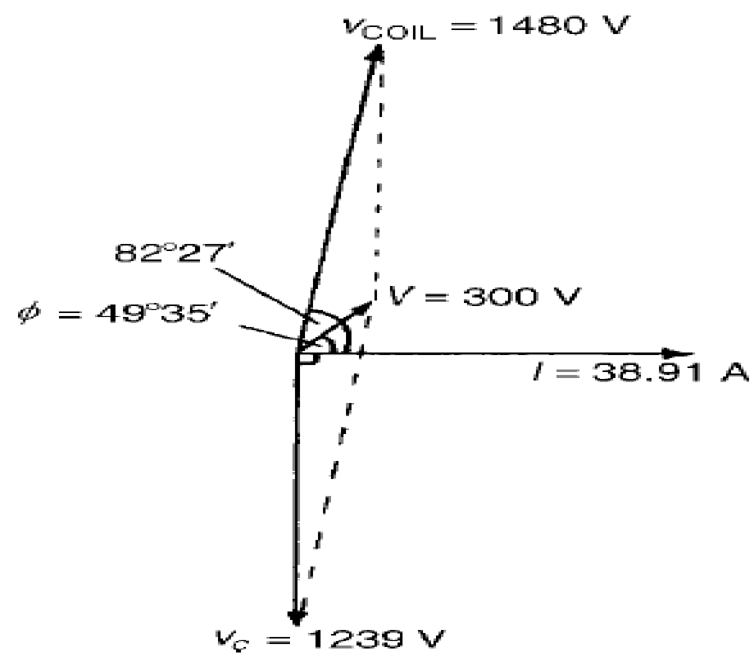
Phase angle of coil $= \tan^{-1}\dfrac{X_L}{R} = \tan^{-1}\left(\dfrac{37.70}{5}\right)$

$= 82.45°$

$= 82°27'$ lagging

(d) Voltage across capacitor $V_C = IX_C = (38.91)(31.83)$

$= \mathbf{1239\ V}$



Thank you!

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

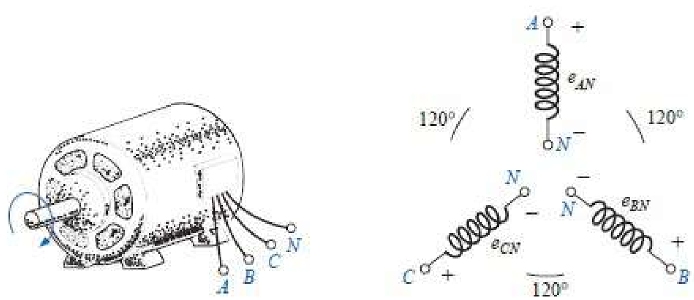
Three phase systems

By,

Meera P. S.

Assistant Professor, SELECT

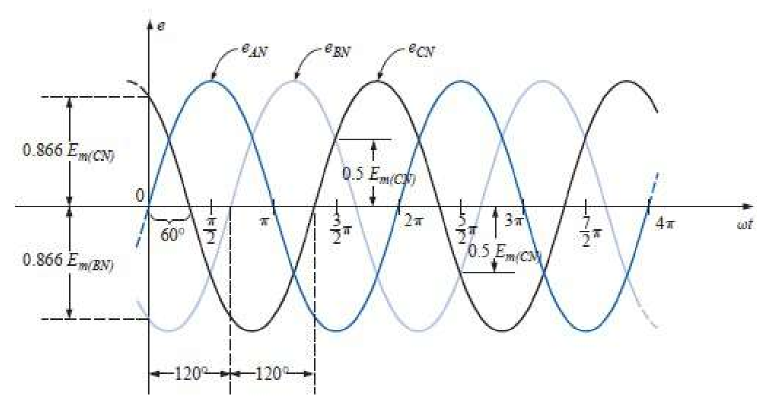
THE THREE-PHASE GENERATOR



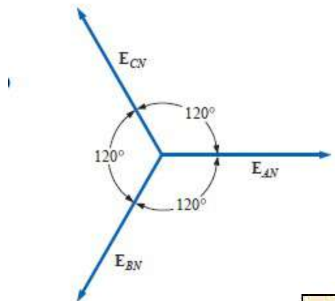
In particular, note that

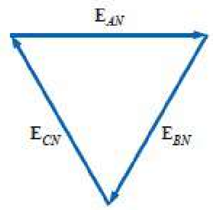
at any instant of time, the algebraic sum of the three phase voltages of a three-phase generator is zero.

Three phase voltage



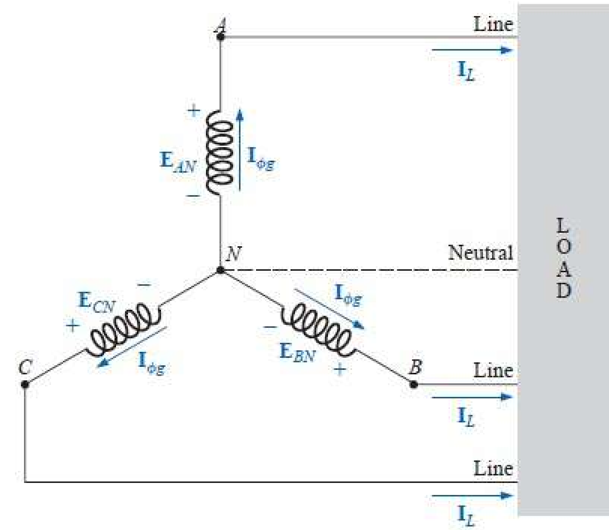
$$e_{AN} = E_{m(AN)} \sin \omega t$$
$$e_{BN} = E_{m(BN)} \sin(\omega t - 120°)$$
$$e_{CN} = E_{m(CN)} \sin(\omega t - 240°) = E_{m(CN)} \sin(\omega t + 120°)$$





$$\mathbf{E}_{AN} + \mathbf{E}_{BN} + \mathbf{E}_{CN} = 0$$

THE Y-CONNECTED GENERATOR

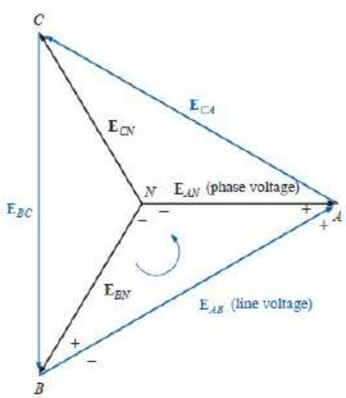


Y-CONNECTION

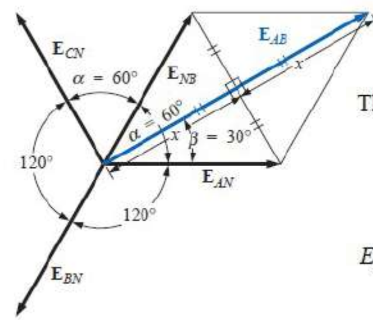
- The line current equals the phase current for each phase.

$$\mathbf{I}_L = \mathbf{I}_{\phi g}$$

- The voltage from one line to another is called a line voltage.



$$\mathbf{E}_{AB} - \mathbf{E}_{AN} + \mathbf{E}_{BN} = 0$$
$$\mathbf{E}_{AB} = \mathbf{E}_{AN} - \mathbf{E}_{BN} = \mathbf{E}_{AN} + \mathbf{E}_{NB}$$



The length x is

$$x = E_{AN} \cos 30° = \frac{\sqrt{3}}{2} E_{AN}$$

$$E_{AB} = 2x = (2)\frac{\sqrt{3}}{2} E_{AN} = \sqrt{3} E_{AN}$$

Noting from the phasor diagram that θ of $\mathbf{E}_{AB} = \beta = 30°$, the result is

$$\mathbf{E}_{AB} = E_{AB} \angle 30° = \sqrt{3} E_{AN} \angle 30°$$

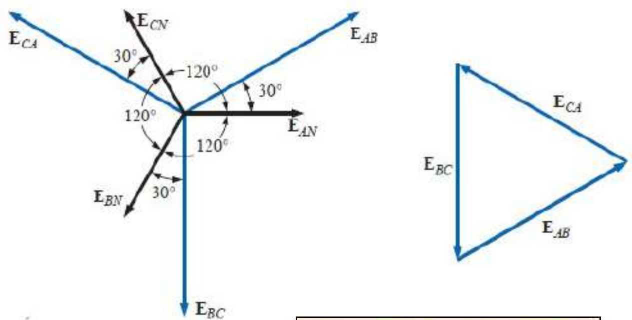
and

$$\mathbf{E}_{CA} = \sqrt{3} E_{CN} \angle 150°$$
$$\mathbf{E}_{BC} = \sqrt{3} E_{BN} \angle 270°$$

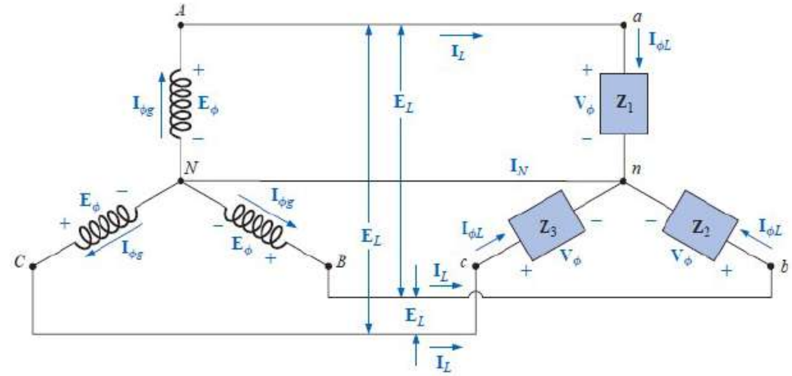
$$E_L = \sqrt{3} E_{\phi}$$

In sinusoidal notation,

$$e_{AB} = \sqrt{2}E_{AB}\sin(\omega t + 30°)$$
$$e_{CA} = \sqrt{2}E_{CA}\sin(\omega t + 150°)$$
and
$$e_{BC} = \sqrt{2}E_{BC}\sin(\omega t + 270°)$$

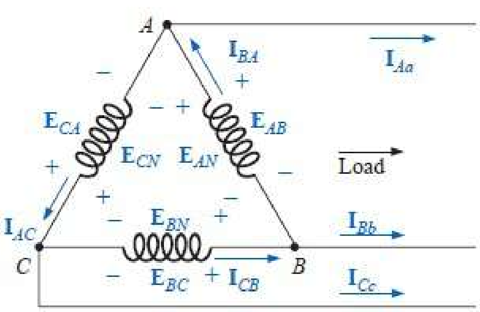


$$\boxed{\mathbf{E}_{AB} + \mathbf{E}_{CA} + \mathbf{E}_{BC} = 0}$$



Y-connected generator with a Y-connected load.

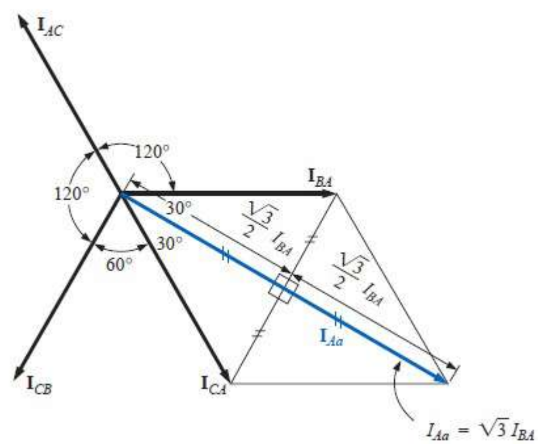
DELTA CONNECTION



The phase and line voltages are equivalent

$$\boxed{\mathbf{E}_L = \mathbf{E}_{\phi g}}$$

DELTA CONNECTION



$$\boxed{I_L = \sqrt{3}I_{\phi g}}$$

VIT

Vellore Institute of Technology

(Deemed to be University under section 3 of UGC Act, 1956)

SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Three phase systems

By,

Meera P. S.

Assistant Professor, SELECT

Problem 1. Three loads, each of resistance 30 Ω, are connected in star to a 415 V, 3-phase supply. Determine (a) the system phase voltage, (b) the phase current and (c) the line current.

For a star connection, $V_L = \sqrt{3}V_p$

Hence phase voltage, $V_p = \dfrac{V_L}{\sqrt{3}} = \dfrac{415}{\sqrt{3}} = \mathbf{239.6\ V\ or\ 240\ V}$

Phase current, $I_p = \dfrac{V_p}{R_p} = \dfrac{240}{30} = \mathbf{8\ A}$

For a star connection, $I_p = I_L$

Hence the line current, $I_L = \mathbf{8\ A}$

Problem 2. A star-connected load consists of three identical coils each of resistance 30 Ω and inductance 127.3 mH. If the line current is 5.08 A, calculate the line voltage if the supply frequency is 50 Hz

Inductive reactance $X_L = 2\pi fL = 2\pi(50)(127.3 \times 10^{-3}) = 40\ \Omega$

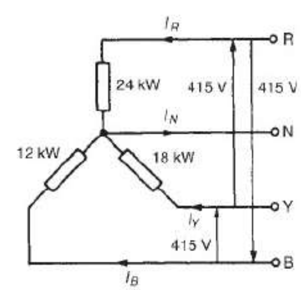
Impedance of each phase $Z_p = \sqrt{(R^2 + X_L{}^2)} = \sqrt{(30^2 + 40^2)} = 50\ \Omega$

For a star connection $I_L = I_p = \dfrac{V_p}{Z_p}$

Hence phase voltage $V_p = I_pZ_p = (5.08)(50) = 254\ V$

Line voltage $V_L = \sqrt{3}V_p = \sqrt{3}(254) = \mathbf{440\ V}$

Problem . A 415 V, 3-phase, 4 wire, star-connected system supplies three resistive loads as shown in Figure 19.7. Determine (a) the current in each line and (b) the current in the neutral conductor.



For a star-connected system $V_L = \sqrt{3}V_p$

Hence $V_p = \dfrac{V_L}{\sqrt{3}} = \dfrac{415}{\sqrt{3}} = 240\ V$

Since current $I = \dfrac{\text{Power } P}{\text{Voltage } V}$ for a resistive load

then $I_R = \dfrac{P_R}{V_R} = \dfrac{24\,000}{240} = \mathbf{100\ A}$

$I_Y = \dfrac{P_Y}{V_Y} = \dfrac{18\,000}{240} = \mathbf{75\ A}$

$I_B = \dfrac{P_B}{V_B} = \dfrac{12\,000}{240} = \mathbf{50\ A}$

Alternatively, by calculation, considering I_R at 90°, I_B at 210° and I_Y at 330°:

$$\text{Total horizontal component} = 100\cos 90° + 75\cos 330° + 50\cos 210° = 21.65$$

$$\text{Total vertical component} = 100\sin 90° + 75\sin 330° + 50\sin 210° = 37.50$$

Hence magnitude of $I_N = \sqrt{(21.65^2 + 37.50^2)} = \mathbf{43.3\ A}$

Problem . Three identical coils each of resistance 30 Ω and inductance 127.3 mH are connected in delta to a 440 V, 50 Hz, 3-phase supply. Determine (a) the phase current, and (b) the line current.

Phase impedance, $Z_p = 50\ \Omega$

Phase current, $I_p = \dfrac{V_p}{Z_p} = \dfrac{V_L}{Z_p} = \dfrac{440}{50} = \mathbf{8.8\ A}$

For a delta connection, $I_L = \sqrt{3}I_p = \sqrt{3}(8.8) = \mathbf{15.24\ A}$

Problem . Three coils each having resistance 3 Ω and inductive reactance 4 Ω are connected (i) in star and (ii) in delta to a 415 V, 3-phase supply. Calculate for each connection (a) the line and phase voltages and (b) the phase and line currents.

For a star connection: $I_L = I_p$ and $V_L = \sqrt{3}V_p$

A 415 V, 3-phase supply means that the line voltage, $V_L = \mathbf{415\ V}$

Phase voltage, $V_p = \dfrac{V_L}{\sqrt{3}} = \dfrac{415}{\sqrt{3}} = \mathbf{240\ V}$

Impedance per phase, $Z_p = \sqrt{(R^2 + X_L^2)} = \sqrt{(3^2 + 4^2)} = 5\ \Omega$

Phase current, $I_p = \dfrac{V_p}{Z_p} = \dfrac{240}{5} = \mathbf{48\ A}$

Line current, $I_L = I_p = \mathbf{48\ A}$

For a delta connection: $V_L = V_p$ and $I_L = \sqrt{3}I_p$

Line voltage, $V_L = 415$ V

Phase voltage, $V_p = V_L = \mathbf{415\ V}$

Phase current, $I_p = \dfrac{V_p}{Z_p} = \dfrac{415}{5} = \mathbf{83\ A}$

Line current, $I_L = \sqrt{3}I_p = \sqrt{3}(83) = \mathbf{144\ A}$

EEE 1001 : Basic Electrical and Electronics Engineering

Module 2- AC Circuits
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Power in three-phase systems

- The power dissipated in a three-phase load is given by the sum of the power dissipated in each phase.
- If a load is balanced then the total power P is given by:

  P=3×power consumed by one phase.
- The power consumed in one phase=$I_p^2 R_p$ or $V_p I_p \cos\varphi$

  where φ is the phase angle between V_p and I_p

For a star connection, $V_p = \frac{V_L}{\sqrt{3}}$ and $I_p = I_L$ hence

$$P = 3\left(\frac{V_L}{\sqrt{3}}\right) I_L \cos\phi$$

$$= \sqrt{3} V_L I_L \cos\phi$$

For a delta connection, $V_p = V_L$ and $I_p = \frac{I_L}{\sqrt{3}}$ hence

$$P = 3V_L\left(\frac{I_L}{\sqrt{3}}\right) \cos\phi$$

$$= \sqrt{3} V_L I_L \cos\phi$$

Hence for either a star or a delta balanced connection the total power P is given by:

$P = \sqrt{3}\, V_L I_L \cos\phi$ watts or $P = 3 I_p^2 R_p$ watts.

Total volt-amperes, $S = \sqrt{3}\, V_L I_L$ volt-amperes

Q1. Three identical coils, each of resistance 10 Ω and inductance 42mH are connected (a) in star and (b) in delta to a 415V, 50Hz, 3-phase supply. Determine the total power dissipated in each case.

(a) Star connection

$$\text{Inductive reactance } X_L = 2\pi f L = 2\pi(50)(42\times10^{-3}) = 13.19\,\Omega$$

$$\text{Phase impedance } Z_p = \sqrt{(R^2 + X_L^2)} = \sqrt{(10^2 + 13.19^2)} = 16.55\,\Omega$$

Line voltage $V_L = 415\text{ V}$ and

$$\text{phase voltage, } V_p = \frac{V_L}{\sqrt{3}} = \frac{415}{\sqrt{3}} = 240\text{ V}$$

$$\text{Phase current, } I_p = \frac{V_p}{Z_p} = \frac{240}{16.55} = 14.50\text{ A}$$

$$\text{Line current, } I_L = I_p = 14.50\text{ A}$$

$$\text{Power factor} = \cos\phi = \frac{R_p}{Z_p} = \frac{10}{16.55} = 0.6042 \text{ lagging}$$

$$\textbf{Power dissipated, } P = \sqrt{3}V_L I_L \cos\phi = \sqrt{3}(415)(14.50)(0.6042) = \mathbf{6.3\,kW}$$

$$\text{(Alternatively, } P = 3I_p^2 R_p = 3(14.50)^2(10) = \mathbf{6.3\,kW}\text{)}$$

b. Delta connection

$$V_L = V_p = 415\text{ V}, Z_p = 16.55\,\Omega,$$
$$\cos\phi = 0.6042 \text{ lagging (from above).}$$

$$\text{Phase current, } I_p = \frac{V_p}{Z_p} = \frac{415}{16.55} = 25.08\text{ A}$$

$$\text{Line current, } I_L = \sqrt{3}I_p = \sqrt{3}(25.08) = 43.44\text{ A}$$

$$\textbf{Power dissipated, } P = \sqrt{3}V_L I_L \cos\phi = \sqrt{3}(415)(43.44)(0.6042) = \mathbf{18.87\,kW}$$

$$\text{(Alternatively, } P = 3I_p^2 R_p = 3(25.08)^2(10) = 18.87\text{ kW)}$$

Q2. The input power to a 3-phase a.c. motor is measured as 5 kW. If the voltage and current to the motor are 400V and 8.6A respectively, determine the power factor of the system.

Power, $P = 5000\text{ W}$; Line voltage $V_L = 400\text{ V}$; Line current, $I_L = 8.6\text{ A}$

Power, $P = \sqrt{3}V_L I_L \cos\phi$

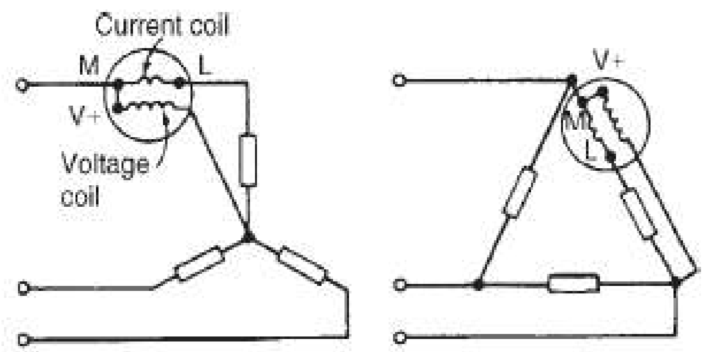
$$\text{Hence power factor} = \cos\phi = \frac{P}{\sqrt{3}V_L I_L} = \frac{5000}{\sqrt{3}(400)(8.6)} = \mathbf{0.839}$$

Measurement of power in three-phase systems

- Power in three-phase loads may be measured by the following methods
  - **One-wattmeter method for a balanced load**
  - **Two-wattmeter method for balanced or unbalanced loads**
  - **Three-wattmeter method for a three-phase, 4-wire system for balanced and unbalanced loads**

One-wattmeter method

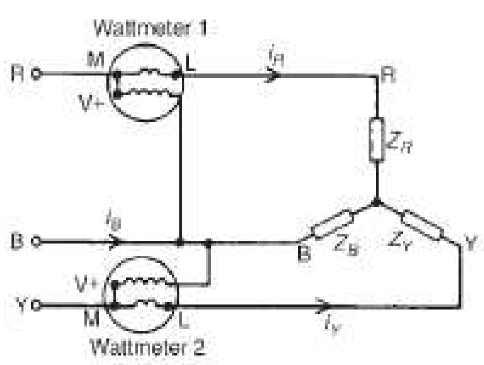
Total power = 3 x wattmeter reading



Two-wattmeter method

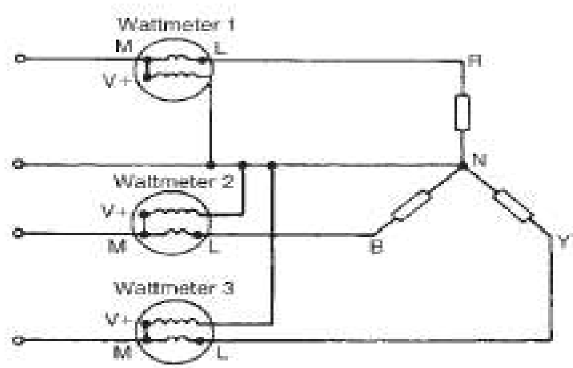
Total power = sum of wattmeter readings

$= P_1 + P_2$



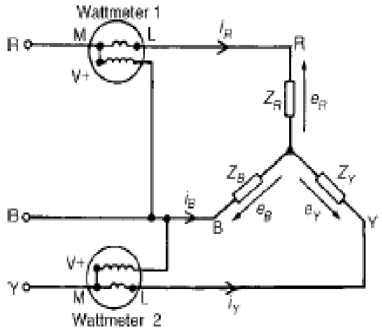
Three-wattmeter method

Total power $= P_1 + P_2 + P_3$



Two-wattmeter method

Total instantaneous power, $p = e_R i_R + e_Y i_Y + e_B i_B$ and in any 3-phase system $i_R + i_Y + i_B = 0$. Hence $i_B = -i_R - i_Y$

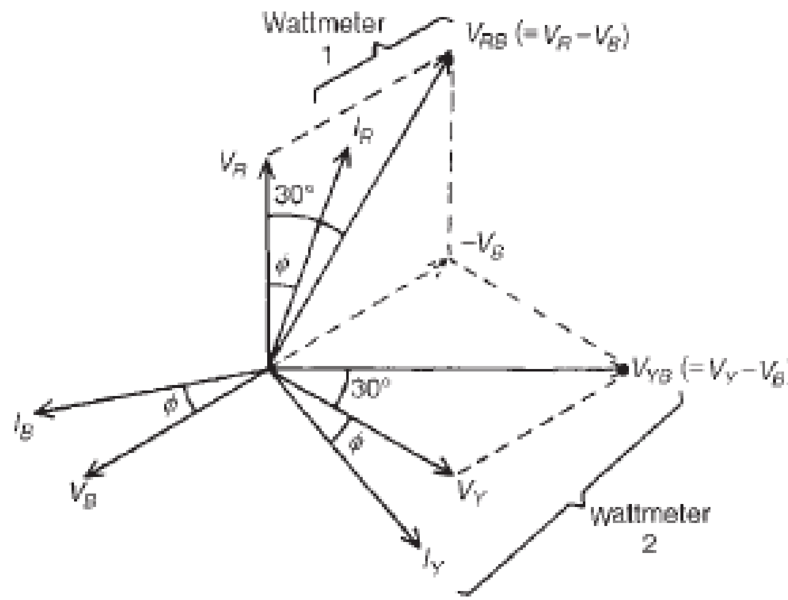


Thus, $p = e_R i_R + e_Y i_Y + e_B(-i_R - i_Y)$

$= (e_R - e_B) i_R + (e_Y - e_B) i_Y$

Hence total instantaneous power,

$p = (\text{wattmeter 1 reading}) + (\text{wattmeter 2 reading})$
$= p_1 + p_2$



Wattmeter 1 reads $V_{RB} I_R \cos(30° - \phi) = P_1$

Wattmeter 2 reads $V_{YB} I_Y \cos(30° + \phi) = P_2$

$$\frac{P_1}{P_2} = \frac{V_{RB} I_R \cos(30° - \phi)}{V_{YB} I_Y \cos(30° + \phi)} = \frac{\cos(30° - \phi)}{\cos(30° + \phi)}$$

since $I_R = I_Y$ and $V_{RB} = V_{YB}$ for a balanced load.

Hence $\dfrac{P_1}{P_2} = \dfrac{\cos 30° \cos\phi + \sin 30° \sin\phi}{\cos 30° \cos\phi - \sin 30° \sin\phi}$

Dividing throughout by $\cos 30° \cos\phi$ gives:

$$\frac{P_1}{P_2} = \frac{1 + \tan 30° \tan\phi}{1 - \tan 30° \tan\phi}$$

$$= \frac{1 + \frac{1}{\sqrt{3}} \tan\phi}{1 - \frac{1}{\sqrt{3}} \tan\phi} \quad \left(\text{since } \frac{\sin\phi}{\cos\phi} = \tan\phi\right)$$

Cross-multiplying gives:

$$P_1 - \frac{P_1}{\sqrt{3}} \tan\phi = P_2 + \frac{P_2}{\sqrt{3}} \tan\phi$$

Hence $\qquad P_1 - P_2 = (P_1 + P_2) \dfrac{\tan\phi}{\sqrt{3}}$

from which $\qquad \boldsymbol{\tan\phi = \sqrt{3}\left(\dfrac{P_1 - P_2}{P_1 + P_2}\right)}$

ϕ, $\cos\phi$ and thus power factor can be determined from this formula.

Q3. Each phase of a delta-connected load comprises a resistance of 30 Ω and an 80μF capacitor in series. The load is connected to a 400V, 50Hz, 3-phase supply. Calculate (a) the phase current, (b) the line current, (c) the total power dissipated and (d) the kVA rating of the load. Draw the complete phasor diagram for the load.

(a) Capacitive reactance, $X_C = \dfrac{1}{2\pi f C}$

$$= \frac{1}{2\pi(50)(80 \times 10^{-6})}$$

$$= 39.79\,\Omega$$

Phase impedance, $Z_p = \sqrt{(R_p^2 + X_C^2)}$

$$= \sqrt{(30^2 + 39.79^2)}$$

$$= 49.83\,\Omega$$

Power factor $= \cos\phi = \dfrac{R_p}{Z_p} = \dfrac{30}{49.83} = 0.602$

Hence $\phi = \cos^{-1} 0.602 = 52.99°$ leading.

Phase current, $I_p = \dfrac{V_p}{Z_p}$ and $V_p = V_L$ for a delta connection

Hence $I_p = \dfrac{400}{49.83} = \mathbf{8.027\,A}$

(b) Line current $I_L = \sqrt{3} I_p$ for a delta connection

Hence $I_L = \sqrt{3}(8.207) = \mathbf{13.90\,A}$

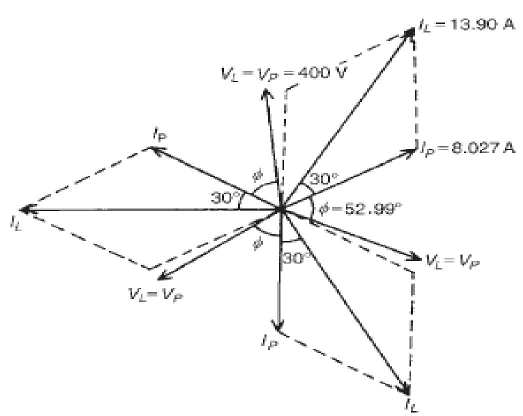
(c) Total power dissipated, $P = \sqrt{3} V_L I_L \cos\phi$

$$= \sqrt{3}(400)(13.90)(0.602)$$

$$= \mathbf{5.797\,kW}$$

(d) Total kVA, $S = \sqrt{3} V_L I_L = \sqrt{3}(400)(13.90)$

$$= \mathbf{9.630\,kVA}$$



Q4. Two wattmeters connected to a 3-phase motor indicate the total power input to be 12kW. The power factor is 0.6. Determine the readings of each wattmeter.

If the two wattmeters indicate P_1 and P_2 respectively

then $P_1 + P_2 = 12\,\text{kW}$ (1)

$\tan\phi = \sqrt{3}\left(\dfrac{P_1 - P_2}{P_1 + P_2}\right)$ and power factor $= 0.6 = \cos\phi$

Angle $\phi = \cos^{-1} 0.6 = 53.13°$ and $\tan 53.13° = 1.3333$

Hence $1.3333 = \dfrac{\sqrt{3}(P_1 - P_2)}{12}$, from which,

$$P_1 - P_2 = \frac{12(1.3333)}{\sqrt{3}}$$

i.e. $P_1 - P_2 = 9.237\,\text{kW}$

Adding equations (1) and (2) gives: $2P_1 = 21.237$

i.e. $P_1 = \frac{21.237}{2}$

$= 10.62\text{ kW}$

Hence wattmeter 1 reads 10.62 kW
From equation (1), wattmeter 2 reads $(12 - 10.62) =$ 1.38 kW

Thank you!

EEE 1001 : Basic Electrical and Electronics Engineering

Module 2- AC Circuits

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Assistant Professor

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Q3. Each phase of a delta-connected load comprises a resistance of 30 Ω and an 80μF capacitor in series. The load is connected to a 400V, 50Hz, 3-phase supply. Calculate (a) the phase current, (b) the line current, (c) the total power dissipated and (d) the kVA rating of the load. Draw the complete phasor diagram for the load.

(a) Capacitive reactance, $X_C = \frac{1}{2\pi f C}$

$= \frac{1}{2\pi(50)(80 \times 10^{-6})}$

$= 39.79\,\Omega$

Phase impedance, $Z_p = \sqrt{(R_p^2 + X_C^2)}$

$= \sqrt{(30^2 + 39.79^2)}$

$= 49.83\,\Omega$

Power factor $= \cos\phi = \dfrac{R_p}{Z_p} = \dfrac{30}{49.83} = 0.602$

Hence $\phi = \cos^{-1} 0.602 = 52.99°$ leading.

Phase current, $I_p = \dfrac{V_p}{Z_p}$ and $V_p = V_L$ for a delta connection

Hence $\quad I_p = \dfrac{400}{49.83} = \mathbf{8.027\,A}$

(b) Line current $I_L = \sqrt{3} I_p$ for a delta connection

Hence $\quad I_L = \sqrt{3}(8.207) = \mathbf{13.90\,A}$

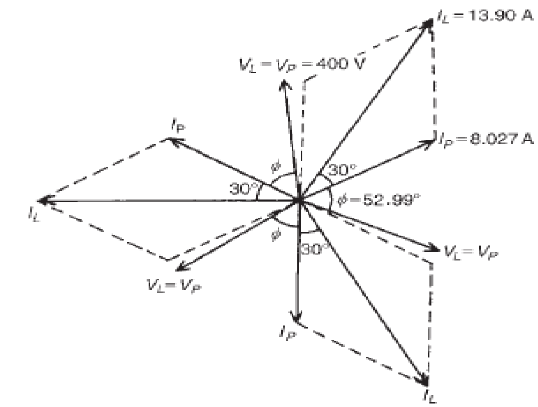
(c) Total power dissipated, $P = \sqrt{3} V_L I_L \cos\phi$

$= \sqrt{3}(400)(13.90)(0.602)$

$= \mathbf{5.797\,kW}$

(d) Total kVA, $S = \sqrt{3} V_L I_L = \sqrt{3}(400)(13.90)$

$= \mathbf{9.630\,kVA}$



Q4. Two wattmeters connected to a 3-phase motor indicate the total power input to be 12kW. The power factor is 0.6. Determine the readings of each wattmeter.

If the two wattmeters indicate P_1 and P_2 respectively

then $P_1 + P_2 = 12\,\text{kW} \qquad (1)$

$\tan\phi = \sqrt{3}\left(\dfrac{P_1 - P_2}{P_1 + P_2}\right)$ and power factor $= 0.6 = \cos\phi$

Angle $\phi = \cos^{-1} 0.6 = 53.13°$ and $\tan 53.13° = 1.3333$

Hence $1.3333 = \dfrac{\sqrt{3}(P_1 - P_2)}{12}$, from which,

$P_1 - P_2 = \dfrac{12(1.3333)}{\sqrt{3}}$

i.e. $\quad P_1 - P_2 = 9.237\,\text{kW}$

Adding equations (1) and (2) gives: $2P_1 = 21.237$

i.e. $\quad P_1 = \dfrac{21.237}{2}$

$= 10.62\,\text{kW}$

Hence **wattmeter 1 reads 10.62 kW**
From equation (1), **wattmeter 2 reads (12 − 10.62) = 1.38 kW**

Q5 .Three similar coils, each having a resistance of 8 Ω and an inductive reactance of 8Ω are connected (a) in star and (b) in delta, across a 415V, 3-phase supply. Calculate for each connection the readings on each of two wattmeters connected to measure the power by the two-wattmeter method.

(a) **Star connection:** $V_L = \sqrt{3} V_p$ and $I_L = I_p$

Phase voltage, $V_p = \dfrac{V_L}{\sqrt{3}} = \dfrac{415}{\sqrt{3}}$ and

phase impedance, $Z_p = \sqrt{(R_p^2 + X_L^2)}$

$= \sqrt{(8^2 + 8^2)} = 11.31\,\Omega$

Hence phase current, $I_p = \dfrac{V_p}{Z_p} = \dfrac{415/\sqrt{3}}{11.31}$
$= 21.18\,\text{A}$

Total power, $P = 3I_p^2 R_p = 3(21.18)^2(8)$
$= 10766\,\text{W}$

If wattmeter readings are P_1 and P_2 then

$P_1 + P_2 = 10766$ (1)

Since $R_p = 8\,\Omega$ and $X_L = 8\,\Omega$, then phase angle $\phi = 45°$ (from impedance triangle)

$\tan\phi = \sqrt{3}\left(\dfrac{P_1 - P_2}{P_1 + P_2}\right)$, hence

$\tan 45° = \dfrac{\sqrt{3}(P_1 - P_2)}{10766}$

from which $P_1 - P_2 = \dfrac{10766(1)}{\sqrt{3}} = 6216\,\text{W}$ (2)

Adding equations (1) and (2) gives:

$2P_1 = 10766 + 6216$
$= 16982\,\text{W}$

Hence $P_1 = 8491\,\text{W}$

From equation (1), $P_2 = 10766 - 8491 = 2275\,\text{W}$

When the coils are star-connected the wattmeter readings are thus 8.491 kW and 2.275 kW.

(b) **Delta connection:** $V_L = V_p$ and $I_L = \sqrt{3} I_p$

Phase current, $I_p = \dfrac{V_p}{Z_p} = \dfrac{415}{11.31} = 36.69\,\text{A}$

Total power, $P = 3I_p^2 R_p = 3(36.69)^2(8) = 32310\,\text{W}$

Hence $P_1 + P_2 = 32310\,\text{W}$ (3)

$\tan\phi = \sqrt{3}\left(\dfrac{P_1 - P_2}{P_1 + P_2}\right)$ thus $1 = \dfrac{\sqrt{3}(P_1 - P_2)}{32310}$

from which, $P_1 - P_2 = \dfrac{32310}{\sqrt{3}} = 18650\,\text{W}$ (4)

Adding equations (3) and (4) gives:

$2P_1 = 50960$, from which $P_1 = 25480\,\text{W}$

From equation (3), $P_2 = 32310 - 25480 = 6830\,\text{W}$

When the coils are delta-connected the wattmeter readings are thus 25.48 kW and 6.83 kW.

Q6 .Three inductive loads, each of resistance 4Ω and reactance 9 Ω are connected in delta. When connected to a 3-phase supply the loads consume 1.2kW. Calculate (a) the power factor of the load, (b) the phase current, (c) the line current and (d) the supply voltage.

Impedance = Z = 4 +j 9 Ω

Z= 9.848 ∠66.03°

Power factor of the load = cos φ = cos (66.03°) = 0.406 (lag)

Power consumed by the load, P= 1.2kW = 1200 W

$P = 3\, I_p^2\, R_p = 1200$

$I_p = 10\,\text{A}$

$P = 3\, V_p I_p \cos\varphi = 1200$

$V_p = 98.53\,\text{V}$

Q7. 8kW is found by the two-wattmeter method to be the power input to a 3-phase motor. Determine the reading of each wattmeter if the power factor of the system is 0.85.

$P_1 + P_2 = 8kW$ -------------------------(1)

$\text{Cos } \varphi = 0.85$

$\varphi = 31.79^\circ$

$\tan \varphi = 0.6198$

$\tan \varphi = \sqrt{3} * (P_1 - P_2)/(P_1 + P_2)$

$P_1 - P_2 = 2.8627$ --------------------------(2)

$P_1 = 5.43$ kW

$P_2 = 2.57$ kW

Q8. A 3-phase, star-connected alternator supplies a delta connected load, each phase of which has a resistance of 15Ω and inductive reactance 20Ω. If the line voltage is 400V, calculate (a) the current supplied by the alternator and (b) the output power and kVA rating of the alternator, neglecting any losses in the line between the alternator and the load.

Q9. Three similar coils, each having a resistance of 8 Ω and an inductive reactance of 10 Ω are connected (a) in star and (b) in delta, across a 415V, 3-phase supply. Calculate for each connection the readings on each of two wattmeters connected to measure the power by the two-wattmeter method.

Thank you!

SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

DC Machines

By,

Meera P. S.

Assistant Professor, SELECT

Introduction

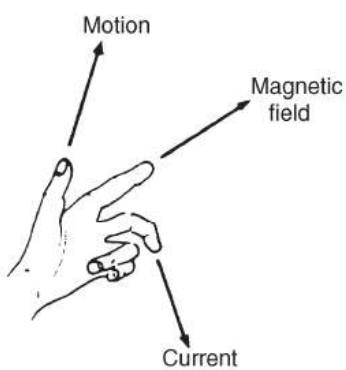
- When the input to an electrical machine is electrical energy and the output is mechanical energy, the machine is called an electric motor. Thus an electric motor converts electrical energy into mechanical energy.

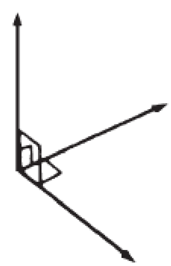
- When the input to an electrical machine is mechanical energy and the output is electrical energy, the machine is called a generator. Thus, a generator converts mechanical energy to electrical energy.

Fleming's left hand rule

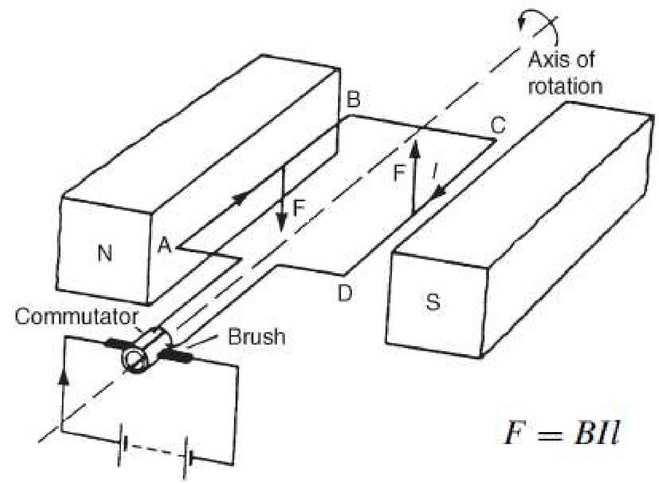
The direction of the force exerted on a conductor can be pre-determined by using **Fleming's left-hand rule** (often called the motor rule) which states:

If the first finger points in the direction of the magnetic field, the second finger points in the direction of the current, then the thumb will point in the direction of the motion of the conductor.





Principle of operation of dc motor



$$F = BIl$$

Principle of operation of dc motor

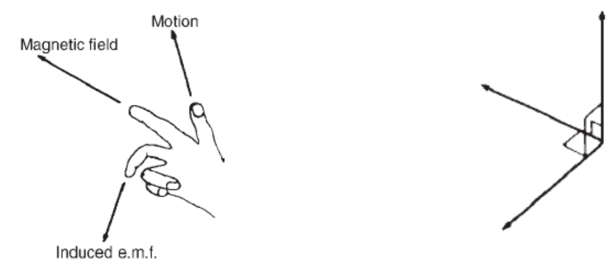
- A direct current is fed into the coil via carbon brushes bearing on a commutator, which consists of a metal ring split into two halves separated by insulation.
- When current flows in the coil a magnetic field is set up around the coil which interacts with the magnetic field produced by the magnets.
- This causes a force F to be exerted on the current-carrying conductor which, by Fleming's left-hand rule, is downwards between points A and B and upward between C and D for the current direction shown. This causes a torque and the coil rotates anticlockwise.
- When the coil has turned through 90°, the brushes connected to the positive and negative terminals of the supply make contact with different halves of the commutator ring, thus reversing the direction of the current flow in the conductor.
- If the current is not reversed and the coil rotates past this position the forces acting on it change direction and it rotates in the opposite direction thus never making more than half a revolution.

Lenz's law states:

'The direction of an induced e.m.f. is always such that it tends to set up a current opposing the motion or the change of flux responsible for inducing that e.m.f.'.

Fleming's right hand rule

If the first finger points in the direction of the magnetic field, the thumb points in the direction of motion of the conductor relative to the magnetic field, then the second finger will point in the direction of the induced e.m.f.



Principle of operation of dc generator

Faraday's laws of electromagnetic induction state:

(i) *'An induced e.m.f. is set up whenever the magnetic field linking that circuit changes.'*

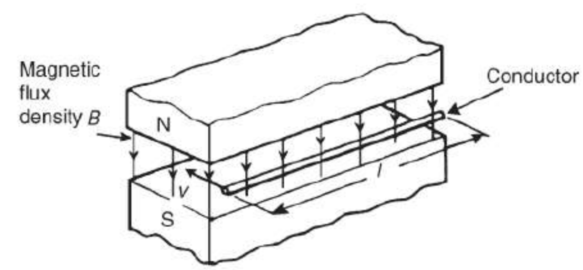
(ii) *'The magnitude of the induced e.m.f. in any circuit is proportional to the rate of change of the magnetic flux linking the circuit.'*

In a generator, conductors forming an electric circuit are made to move through a magnetic field. By Faraday's law an e.m.f. is induced in the conductors and thus a source of e.m.f. is created. A generator converts mechanical energy into electrical energy.

$$\boxed{E = Blv \text{ volts,}}$$

where B, the flux density, is measured in teslas, l, the length of conductor in the magnetic field, is measured in metres, and v, the conductor velocity, is measured in metres per second.

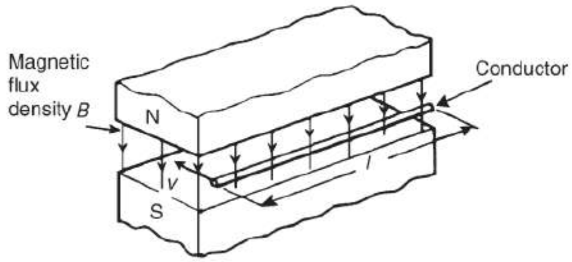
Principle of operation of dc generator



If the conductor moves at an angle $\theta°$ to the magnetic field (instead of at 90° as assumed above) then

$$\boxed{E = Blv \sin\theta \text{ volts}}$$

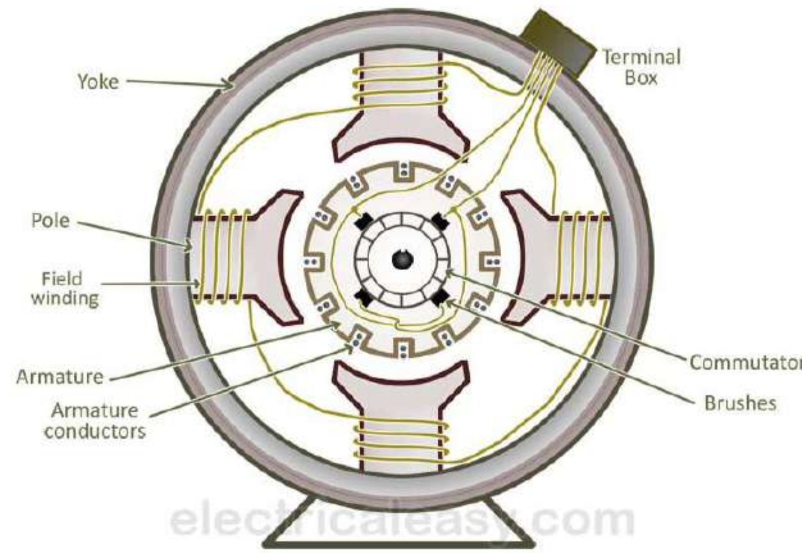
Principle of operation of dc generator

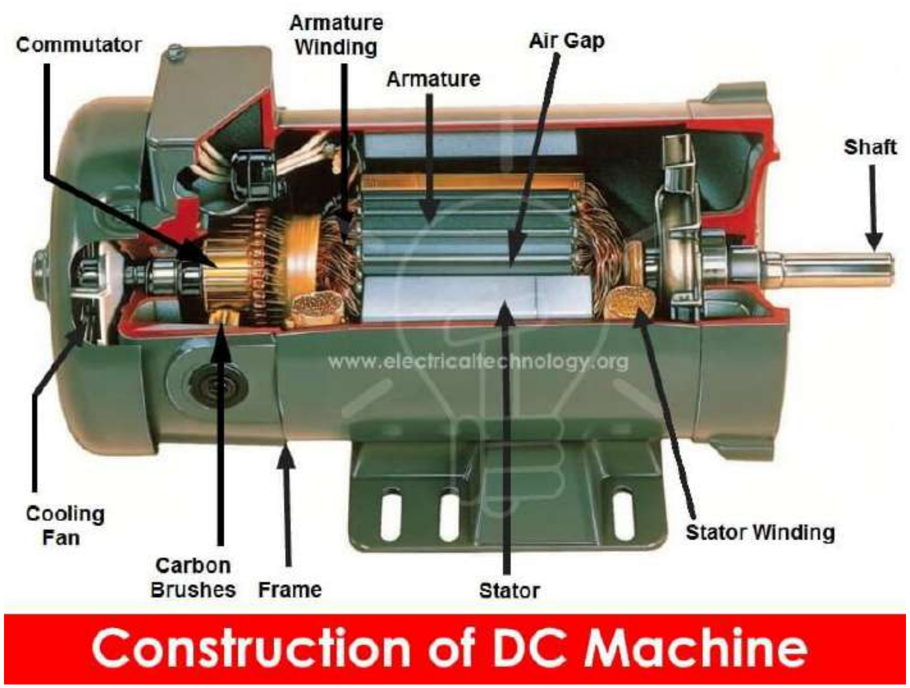


If the conductor moves at an angle $\theta°$ to the magnetic field (instead of at $90°$ as assumed above) then

$$\boxed{E = Blv \sin\theta \text{ volts}}$$

D.C. machine construction





The basic parts of any d.c. machine are

(a) a stationary part called the **stator** having,
 (i) a steel ring called the **yoke**, to which are attached
 (ii) the magnetic **poles**, around which are the
 (iii) **field windings**, i.e. many turns of a conductor wound round the pole core; current passing through this conductor creates an electromagnet,

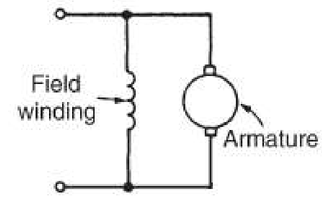
(b) a rotating part called the **armature** mounted in bearings housed in the stator and having,
 (iv) a laminated cylinder of iron or steel called the **core**, on which teeth are cut to house the
 (v) **armature winding**, i.e. a single or multi-loop conductor system and
 (vi) the **commutator**,

Armature windings can be divided into two groups, depending on how the wires are joined to the commutator. These are called **wave windings** and **lap windings**.

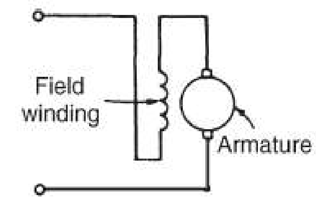
(a) In **wave windings** there are two paths in parallel irrespective of the number of poles, each path supplying half the total current output. Wave wound generators produce high voltage, low current outputs.

(b) In **lap windings** there are as many paths in parallel as the machine has poles. The total current output divides equally between them. Lap wound generators produce high current, low voltage output.

Shunt, series and compound windings



(a) Shunt-wound machine



(b) Series-wound machine

E.m.f. generated in an armature winding

Let Z = number of armature conductors,

Φ = useful flux per pole, in webers

p = number of pairs of poles

and n = armature speed in rev/s

Let c = number of parallel paths through the winding between positive and negative brushes

c = 2 for a wave winding

$c = 2p$ for a lap winding

$$\boxed{\textbf{generated e.m.f., } E = \frac{2p\Phi nZ}{c} \textbf{ volts}}$$

$$\boxed{\text{generated e.m.f., } E \propto \Phi\omega}$$

Problem   A 4-pole generator has a lap-wound armature with 50 slots with 16 conductors per slot. The useful flux per pole is 30 mWb. Determine the speed at which the machine must be driven to generate an e.m.f. of 240 V.

$E = 240$ V, $c = 2p$ (for a lap winding), $Z = 50 \times 16 = 800$,

$\Phi = 30 \times 10^{-3}$ Wb.

Generated e.m.f. $E = \dfrac{2p\Phi nZ}{c} = \dfrac{2p\Phi nZ}{2p} = \Phi nZ$

Rearranging gives, speed, $n = \dfrac{E}{\Phi Z} = \dfrac{240}{(30 \times 10^{-3})(800)}$

$= \mathbf{10\ rev/s\ or\ 600\ rev/min}$

Problem . A d.c. shunt-wound generator running at constant speed generates a voltage of 150 V at a certain value of field current. Determine the change in the generated voltage when the field current is reduced by 20%, assuming the flux is proportional to the field current.

$$\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2} = \frac{\Phi_1 n_1}{0.8\Phi_1 n_1} = \frac{1}{0.8}$$

$$E_2 = 150 \times 0.8 = 120 \text{ V}$$

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EEE 1001

Basic Electrical & Electronics Engineering

DC Machines

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E.m.f. generated in an armature winding

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p = number of pairs of poles

and n = armature speed in rev/s

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Generated e.m.f. $E = \dfrac{2p\Phi nZ}{c} = \dfrac{2p\Phi nZ}{2p} = \Phi nZ$

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$= \mathbf{10\ rev/s\ or\ 600\ rev/min}$

Problem . A d.c. shunt-wound generator running at constant speed generates a voltage of 150 V at a certain value of field current. Determine the change in the generated voltage when the field current is reduced by 20%, assuming the flux is proportional to the field current.

$$\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2} = \frac{\Phi_1 n_1}{0.8\Phi_1 n_1} = \frac{1}{0.8}$$

$$E_2 = 150 \times 0.8 = 120 \text{ V}$$

Problem . A d.c. generator running at 30 rev/s generates an e.m.f. of 200 V. Determine the percentage increase in the flux per pole required to generate 250 V at 20 rev/s.

Let $E_1 = 200$ V, $n_1 = 30$ rev/s and flux per pole at this speed be Φ_1

Let $E_2 = 250$ V, $n_1 = 20$ rev/s and flux per pole at this speed be Φ_2

Since $E \propto \Phi n$ then $\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2}$

Hence $\frac{200}{250} = \frac{\Phi_1(30)}{\Phi_2(20)}$

from which, $\Phi_2 = \frac{\Phi_1(30)(250)}{(20)(200)} = 1.875\ \Phi_1$

Hence the increase in flux per pole needs to be **87.5%**

DC Generators

D.c. generators are classified according to the method of their field excitation. These groupings are:

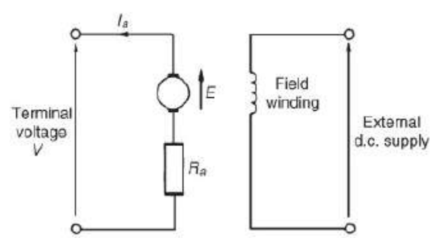
(i) **Separately-excited generators**, where the field winding is connected to a source of supply other than the armature of its own machine.

(ii) **Self-excited generators**, where the field winding receives its supply from the armature of its own machine, and which are sub-divided into (a) shunt, (b) series, and (c) compound wound generators.

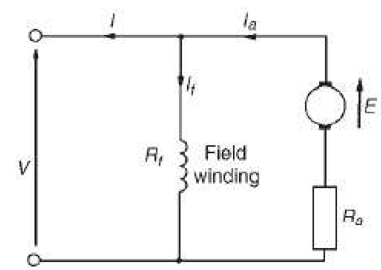
(a) Separately-excited generator

terminal voltage, $V = E - I_a R_a$

generated e.m.f., $E = V + I_a R_a$



(b) Shunt-wound generator



terminal voltage $V = E - I_a R_a$

or generated e.m.f., $E = V + I_a R_a$

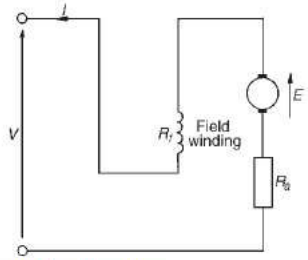
$I_a = I_f + I$, from Kirchhoff's current law,

where I_a = armature current

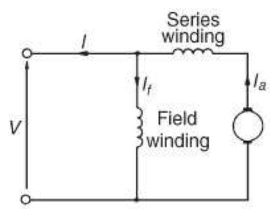
I_f = field current $\left(= \frac{V}{R_f}\right)$

and I = load current

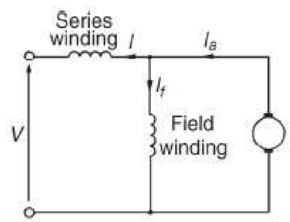
(c) Series-wound generator



(d) Compound-wound generator



Long Shunt



Short Shunt

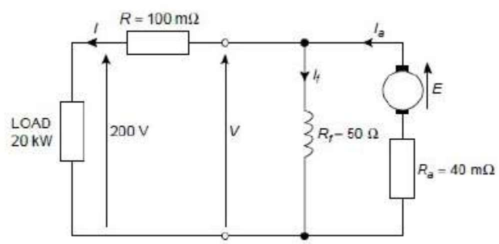
Problem . A separately-excited generator develops a no-load e.m.f. of 150 V at an armature speed of 20 rev/s and a flux per pole of 0.10 Wb. Determine the generated e.m.f. when (a) the speed increases to 25 rev/s and the pole flux remains unchanged, (b) the speed remains at 20 rev/s and the pole flux is decreased to 0.08 Wb, and (c) the speed increases to 24 rev/s and the pole flux is decreased to 0.07 Wb.

$$\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2} \qquad E_2 = \frac{(150)(0.10)(25)}{(0.10)(20)} = \mathbf{187.5\ volts}$$

$$E_3 = \frac{(150)(0.08)(20)}{(0.10)(20)} = \mathbf{120\ volts}$$

$$E_4 = \frac{(150)(0.07)(24)}{(0.10)(20)} = \mathbf{126\ volts}$$

Problem . A shunt generator supplies a 20 kW load at 200 V through cables of resistance, $R = 100\ \text{m}\Omega$. If the field winding resistance, $R_f = 50\ \Omega$ and the armature resistance, $R_a = 40\ \text{m}\Omega$, determine (a) the terminal voltage, and (b) the e.m.f. generated in the armature.



Load current, $I = \dfrac{20\,000 \text{ watts}}{200 \text{ volts}} = 100$ A

Volt drop in the cables to the load $= IR = (100)(100 \times 10^{-3})$

$= 10$ V

Hence terminal voltage, $V = 200 + 10 = \mathbf{210\ volts}$

Armature current $I_a = I_f + I$

Field current, $I_f = \dfrac{V}{R_f} = \dfrac{210}{50} = 4.2$ A

Hence $I_a = I_f + I = 4.2 + 100 = 104.2$ A

Generated e.m.f. $E = V + I_a R_a$

$= 210 + (104.2)(40 \times 10^{-3})$

$= 210 + 4.168$

$= \mathbf{214.17\ volts}$

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

DC Machines

By,
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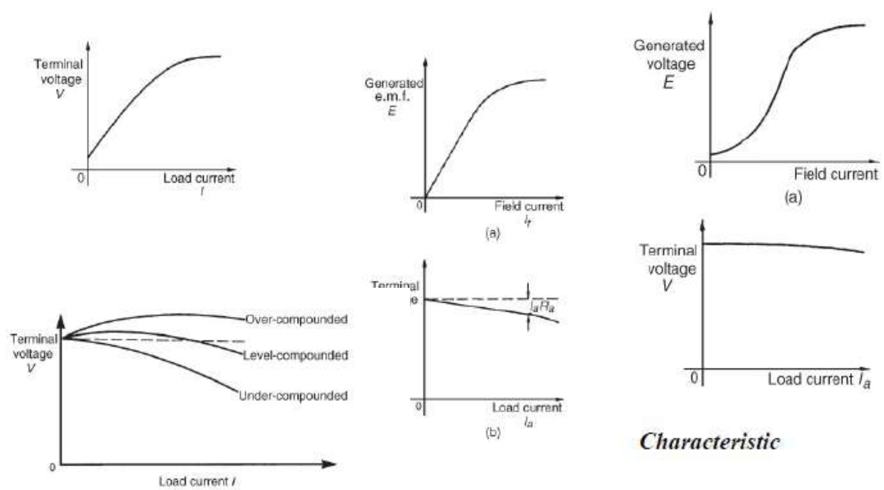
Problem A short-shunt compound generator supplies 80 A at 200 V. If the field resistance, $R_f = 40\ \Omega$, the series resistance, $R_{Se} = 0.02\ \Omega$ and the armature resistance, $R_a = 0.04\ \Omega$, determine the e.m.f. generated.

Ans.: 205 volts

Assignment 2. Q.1
Identify the characteristics given below and explain about it. Mention the applications of the various dc generators .



Characteristic

D.c. machine losses

The principal losses of machines are:

(i) **Copper loss**, due to I^2R heat losses in the armature and field windings.

(ii) **Iron (or core) loss**, due to hysteresis and eddy-current losses in the armature. This loss can be reduced by constructing the armature of silicon steel laminations having a high resistivity and low hysteresis loss. At constant speed, the iron loss is assumed constant.

(iii) **Friction and windage losses**, due to bearing and brush contact friction and losses due to air resistance against moving parts (called windage). At constant speed, these losses are assumed to be constant.

(iv) **Brush contact loss** between the brushes and commutator. This loss is approximately proportional to the load current.

The total losses of a machine can be quite significant and operating efficiencies of between 80% and 90% are common.

Efficiency of a d.c. generator

$$\text{efficiency}, \eta = \left(\frac{\text{output power}}{\text{input power}}\right) \times 100\%$$

If the total resistance of the armature circuit (including brush contact resistance) is R_a, then **the total loss in the armature circuit is $I_a^2 R_a$**

If the terminal voltage is V and the current in the shunt circuit is I_f, then **the loss in the shunt circuit is $I_f V$**

If the sum of the iron, friction and windage losses is C then **the total losses is given by:**

$I_a^2 R_a + I_f V + C$ ($I_a^2 R_a + I_f V$ is, in fact, the 'copper loss')

If the output current is I, then **the output power is VI**

Total input power $= VI + I_a^2 R_a + I_f V + C$. Hence

$$\text{efficiency}, \eta = \frac{\text{output}}{\text{input}} = \left(\frac{VI}{VI + I_a^2 R_a + I_f V + C}\right) \times 100\%$$

The **efficiency of a generator is a maximum** when the load is such that:

$$I_a^2 R_a = VI_f + C$$

Problem A 10 kW shunt generator having an armature circuit resistance of 0.75 Ω and a field resistance of 125 Ω, generates a terminal voltage of 250 V at full load. Determine the efficiency of the generator at full load, assuming the iron, friction and windage losses amount to 600 W.

$$\text{Output power} = 10\,000\ W = VI$$

$$\text{from which, load current } I = \frac{10\,000}{V} = \frac{10\,000}{250} = 40\ \text{A}$$

$$\text{Field current, } I_f = \frac{V}{R_f} = \frac{250}{125} = 2\ \text{A}$$

$$\text{Armature current, } I_a = I_f + I = 2 + 40 = 42\ \text{A}$$

$$\text{Efficiency}, \eta = \left(\frac{VI}{VI + I_a^2 R_a + I_f V + C}\right) \times 100\%$$

$$= \left(\frac{10\,000}{10\,000 + (42)^2(0.75) + (2)(250) + 600}\right) \times 100\%$$

$$= \frac{10\,000}{12\,423} \times 100\% = \mathbf{80.50\%}$$

D.c. motors

Back e.m.f.

When a d.c. motor rotates, an e.m.f. is induced in the armature conductors. By Lenz's law this induced e.m.f. E opposes the supply voltage V and is called a **back e.m.f.**, and the supply voltage, V is given by:

$\boxed{V = E + I_a R_a}$ or $\boxed{E = V - I_a R_a}$

Torque of a d.c. machine

$$V = E + I_a R_a$$

Multiplying each term by current I_a gives:

$$VI_a = EI_a + I_a^2 R_a$$

The term VI_a is the **total electrical power supplied to the armature**, the term $I_a^2 R_a$ is the **loss due to armature resistance**, and the term EI_a is the **mechanical power developed by the armature**

If T is the torque, in newton metres, then the mechanical power developed is given by $T\omega$ watts

Hence $T\omega = 2\pi nT = EI_a$ from which,

$$\boxed{\text{torque } T = \frac{EI_a}{2\pi n} \text{ newton metres}}$$

$$E = \frac{2p\Phi nZ}{c}$$

$$\text{Hence } 2\pi nT = EI_a = \left(\frac{2p\Phi nZ}{c}\right) I_a$$

$$\text{and torque } T = \frac{\left(\frac{2p\Phi nZ}{c}\right) I_a}{2\pi n}$$

i.e., $\boxed{T = \frac{p\Phi Z I_a}{\pi c} \text{ newton metres}}$

For a given machine, Z, c and p are fixed values

Hence torque, $\boxed{T \propto \Phi I_a}$

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Problem . The armature of a d.c. machine has a resistance of 0.25 Ω and is connected to a 300 V supply. Calculate the e.m.f. generated when it is running: (a) as a generator giving 100 A, and (b) as a motor taking 80 A.

(a) As a generator, generated e.m.f.,

$$E = V + I_a R_a,$$

$$= 300 + (100)(0.25)$$

$$= 300 + 25 = \mathbf{325\ volts}$$

(b) As a motor, generated e.m.f. (or back e.m.f.),

$$E = V - I_a R_a,$$

$$= 300 - (80)(0.25) = \mathbf{280\ volts}$$

Problem . A six-pole lap-wound motor is connected to a 250 V d.c. supply. The armature has 500 conductors and a resistance of 1 Ω. The flux per pole is 20 mWb. Calculate (a) the speed and (b) the torque developed when the armature current is 40 A

$V = 250\ V$, $Z = 500$, $R_a = 1\ \Omega$, $\Phi = 20 \times 10^{-3}$ Wb, $I_a = 40$ A, $c = 2p$ for a lap winding

(a) Back e.m.f. $E = V - I_a R_a = 250 - (40)(1) = 210$ V

$$\text{E.m.f. } E = \frac{2p\Phi n Z}{c} \qquad \text{i.e. } 210 = \frac{2p(20 \times 10^{-3})n(500)}{2p}$$

$$\text{Hence speed } n = \frac{210}{(20 \times 10^{-3})(500)} = \mathbf{21\ rev/s}$$

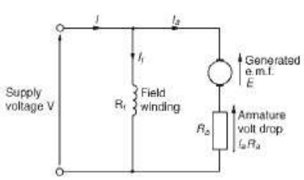
$$\text{or} \quad (21 \times 60) = \mathbf{1260\ rev/min}$$

$$\text{Torque } T = \frac{EI_a}{2\pi n} = \frac{(210)(40)}{2\pi(21)} = \mathbf{63.66\ Nm}$$

Assignment 2. Q.2

Identify the characteristics of the various dc motors and explain about it. Mention the applications of the various dc motors .

Types of d.c. motor and their characteristics

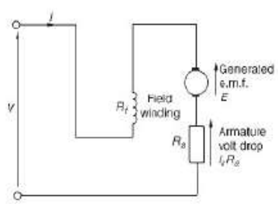


Shunt motor

Supply voltage, $V = E + I_a R_a$

or generated e.m.f., $E = V - I_a R_a$

Supply current, $I = I_a + I_f$,

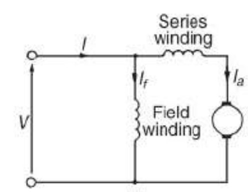


Supply voltage $V = E + I(R_a + R_f)$

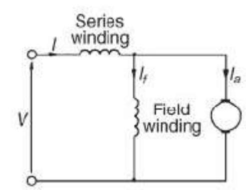
or generated e.m.f. $E = V - I(R_a + R_f)$

Series motor

Compound motor



(a)



(b)

Problem . A 200 V, d.c. shunt-wound motor has an armature resistance of 0.4 Ω and at a certain load has an armature current of 30 A and runs at 1350 rev/min. If the load on the shaft of the motor is increased so that the armature current increases to 45 A, determine the speed of the motor, assuming the flux remains constant.

$$E \propto \Phi n$$

Hence $E_1 = 200 - 30 \times 0.4 = 188$ V,

$$E_2 = 200 - 45 \times 0.4 = 182 \text{ V}.$$

$$\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2} \qquad \frac{188}{182} = \frac{\Phi_1 \times \left(\frac{1350}{60}\right)}{\Phi_1 \times n_2}$$

$$n_2 = \frac{22.5 \times 182}{188} = 21.78 \text{ rev/s}$$

1307 rev/min

Problem . A series motor has an armature resistance of 0.2 Ω and a series field resistance of 0.3 Ω. It is connected to a 240 V supply and at a particular load runs at 24 rev/s when drawing 15 A from the supply.

(a) Determine the generated e.m.f. at this load.
(b) Calculate the speed of the motor when the load is changed such that the current is increased to 30 A. Assume that this causes a doubling of the flux.

$$E_1 = V - I_a(R_a + R_f)$$

$$= 240 - (15)(0.2 + 0.3) = 240 - 7.5 = \mathbf{232.5 \text{ volts}}$$

When the current is increased to 30 A, the generated e.m.f. is given by:

$$E_2 = V - I_a(R_a + R_f)$$
$$= 240 - (30)(0.2 + 0.3) = 240 - 15 = 225 \text{ volts}$$

$$\frac{E_1}{E_2} = \frac{\Phi_1 n_1}{\Phi_2 n_2}$$

$$\frac{232.5}{225} = \frac{\Phi_1(24)}{(2\Phi_1)(n_2)} \text{ since } \Phi_2 = 2\Phi_1$$

Hence speed of motor, $n_2 = \frac{(24)(225)}{(232.5)(2)} = 11.6$ rev/s

The efficiency of a d.c. motor

For a motor, the input power $= VI$

and the output power $= VI -$ losses

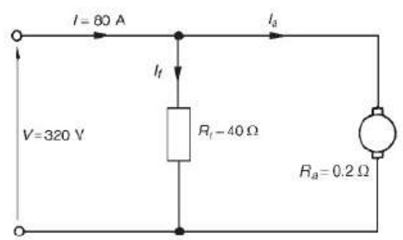
$$= VI - I_a^2 R_a - I_f V - C$$

Hence $\boxed{\textbf{efficiency } \eta = \left(\frac{VI - I_a^2 R_a - I_f V - C}{VI}\right) \times 100\%}$

The efficiency of a motor is a maximum when the load is such that:

$$I_a^2 R_a = I_f V + C$$

Problem . A 320 V shunt motor takes a total current of 80 A and runs at 1000 rev/min. If the iron, friction and windage losses amount to 1.5 kW, the shunt field resistance is 40 Ω and the armature resistance is 0.2 Ω, determine the overall efficiency of the motor.



Field current, $I_f = \frac{V}{R_f} = \frac{320}{40} = 8$ A

Armature current $I_a = I - I_f = 80 - 8 = 72$ A

C = iron, friction and windage losses = 1500 W

$$\text{Efficiency, } \eta = \left(\frac{VI - I_a^2 R_a - I_f V - C}{VI}\right) \times 100\%$$

$$= \left(\frac{(320)(80) - (72)^2(0.2) - (8)(320) - 1500}{(320)(80)}\right) \times 100\%$$

$$= \left(\frac{25\,600 - 1036.8 - 2560 - 1500}{25\,600}\right) \times 100\%$$

$$= \left(\frac{20\,503.2}{25\,600}\right) \times 100\% = \mathbf{80.1\%}$$

Problem A 200 V d.c. motor develops a shaft torque of 15 Nm at 1200 rev/min. If the efficiency is 80%, determine the current supplied to the motor.

$$\text{for a motor, efficiency, } \eta = \frac{T(2\pi n)}{VI} \times 100\%$$

$$80 = \left[\frac{(15)(2\pi)(1200/60)}{(200)(I)}\right](100)$$

$$\text{Thus the current supplied, } I = \frac{(15)(2\pi)(20)(100)}{(200)(80)} = \mathbf{11.8\ A}$$

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Transformers

By,

Meera P. S.

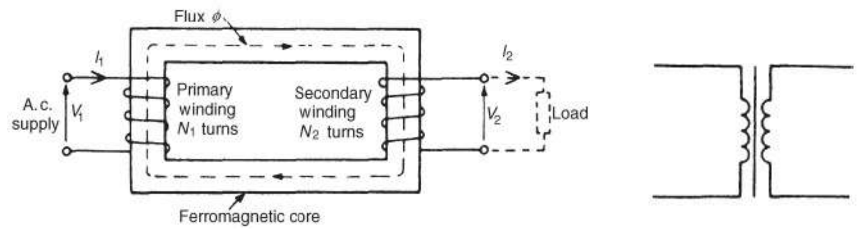
Assistant Professor, SELECT

Introduction

- A transformer is a device which uses the phenomenon of mutual induction to change the values of alternating voltages and currents.
- In fact, one of the main advantages of a.c. transmission and distribution is the ease with which an alternating voltage can be increased or decreased by transformers.
- Losses in transformers are generally low and thus efficiency is high.
- Being static they have a long life and are very stable.

Introduction

- A transformer is represented in as consisting of two electrical circuits linked by a common ferromagnetic core. One coil is termed the primary winding which is connected to the supply of electricity, and the other the secondary winding, which may be connected to a load.



Transformer principle of operation

When the secondary is an open-circuit and an alternating voltage V_1 is applied to the primary winding, a small current—called the no-load current I_0—flows, which sets up a magnetic flux in the core. This alternating flux links with both primary and secondary coils and induces in them e.m.f.'s of E_1 and E_2 respectively by mutual induction.

The induced e.m.f. E in a coil of N turns is given by

$$E = -N\frac{d\Phi}{dt} \text{ volts,}$$

where $d\Phi/dt$ is the rate of change of flux. In an ideal transformer, the rate of change of flux is the same for both primary and secondary and thus $E_1/N_1 = E_2/N_2$, i.e. **the induced e.m.f. per turn is constant.**

Assuming no losses, $E_1 = V_1$ and $E_2 = V_2$ Hence

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} \text{ or } \frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Transformer principle of operation

V_1/V_2 is called the voltage ratio and N_1/N_2 the turns ratio, or the **'transformation ratio'** of the transformer. If N_2 is less than N_1 then V_2 is less than V_1 and the device is termed a **step-down transformer**. If N_2 is greater then N_1 then V_2 is greater than V_1 and the device is termed a **step-up transformer**.

In an ideal transformer losses are neglected and a transformer is considered to be 100% efficient.

Hence input power = output power, or $V_1 I_1 = V_2 I_2$, i.e., in an ideal transformer, the **primary and secondary volt-amperes are equal**.

Thus $$\frac{V_1}{V_2} = \frac{I_2}{I_1}$$

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Transformer principle of operation

$$\boxed{\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}}$$

> Problem An ideal transformer, connected to a 240 V mains, supplies a 12 V, 150 W lamp. Calculate the transformer turns ratio and the current taken from the supply.

$V_1 = 240$ V, $V_2 = 12$ V, $I_2 = \frac{P}{V_2} = \frac{150}{12} = 12.5$ A

Turns ratio $= \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{240}{12} = \mathbf{20}$

$\frac{V_1}{V_2} = \frac{I_2}{I_1}$, from which, $I_1 = I_2\left(\frac{V_2}{V_1}\right) = 12.5\left(\frac{12}{240}\right)$

Hence current taken from the supply, $I_1 = \frac{12.5}{20} = \mathbf{0.625\ A}$

> Problem A 5 kVA single-phase transformer has a turns ratio of 10:1 and is fed from a 2.5 kV supply. Neglecting losses, determine (a) the full-load secondary current, (b) the minimum load resistance which can be connected across the secondary winding to give full load kVA, (c) the primary current at full load kVA.

(a) $\frac{N_1}{N_2} = \frac{10}{1}$ and $V_1 = 2.5\text{ kV} = 2500$ V

Since $\frac{N_1}{N_2} = \frac{V_1}{V_2}$, secondary voltage $V_2 = V_1\left(\frac{N_2}{N_1}\right)$

$$= 2500\left(\frac{1}{10}\right) = 250\text{ V}$$

The transformer rating in volt-amperes $= V_2 I_2$ (at full load), i.e., $5000 = 250 I_2$

Hence full load secondary current $I_2 = \frac{5000}{250} = \mathbf{20\ A}$

(b) Minimum value of load resistance, $R_L = \frac{V_2}{I_2} = \frac{250}{20} = \mathbf{12.5\ \Omega}$

(c) $\frac{N_1}{N_2} = \frac{I_2}{I_1}$, from which primary current $I_1 = I_2\left(\frac{N_2}{N_1}\right)$

$$= 20\left(\frac{1}{10}\right) = \mathbf{2\ A}$$

EMF equation of a transformer

Let Φ_m be the maximum value of the flux and f be the frequency of the supply. The time for 1 cycle of the alternating flux is the periodic time T, where $T = 1/f$ seconds

The flux rises sinusoidally from zero to its maximum value in $\frac{1}{4}$ cycle, and the time for $\frac{1}{4}$ cycle is $1/4f$ seconds.

Hence the average rate of change of flux $= \dfrac{\Phi_m}{(1/4f)} = 4f\Phi_m$ Wb/s, and since 1 Wb/s = 1 volt, the average e.m.f. induced in each turn $= 4f\Phi_m$ volts.

As the flux Φ varies sinusoidally, then a sinusoidal e.m.f. will be induced in each turn of both primary and secondary windings.

For a sine wave, form factor $= \dfrac{\text{rms value}}{\text{average value}} = 1.11$

Hence rms value = form factor × average value

$= 1.11 \times$ average value

EMF equation of a transformer

Thus rms e.m.f. induced in each turn $= 1.11 \times 4f\Phi_m$ volts

$= 4.44f\Phi_m$ volts

Therefore, rms value of e.m.f. induced in primary,

$\mathbf{E_1 = 4.44 f \Phi_m N_1}$ **volts**

and rms value of e.m.f. induced in secondary,

$\mathbf{E_2 = 4.44 f \Phi_m N_2}$ **volts**

Problem . A single-phase, 50 Hz transformer has 25 primary turns and 300 secondary turns. The cross-sectional area of the core is 300 cm^2. When the primary winding is connected to a 250 V supply, determine (a) the maximum value of the flux density in the core, and (b) the voltage induced in the secondary winding.

maximum flux density, $\Phi_m = \dfrac{250}{(4.44)(50)(25)}$ Wb

$= 0.04505$ Wb

However, $\Phi_m = B_m \times A$, where B_m = maximum flux density in the core and A = cross-sectional area of the core

Hence $B_m \times 300 \times 10^{-4} = 0.04505$

from which, **maximum flux density**, $B_m = \dfrac{0.04505}{300 \times 10^{-4}} = \mathbf{1.50\ T}$

$$V_2 = (250)\left(\frac{300}{25}\right) = \mathbf{3000\ V\ or\ 3\ kV}$$

Problem A single-phase 500 V/100 V, 50 Hz transformer has a maximum core flux density of 1.5 T and an effective core cross-sectional area of 50 cm^2. Determine the number of primary and secondary turns.

The e.m.f. equation for a transformer is $E = 4.44f\Phi_m N$

and maximum flux, $\Phi_m = B \times A = (1.5)(50 \times 10^{-4}) = 75 \times 10^{-4}$ Wb

Since $E_1 = 4.44f\Phi_m N_1$

then primary turns, $N_1 = \dfrac{E_1}{4.44f\Phi_m} = \dfrac{500}{4.44(50)(75 \times 10^{-4})}$

$= \mathbf{300\ turns}$

Since $E_2 = 4.4f\Phi_m N_2$

then secondary turns, $N_2 = \dfrac{E_2}{4.4f\Phi_m} = \dfrac{100}{4.44(50)(75 \times 10^{-4})}$

$= \mathbf{60\ turns}$

Problem A 4500 V/225 V, 50 Hz single-phase transformer is to have an approximate e.m.f. per turn of 15 V and operate with a maximum flux of 1.4 T. Calculate (a) the number of primary and secondary turns and (b) the cross-sectional area of the core.

(a) E.m.f. per turn $= \dfrac{E_1}{N_1} = \dfrac{E_2}{N_2} = 15$

Hence primary turns, $N_1 = \dfrac{E_1}{15} = \dfrac{4500}{15} = \mathbf{300}$

and secondary turns, $N_2 = \dfrac{E_2}{15} = \dfrac{225}{15} = \mathbf{15}$

(b) E.m.f. $E_1 = 4.44 f \Phi_m N_1$

from which, $\Phi_m = \dfrac{E_1}{4.44 f N_1} = \dfrac{4500}{4.44(50)(300)} = 0.0676$ Wb

Now flux $\Phi_m = B_m \times A$, where A is the cross-sectional area of the core, hence

area $A = \dfrac{\Phi_m}{B_m} = \dfrac{0.0676}{1.4} = \mathbf{0.0483\ m^2}$ or $\mathbf{483\ cm^2}$

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SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Digital Systems

By,

Meera P. S.

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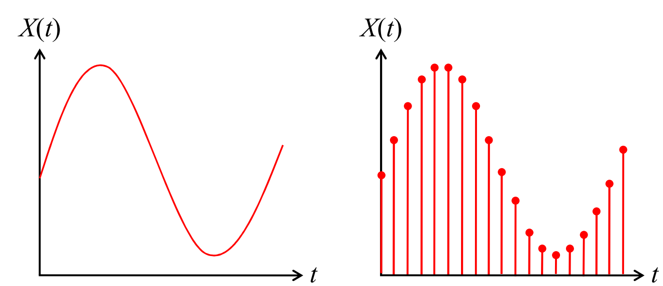
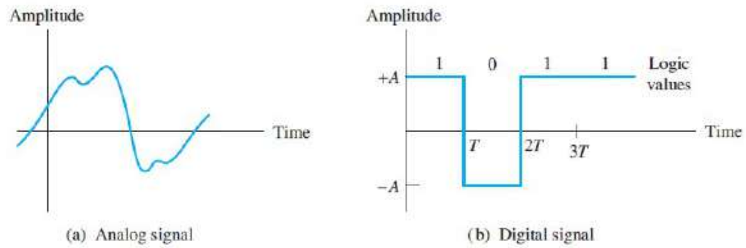
Analog and Digital Signal

- Analog system
  - The physical quantities or signals may vary continuously over a specified range.
- Digital system
  - The physical quantities or signals can assume only discrete values.
  - Greater accuracy

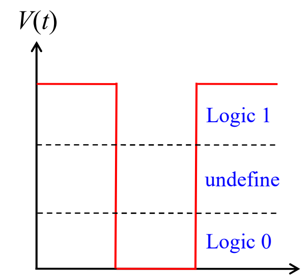


Analog signal Digital signal



Binary Digital Signal

- An information variable represented by physical quantity.
- For digital systems, the variable takes on discrete values.
  - Two level, or binary values are the most prevalent values.
- Binary values are represented abstractly by:
  - Digits 0 and 1
  - Words (symbols) False (F) and True (T)
  - Words (symbols) Low (L) and High (H)
  - And words On and Off
- Binary values are represented by values or ranges of values of physical quantities.



Binary digital signal

Decimal Number System

- Base (also called radix) = 10
  - 10 digits { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 }
- Digit Position
  - Integer & fraction
- Digit Weight
  - Weight = $(Base)^{Position}$
- Magnitude
  - Sum of "*Digit* x *Weight*"
- Formal Notation

2	1	0		-1	-2
5	1	2	.	9	4
100	10	1		0.1	0.01
			.		
500	10	2		0.9	0.04

$$d_2*B^2+d_1*B^1+d_0*B^0+d_{-1}*B^{-1}+d_{-2}*B^{-2}$$

$$(512.94)_{10}$$

Binary Number System

- Base = 2
  - 2 digits { 0, 1 }, called *b*inary dig*its* or "*bits*"
- Weights
  - Weight = $(Base)^{Position}$
- Magnitude
  - Sum of "*Bit* x *Weight*"
- Formal Notation
- Groups of bits   4 bits = *Nibble*
  8 bits = *Byte*

4	2	1		1/2	1/4
1	0	1	.	0	1
2	1	0		-1	-2

$$1*2^2+0*2^1+1*2^0+0*2^{-1}+1*2^{-2}$$

$$=(5.25)_{10}$$

$$(101.01)_2$$

1 0 1 1

1 1 0 0 0 1 0 1

Decimal (*Integer*) to Binary Conversion

- Divide the number by the 'Base' (=2)
- Take the remainder (either 0 or 1) as a coefficient
- Take the quotient and repeat the division

Example: $(13)_{10}$

	Quotient	Remainder	Coefficient
13 / 2 =	6	1	$a_0 = 1$
6 / 2 =	3	0	$a_1 = 0$
3 / 2 =	1	1	$a_2 = 1$
1 / 2 =	0	1	$a_3 = 1$

Answer: $(13)_{10} = (a_3\, a_2\, a_1\, a_0)_2 = (1101)_2$

MSB LSB

Decimal (*Fraction*) to Binary Conversion

- Multiply the number by the 'Base' (=2)
- Take the integer (either 0 or 1) as a coefficient
- Take the resultant fraction and repeat the division

Example: $(0.625)_{10}$

	Integer		Fraction	Coefficient
0.625 * 2 =	1	.	25	$a_{-1} = 1$
0.25 * 2 =	0	.	5	$a_{-2} = 0$
0.5 * 2 =	1	.	0	$a_{-3} = 1$

Answer: $(0.625)_{10} = (0.a_{-1}\, a_{-2}\, a_{-3})_2 = (0.101)_2$

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Basic Electrical & Electronics Engineering

Digital Systems

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Conversion of 343_{10} to binary form

		Quotient	Remainder
343/2	=	171	1
171/2	=	85	1
85/2	=	42	1
42/2	=	21	0
21/2	=	10	1
10/2	=	5	0
5/2	=	2	1
2/2	=	1	0
1/2	=	0	1

$\rightarrow 101010111_2$

Read binary equivalent in reverse order

Stop when quotient equals zero

Conversion of 0.392_{10} to binary.

$$
\begin{array}{lclcl}
2 \times 0.392 & = & 0 & + & 0.784 \\
2 \times 0.784 & = & 1 & + & 0.568 \\
2 \times 0.568 & = & 1 & + & 0.136 \\
2 \times 0.136 & = & 0 & + & 0.272 \\
2 \times 0.272 & = & 0 & + & 0.544 \\
2 \times 0.544 & = & 1 & + & 0.088
\end{array}
$$

$0.\overbrace{011001}_2$ (approximate binary equivalent)

Convert the following numbers to binary form, stopping after you have found six bits (if necessary) for the fractional part: **a.** 23.75; **b.** 17.25; **c.** 4.3.

Convert the following to decimal equivalents: **a.** 1101.111_2; **b.** 100.001_2.

Binary Arithmetic

We add binary numbers in much the same way that we add decimal numbers, except that the rules of addition are different (and much simpler). The rules for binary addition are shown in Figure

		Sum	Carry
0 + 0	=	0	0
0 + 1	=	1	0
1 + 1	=	0	1
1 + 1 + 1	=	1	1

Figure Rules of binary addition.

Add the binary numbers 1000.111 and 1100.011.

$$
\begin{array}{r}
0001\ 11 \quad \longleftarrow \text{Carries} \\
1000.111 \\
+1100.011 \\
\hline
10101.010
\end{array}
$$

Hexadecimal and Octal Numbers

Table Symbols for Octal and Hexadecimal Numbers and Their Binary Equivalents

Octal		Hexadecimal	
0	000	0	0000
1	001	1	0001
2	010	2	0010
3	011	3	0011
4	100	4	0100
5	101	5	0101
6	110	6	0110
7	111	7	0111
		8	1000
		9	1001
		A	1010
		B	1011
		C	1100
		D	1101
		E	1110
		F	1111

Convert the numbers 317.2_8 and $F3A.2_{16}$ to binary.

$$317.2_8 = 011\ 001\ 111.\ 010_2$$
$$= 011001111.010_2$$

$$F3A.2_{16} = 1111\ 0011\ 1010.\ 0010$$
$$= 111100111010.0010_2$$

Convert the following numbers to binary, octal, and hexadecimal forms: **a.** 97_{10}; **b.** 229_{10}.

Convert the following numbers to binary form: **a.** 72_8; **b.** $FA6_{16}$.

Convert 11110110.1_2 to octal and to hexadecimal.

$$11110110.1_2 = 011\ 110\ 110.\ 100$$

$$11110110.1_2 = 011\ 110\ 110.\ 100 = 366.4_8$$

$$11110110.1_2 = 1111\ 0110.\ 1000 = F6.8_{16}$$

Binary-Coded Decimal Format

Sometimes, decimal numbers are represented in binary form simply by writing the four-bit equivalents for each digit. The resulting numbers are said to be in **binary-coded decimal** (BCD) format.

$$93.2 = 1001\ 0011.\ 0010_{BCD}$$

Code groups 1010, 1011, 1100, 1101, 1110, and 1111 do not occur in BCD

Express 197_{10} in BCD form.

$$197_{10} = 000110010111_{BCD}$$

Complement Arithmetic

The **one's complement** of a binary number is obtained by replacing 1s by 0s,

01001101 10110010 (one's complement)

The **two's complement** of a binary number is obtained by adding 1 to the one's complement, neglecting the carry (if any) out of the most significant bit.

$$\begin{array}{rl} 10110011 & \text{One's complement} \\ +1 & \\ \hline 10110100 & \text{Two's complement} \end{array}$$

Complements are useful for representing negative numbers and performing subtraction in computers. Furthermore, the use of complement arithmetic simplifies the design of digital computers. Most common is the **signed two's-complement** representation, in which the first bit is taken as the sign bit. If the number is positive, the first bit is 0, whereas if the number is negative, the first bit is 1. Negative numbers are represented as the two's complement of the corresponding positive number.

Carry out $19_{10} - 4_{10}$ in eight-bit signed two's-complement form.

$$\begin{array}{rr} 19 & 00010011 \\ +\underline{(-4)} & +\underline{11111100} \\ 15 & 00001111 \end{array}$$

Perform the operation $29_{10} - 27_{10}$ by using eight-bit signed two's-complement arithmetic.

First, we convert 29_{10} and 27_{10} to binary form.

$$29_{10} = 00011101$$

$$27_{10} = 00011011$$

find the two's complement of the subtrahend:

$$-27_{10} = 11100101$$

Finally, we add the numbers to find the result:

$$\begin{array}{rrr} & 00011101 & 29 \\ \text{ignore carry} & +\underline{11100101} & +\underline{(-27)} \\ \text{out of sign bit} \rightarrow & 00000010 & 2 \end{array}$$

COMBINATORIAL LOGIC CIRCUITS

In this section, we consider circuits called **logic gates** that combine several logic-variable inputs to produce a logic-variable output.

The circuits that we are about to discuss are said to be **memoryless** because their output values at a given instant depend only on the input values at that instant. Later, we consider logic circuits that are said to possess **memory**, because their present output values depend on previous, as well as present, input values.

AND Gate

An important logic function is called the AND operation. The AND operation on two logic variables, A and B, is represented as AB, read as "A and B." The AND operation is also called **logical multiplication**.

AND Gate

An important logic function is called the AND operation. The AND operation on two logic variables, A and B, is represented as AB, read as "A and B." The AND operation is also called **logical multiplication**.

$$AA = A$$

$$A1 = A$$

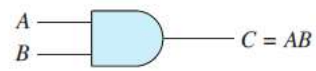
$$A0 = 0$$

$$AB = BA$$

$$A(BC) = (AB)C = ABC$$

A	B	$C = AB$
0	0	0
0	1	0
1	0	0
1	1	1

(a) Truth table



(b) Symbol for two-input AND gate

Logic Inverter

The NOT operation on a logic variable is represented by placing a bar over the symbol for the logic variable. The symbol $\overline{A}$ is read as "not A" or as "A inverse." If A is 0, $\overline{A}$ is 1, and vice versa.

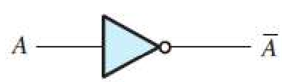
Circuits that perform the NOT operation are called **inverters**. The truth table and circuit symbol for an inverter are shown in Figure . The *bubble* placed at the output of the inverter symbol is used to indicate inversion.

$$A\overline{A} = 0$$

$$A = A$$

A	$\overline{A}$
0	1
1	0

(a) Truth table



(b) Symbol for an inverter

OR Gate

The OR operation of logic variables is written as $A + B$, which is read as "A or B." The truth table and the circuit symbol for a two-input OR gate are shown in Figure . Notice that $A + B$ is 1 if A or B (or both) are 1. The OR operation is also called **logical addition**.

$$(A + B) + C = A + (B + C) = A + B + C$$

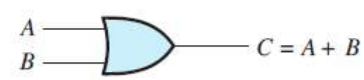
$$A(B + C) = AB + AC$$

$$A + 0 = A$$

$$A + 1 = 1$$

A	B	$C = A + B$
0	0	0
0	1	1
1	0	1
1	1	1

(a) Truth table



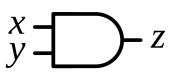
(b) Symbol for two-input OR gate

- Truth Tables, Boolean Expressions, and Logic Gates

AND

x	y	z
0	0	0
0	1	0
1	0	0
1	1	1

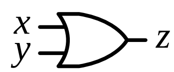
$z = x \bullet y = x\,y$



OR

x	y	z
0	0	0
0	1	1
1	0	1
1	1	1

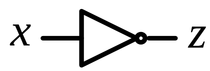
$z = x + y$



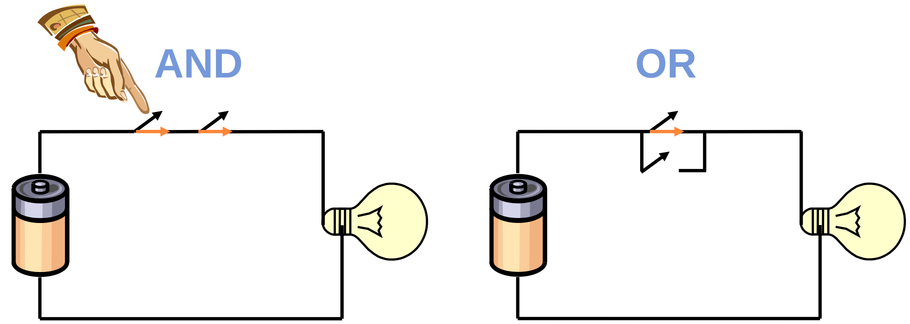
NOT

x	z
0	1
1	0

$z = \overline{x} = x'$

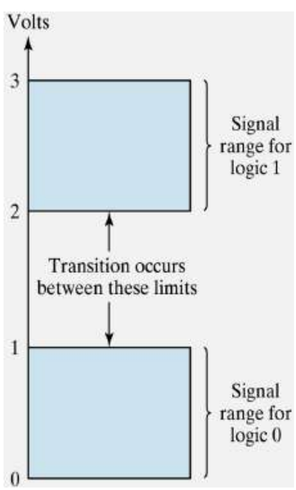


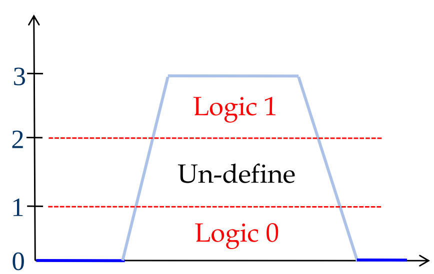
Switching Circuits

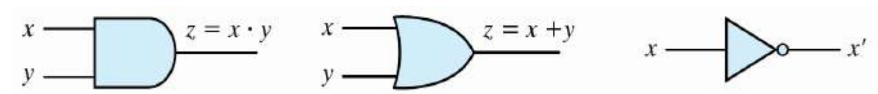


Binary Logic

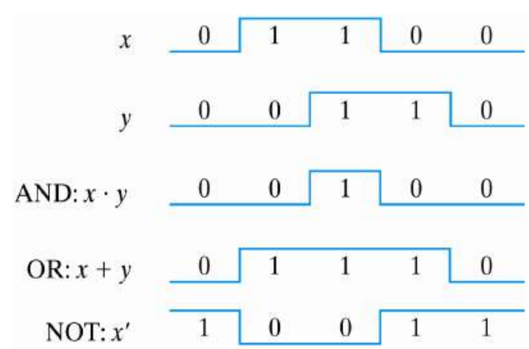
- Example of binary signals

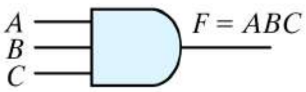




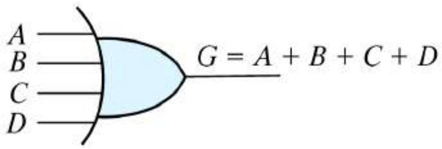


(a) Two-input AND gate (b) Two-input OR gate (c) NOT gate or inverter



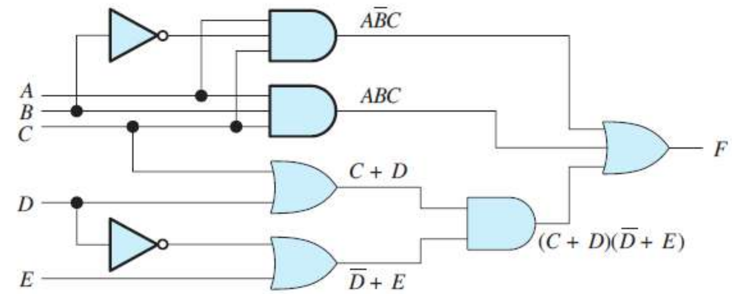


(a) Three-input AND gate



(b) Four-input OR gate

A circuit that implements the logic expression $F = A\overline{B}C + ABC + (C + D)(\overline{D} + E)$.



Vellore Institute of Technology
(Deemed to be University under section 3 of UGC Act, 1956)

SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

Digital Systems

By,

Meera P. S.

Assistant Professor, SELECT

Boolean Algebra

Using a Truth Table to Prove a Boolean Expression

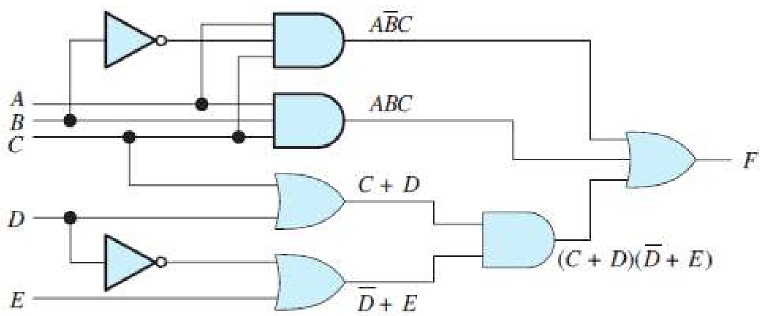
Prove the associative law for the OR operation

$$(A + B) + C = A + (B + C)$$

A	B	C	$(A+B)$	$(B+C)$	$A+(B+C)$	$(A+B)+C$	$A+B+C$
0	0	0	0	0	0	0	0
0	0	1	0	1	1	1	1
0	1	0	1	1	1	1	1
0	1	1	1	1	1	1	1
1	0	0	1	0	1	1	1
1	0	1	1	1	1	1	1
1	1	0	1	1	1	1	1
1	1	1	1	1	1	1	1

Implementation of Boolean Expressions

$$F = A\overline{B}C + ABC + (C + D)(\overline{D} + E)$$



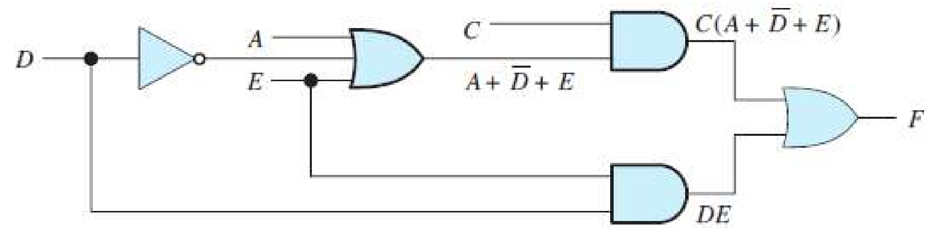
Sometimes, we can manipulate a logic expression to find an equivalent expression that is simpler.

$$F = A\overline{B}C + ABC + C\overline{D} + CE + D\overline{D} + DE$$

$$F = AC(\overline{B} + B) + C\overline{D} + CE + DE$$

$$F = AC + C\overline{D} + CE + DE$$

$$F = C(A + \overline{D} + E) + DE$$



De Morgan's Laws

Two important results in Boolean algebra are De Morgan's laws, which are given by

$$ABC = \overline{\overline{A} + \overline{B} + \overline{C}}$$

and

$$(A + B + C) = \overline{\overline{A}\,\overline{B}\,\overline{C}}$$

Apply De Morgan's laws to the right-hand side of the logic expression:

$$D = AC + \overline{B}C + \overline{A}(\overline{B} + BC)$$

First, we replace each variable by its inverse, resulting in the expression

$$\overline{A}\,\overline{C} + B\overline{C} + A(B + \overline{B}\,\overline{C})$$

Then, we replace the AND operation by OR, and vice versa:

$$(\overline{A} + \overline{C})(B + \overline{C})[A + B(\overline{B} + \overline{C})]$$

Finally, inverting the expression, we can write

$$D = \overline{(\overline{A} + \overline{C})(B + \overline{C})[A + B(\overline{B} + \overline{C})]}$$

De Morgan's Theorem

$$\overline{a\,[b+c\,(d+\overline{e}\,)]}$$

$$\overline{a}+\overline{[b+c\,(d+\overline{e}\,)]}$$

$$\overline{a}+\overline{b}\,(\overline{c\,(d+\overline{e}\,}))$$

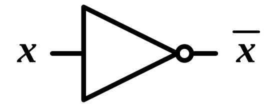
$$\overline{a}+\overline{b}\,(\overline{c}+(\overline{d+\overline{e}}\,))$$

$$\overline{a}+\overline{b}\,(\overline{c}+(\overline{d}\,\overline{\overline{e}}))$$

$$\overline{a}+\overline{b}\,(\overline{c}+\overline{d}\,e)$$

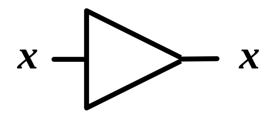
Logic Operators

★ **NOT (Inverter)**



x	NOT
0	1
1	0

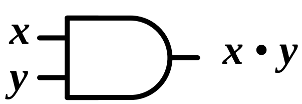
★ **Buffer**



x	Buffer
0	0
1	1

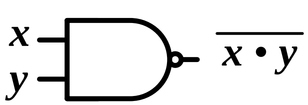
Logic Operators

★ **AND**



x	y	AND
0	0	0
0	1	0
1	0	0
1	1	1

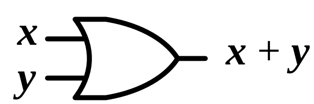
★ **NAND (Not AND)**



x	y	NAND
0	0	1
0	1	1
1	0	1
1	1	0

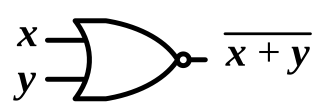
Logic Operators

★ **OR**



x	y	OR
0	0	0
0	1	1
1	0	1
1	1	1

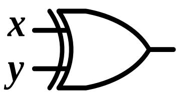
★ **NOR (Not OR)**



x	y	NOR
0	0	1
0	1	0
1	0	0
1	1	0

Logic Operators

★ **XOR (Exclusive-OR)**

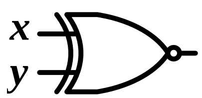


$x \oplus y$ $\bar{x}\,y + x\,\bar{y}$

x	y	XOR
0	0	0
0	1	1
1	0	1
1	1	0

The XOR operation is also known as **modulo-two addition.**

★ **XNOR (Exclusive-NOR) (Equivalence)**



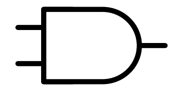
$\overline{x \oplus y}$ $x \odot y$ $\bar{x}\,\bar{y} + x\,y$

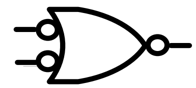
x	y	$XNOR$
0	0	1
0	1	0
1	0	0
1	1	1

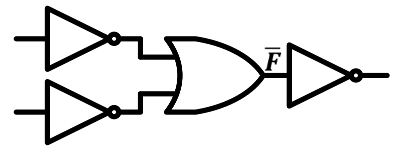
DeMorgan's Theorem on Gates

★ **AND Gate**

- $F = x \bullet y$ $\overline{F} = \overline{(x \bullet y)}$ $\overline{F} = \bar{x} + \bar{y}$

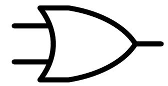


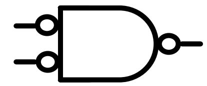


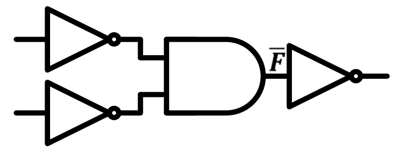


★ **OR Gate**

- $F = x + y$ $\overline{F} = \overline{(x + y)}$ $\overline{F} = \bar{x} \bullet \bar{y}$







➔ **Change the "Shape" and "bubble" all lines**

Canonical Forms

★ **Minterm**

- **Product (*AND* function)**
- **Contains all variables**
- **Evaluates to '1' for a specific combination**

Example

$A = 0$, $B = 0$, $C = 0$ → $\bar{A}$ $\bar{B}$ $\bar{C}$ → $(\bar{0}) \bullet (\bar{0}) \bullet (\bar{0})$ → $1 \bullet 1 \bullet 1 = 1$

	A B C	Minterm	
0	0 0 0	m_0	$\bar{A}\bar{B}\bar{C}$
1	0 0 1	m_1	$\bar{A}\bar{B}C$
2	0 1 0	m_2	$\bar{A}B\bar{C}$
3	0 1 1	m_3	$\bar{A}BC$
4	1 0 0	m_4	$A\bar{B}\bar{C}$
5	1 0 1	m_5	$A\bar{B}C$
6	1 1 0	m_6	$AB\bar{C}$
7	1 1 1	m_7	ABC

Canonical Forms

★ **Maxterm**

- **Sum (*OR* function)**
- **Contains all variables**
- **Evaluates to '0' for a specific combination**

Example

$A = 1$, $B = 1$, $C = 1$ → $\bar{A}$ $\bar{B}$ $\bar{C}$ → $(\bar{1}) + (\bar{1}) + (\bar{1})$ → $0 + 0 + 0 = 0$

	A B C	Maxterm	
0	0 0 0	M_0	$A+B+C$
1	0 0 1	M_1	$A+B+\bar{C}$
2	0 1 0	M_2	$A+\bar{B}+C$
3	0 1 1	M_3	$A+\bar{B}+\bar{C}$
4	1 0 0	M_4	$\bar{A}+B+C$
5	1 0 1	M_5	$\bar{A}+B+\bar{C}$
6	1 1 0	M_6	$\bar{A}+\bar{B}+C$
7	1 1 1	M_7	$\bar{A}+\bar{B}+\bar{C}$

Canonical Forms

★ Truth Table *to* Boolean Function

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

$$F = \bar{A}\bar{B}C + A\bar{B}\bar{C} + A\bar{B}C + ABC$$

Canonical Forms

	A	B	C	F	$\bar{F}$
0	0	0	0	0	1
1	0	0	1	1	0
2	0	1	0	0	1
3	0	1	1	0	1
4	1	0	0	1	0
5	1	0	1	1	0
6	1	1	0	0	1
7	1	1	1	1	0

★ Sum of *Minterms*

$$F = \bar{A}\bar{B}C + A\bar{B}\bar{C} + A\bar{B}C + ABC$$

$$F = m_1 + m_4 + m_5 + m_7$$

$$F = \sum(1,4,5,7)$$

★ Product of *Maxterms*

$$\bar{F} = \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + AB\bar{C}$$

$$\bar{\bar{F}} = \overline{\bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + AB\bar{C}}$$

$$F = \overline{\bar{A}\bar{B}\bar{C}} \bullet \overline{\bar{A}B\bar{C}} \bullet \overline{\bar{A}BC} \bullet \overline{AB\bar{C}}$$

$$F = (A+B+C)(A+\bar{B}+C)(A+\bar{B}+\bar{C})(\bar{A}+\bar{B}+C)$$

$$F = M_0 \quad M_2 \quad M_3 \quad M_6$$

$$F = \prod(0,2,3,6)$$

Standard Forms

★ Sum of Products (SOP)

$$F = \bar{A}\bar{B}C + A\bar{B}\bar{C} + A\bar{B}C + ABC$$

$$A\bar{B}(\bar{C}+C)$$
$$= A\bar{B}(1)$$
$$= A\bar{B}$$
$$AC(\bar{B}+B)$$
$$= AC$$
$$\bar{B}C(\bar{A}+A)$$
$$= \bar{B}C$$

$$F = \bar{B}C\cancel{(\bar{A}+A)} + A\bar{B}\cancel{(\bar{C}+C)} + AC\cancel{(\bar{B}+B)}$$

$$F = \bar{B}C + A\bar{B} + AC$$

Standard Forms

★ Product of Sums (POS)

$$\bar{F} = \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + AB\bar{C}$$

$$\bar{A}B(\bar{C}+C)$$
$$B\bar{C}(\bar{A}+A)$$
$$\bar{A}\bar{C}(\bar{B}+B)$$

$$\bar{F} = \bar{A}\bar{C}\cancel{(\bar{B}+B)} + \bar{A}B\cancel{(\bar{C}+C)} + B\bar{C}\cancel{(\bar{A}+A)}$$

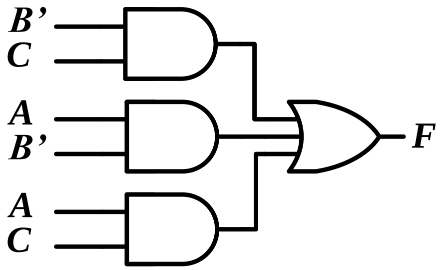
$$\bar{\bar{F}} = \overline{\bar{A}\bar{C} + \bar{A}B + B\bar{C}}$$

$$F = (A+C)(A+\bar{B})(\bar{B}+C)$$

Two-Level Implementations

★ **Sum of Products (SOP)**

$$F = \overline{B}C + A\overline{B} + AC$$



★ **Product of Sums (POS)**

$$F = (A+C)(A+\overline{B})(\overline{B}+C)$$

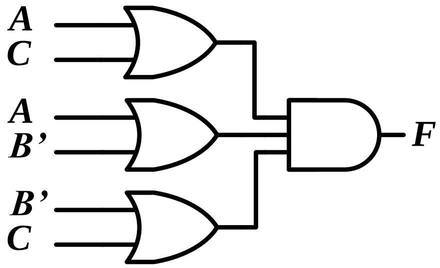


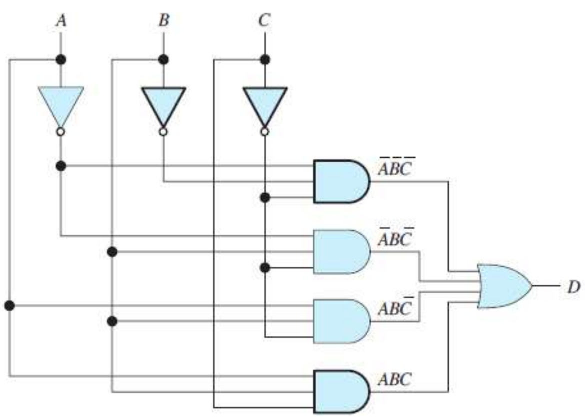
Table Truth Table Used to Illustrate SOP and POS Logical Expressions

Row	A	B	C	D
0	0	0	0	1
1	0	0	1	0
2	0	1	0	1
3	0	1	1	0
4	1	0	0	0
5	1	0	1	0
6	1	1	0	1
7	1	1	1	1

Sum-of-Products Implementation

$$D = \overline{A}\,\overline{B}\,\overline{C} + \overline{A}B\overline{C} + AB\overline{C} + ABC$$

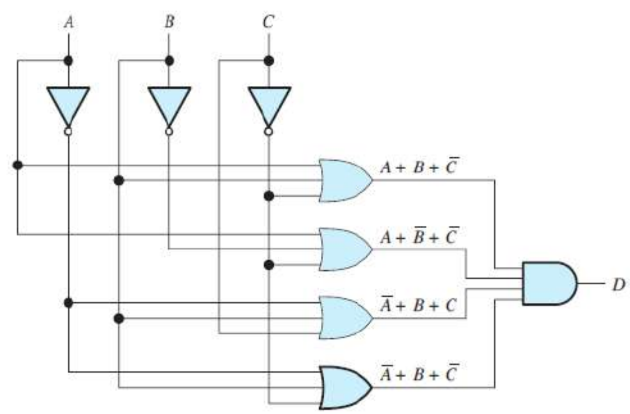
$$D = \sum m(0, 2, 6, 7)$$



Product-of-Sums Implementation

$$D = (A+B+\overline{C})(A+\overline{B}+\overline{C})(\overline{A}+B+C)(\overline{A}+B+\overline{C})$$

$$D = \prod M(1, 3, 4, 5)$$



The control logic for a residential heating system is to operate as follows: During the daytime, heating is required only if the temperature falls below 68°F. At night, heating is required only for temperatures below 62°F. Assume that logic signals D, L, and H are available. D is high during the daytime and low at night. H is high only if the temperature is above 68°F. L is high only if the temperature is above 62°F. Design a logic circuit that produces an output signal F that is high only when heating is required.

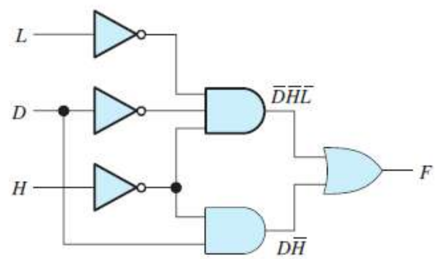
$$F = \overline{D}\,\overline{H}\,\overline{L} + D\overline{H}\,\overline{L} + D\overline{H}L \qquad F = \sum m(0, 4, 5)$$

D	H	L	F
0	0	0	1
0	0	1	0
0	1	0	×
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	×
1	1	1	0

These input combinations do not occur

Don't cares

(a) Truth table



(b) Diagram of a possible implementation

Semiconductor devices and Circuits

SCHOOL OF ELECTRICAL ENGINEERING

EEE 1001

Basic Electrical & Electronics Engineering

By,

Meera P. S.

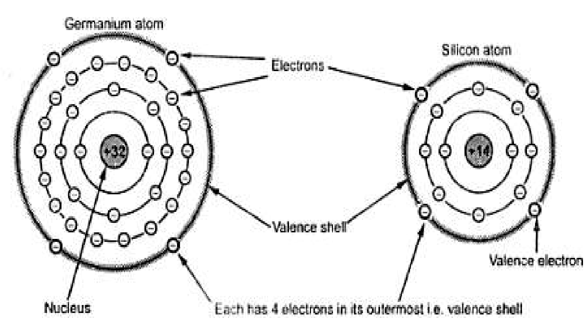
Assistant Professor, SELECT

Materials

- Semiconductor has conductivity between insulators and conductors .
  - Germanium , silicon etc.,
- Conductors - Good conductors of electricity
  - Gold, copper etc.,
- Insulators – Bad conductors of electricity
  - Wood , rubber , mica etc.,

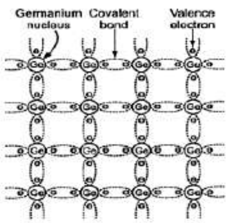
Structure of semiconductor materials

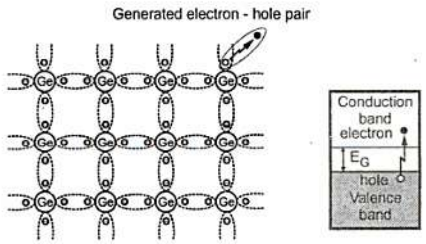
- Ge and Si have four electrons in the valence shell i.e., outermost shell.



Intrinsic semiconductor

- Purest form of semiconductor - Intrinsic semiconductor

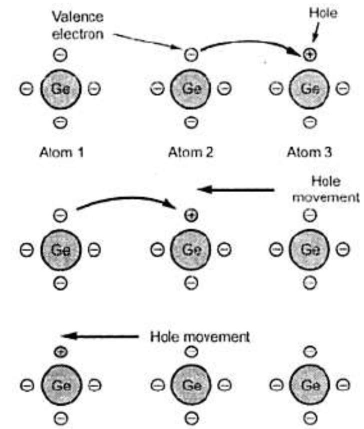




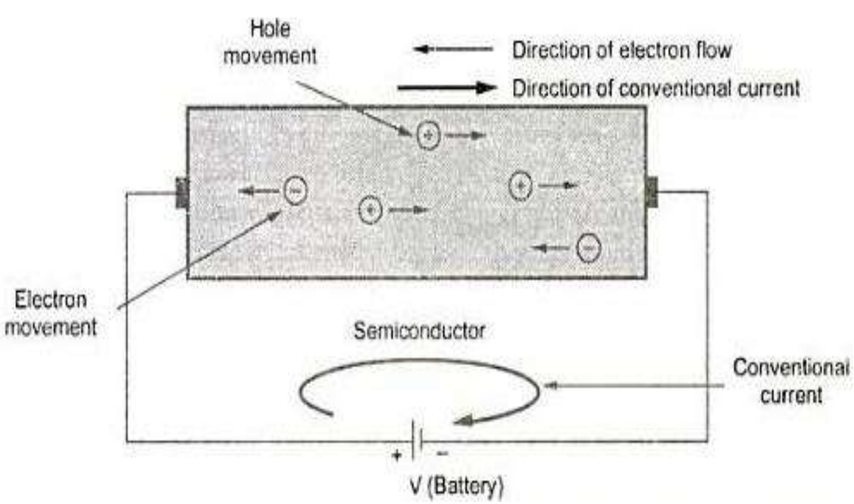
- At room temperature, valence electrons absorb the thermal energy and break the covalent bond and drift to the conduction band .
- Electron is negatively charged particle and the hole getting created due to the electron drift is said to be positively charged.

Conduction by electrons and holes

- When battery is connected to an intrinsic material, free electrons move towards positive of the battery and responsible for flow of current called electron current.
- Movement of holes cause the current called hole current.
- Conventional current:
  Current flowing from positive of the battery to the negative of the battery.



Conventional current



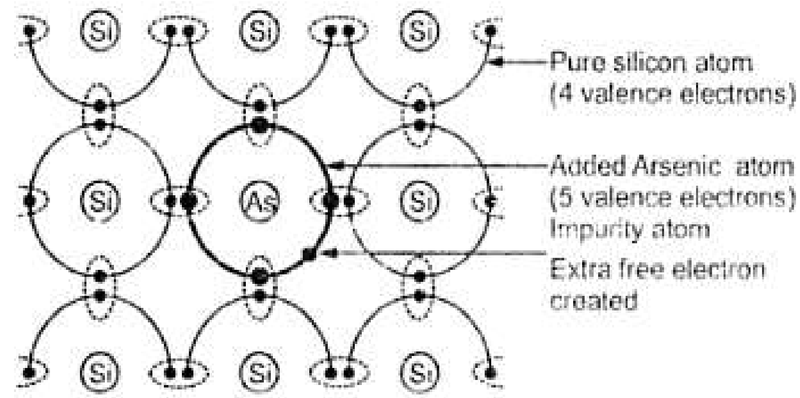
Extrinsic semiconductor

- Doping :
  - Process of adding impurity to intrinsic semiconductor to improve its conductivity is called doping.
- Dopant:
  - Impurity added is called dopant
- **Extrinsic semiconductor**
  - Doped semiconductor material is called extrinsic semiconductor
- Types of extrinsic semiconductor
  - N type material
  - P type material

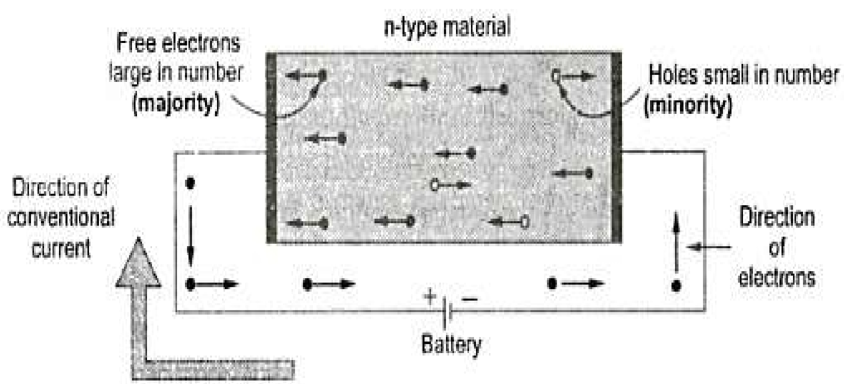
N-type and P-type material

- Pentavalent impurities added to the intrinsic semiconductor –Each impurity atom donates one free electron- Donor doping -results in N type material.
- Pentavalent – Arsenic , Bismuth, Phosphorus etc.,
- Trivalent impurities added to intrinsic semiconductor – creates holes and readily accepts an electron – Acceptor doping – results in P type material.
- Trivalent – Indium, Gallium, Boron etc.,

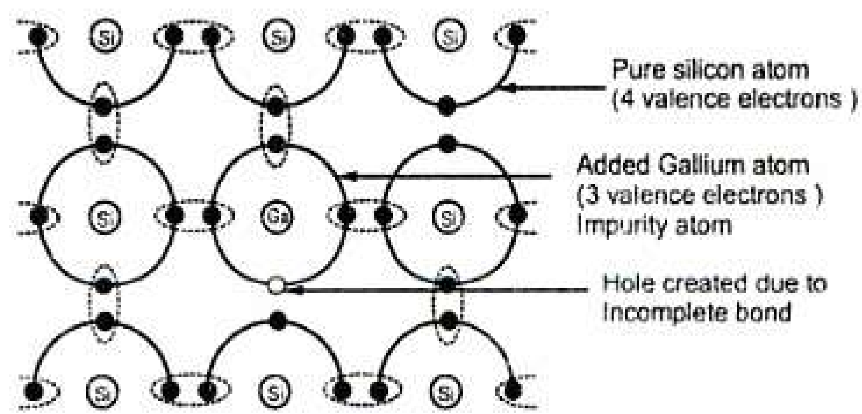
N type semiconductor



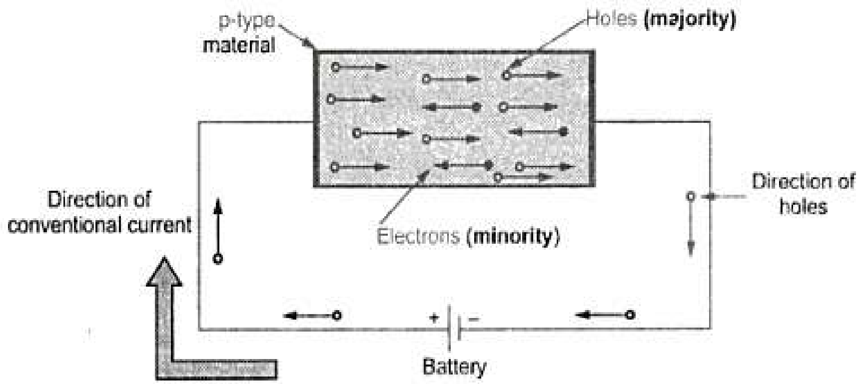
Conduction in N type material



P type semiconductor

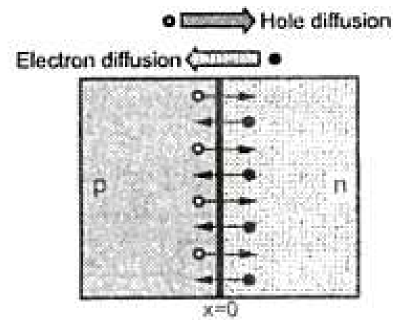


Conduction in P type material

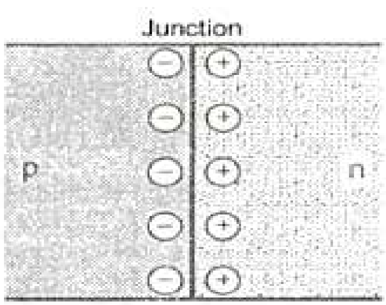


P N Junction

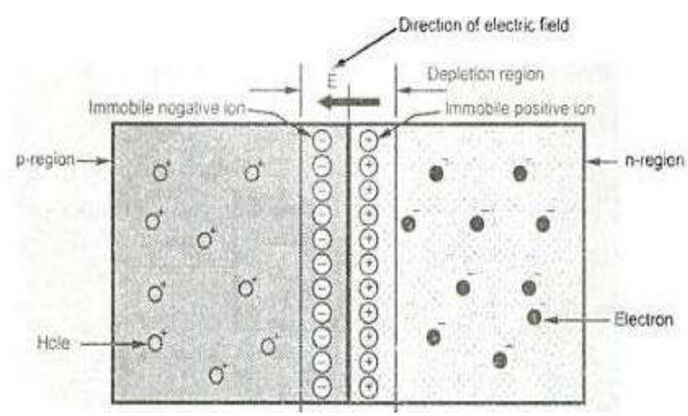
- P type and N type are combined with a fabrication technique to form a PN junction and forms a semiconductor device called Diode.
- Unbiased PN Junction:



Formation of Depletion region

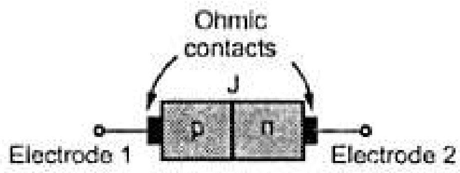


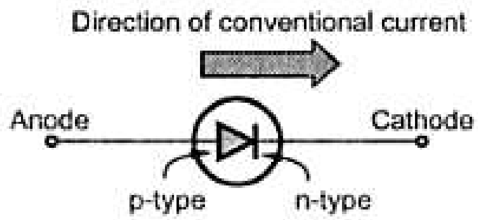
Barrier Potential



Semiconductor material	Symbol	Barrier potential
Silicon	Si	0.6 V
Germanium	Ge	0.2 V

P-N junction Diode

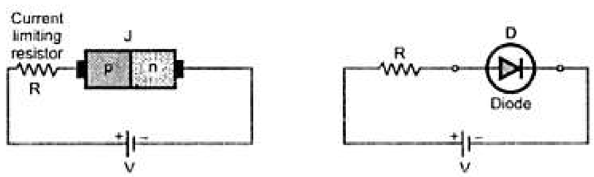


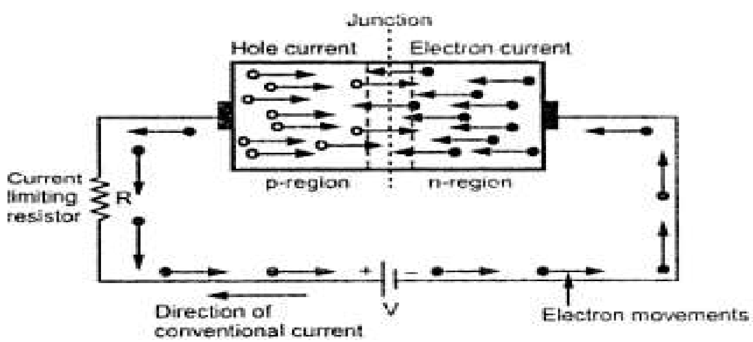


Biasing of PN Junction diode

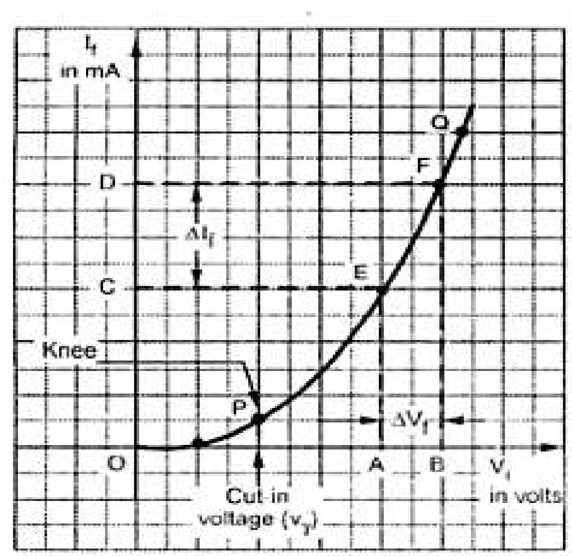
- Biasing –connecting external DC voltage
  - Forward biasing - P type to positive and n type to negative of the battery
  - Reverse biasing - P type to negative and n type to positive of the battery
- PN junction diode allows current in only one direction under biased condition.

Forward biasing of PN junction diode

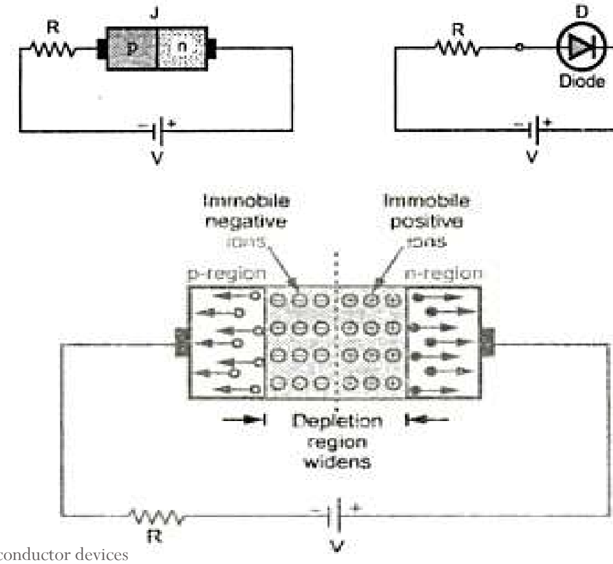




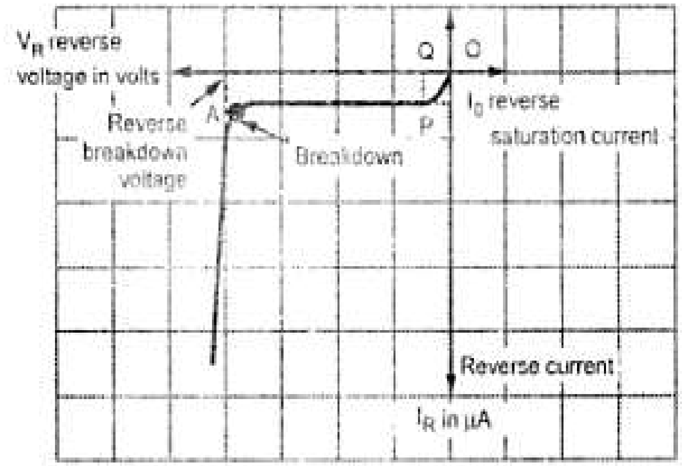
Forward V-I characteristics



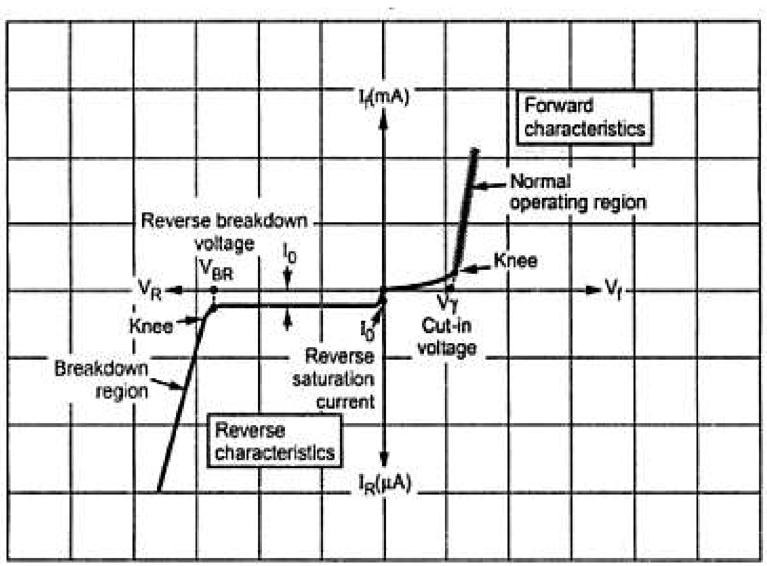
Reverse biasing of PN junction diode



Reverse V-I characteristics

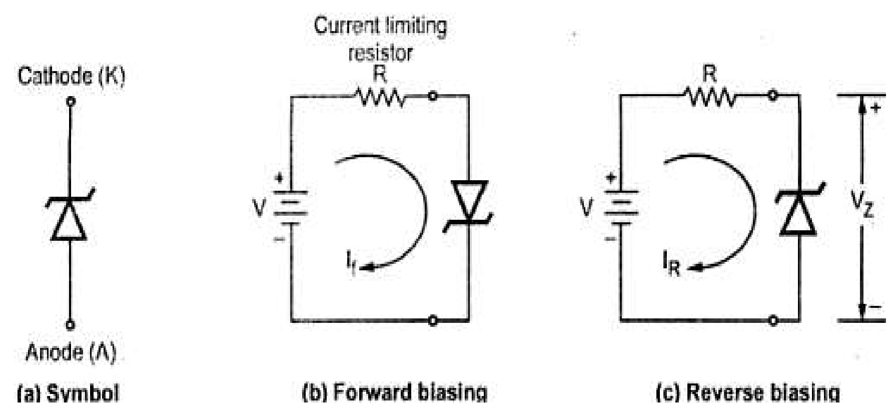


V-I Characteristics of Diode

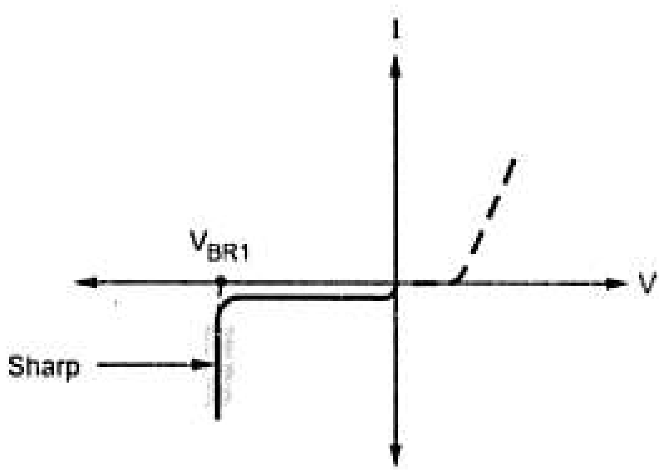


Zener diode

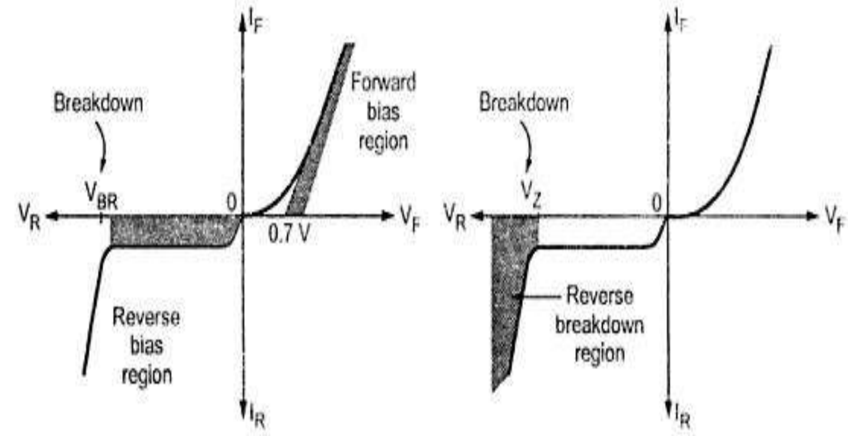
- PN junction diode operated in its reverse breakdown region.



V- I Characteristics of Zener diode



Operating regions



(a) Operating regions shown shaded for normal diode

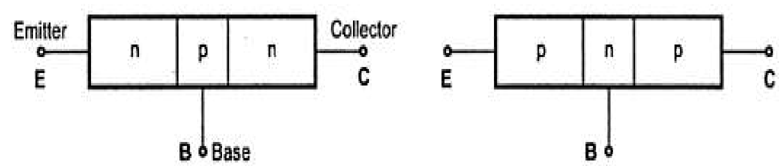
(b) Operating regions shown shaded for zener diode

Bipolar Junction Transistor

- Transistor – A semiconductor device that can amplify electronic signals such as radio and television signals .
- Transistor – 3 terminals
  - Base
  - Emitter
  - Collector
- Base is very thin compared to other sections.
- Doping:
  - Emitter – heavily doped
  - Base –lightly doped
  - Collector – Moderately doped
- Operating configurations
  - Common Base
  - Common Emitter
  - Common Collector

BJT

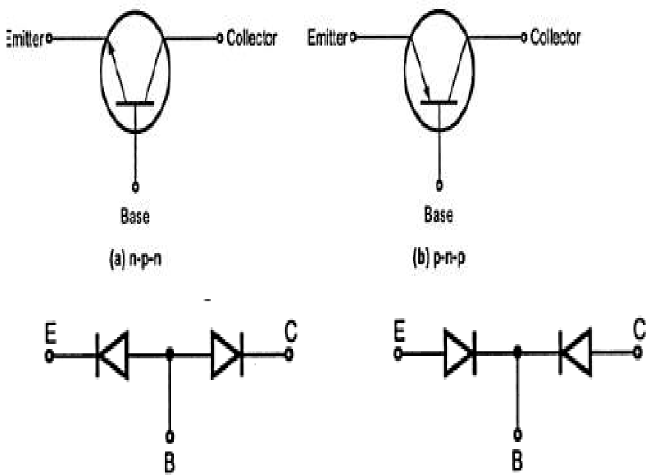
- Bipolar Junction Transistor
  - Current conduction is due to both types of charge carriers , holes and electrons
  - Types of BJT
    - n-p-n type
    - p-n-p type



(a) n-p-n

(b) p-n-p

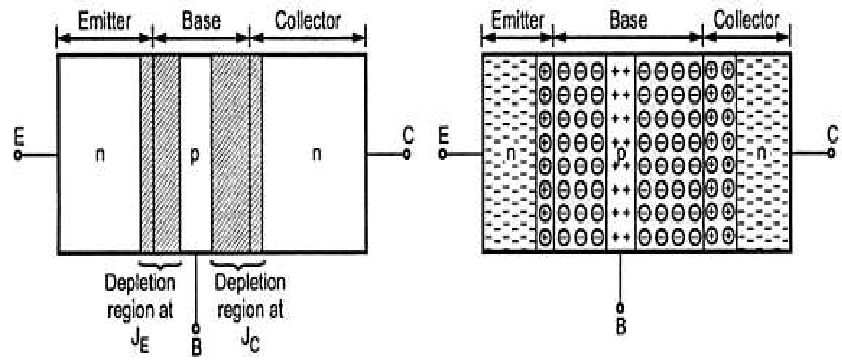
Circuit symbol and 2 diode analogy



(a) n-p-n transistor (b) p-n-p transistor

Unbiased npn Transistor

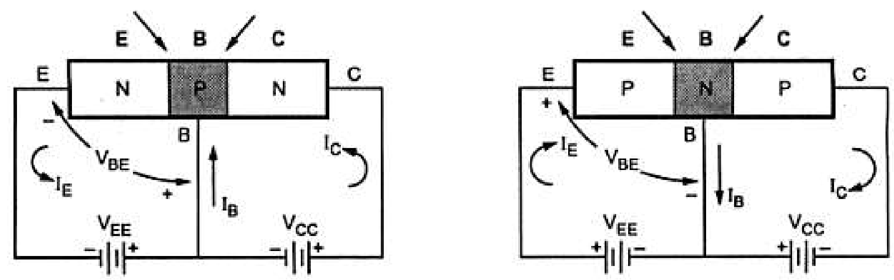
- Depletion layers at both emitter base junction and collector base junction



Biased transistor

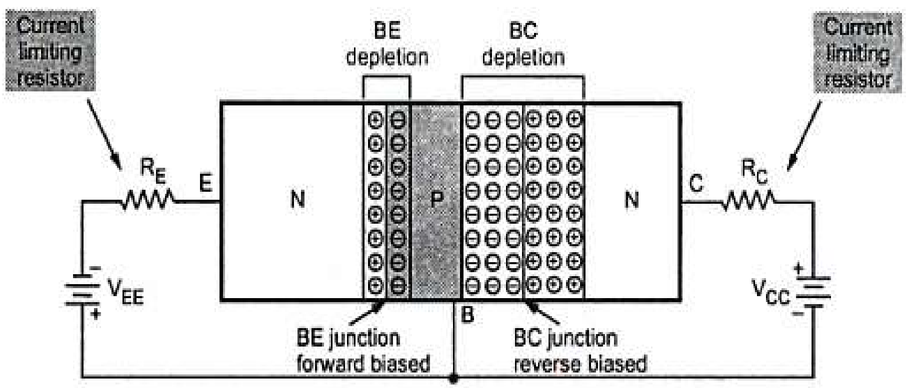
- To operate transistor as an amplifier, correct biasing of junctions is necessary.
- Regions of operation :
  - Active, cut-off region, saturation region

Region	Emitter base junction	Collector base junction
Active	Forward biased	Reverse biased
Cut-off	Reverse biased	Reverse biased
Saturation	Forward biased	Forward biased

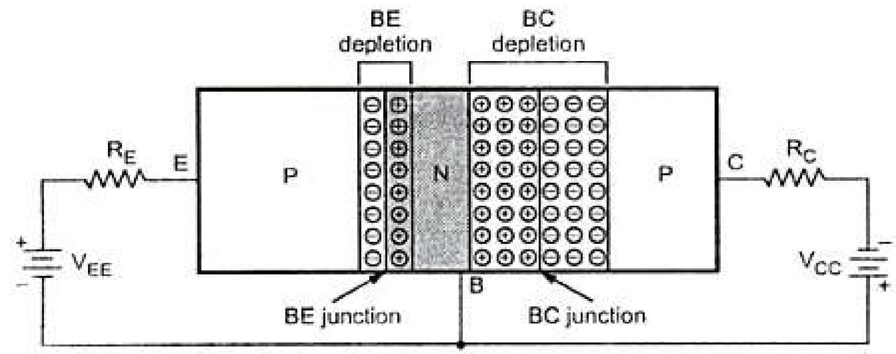


(a) npn (b) pnp

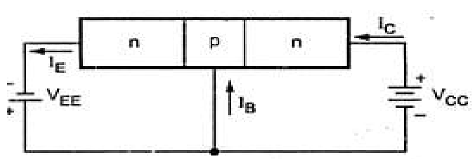
Operation of npn transistor



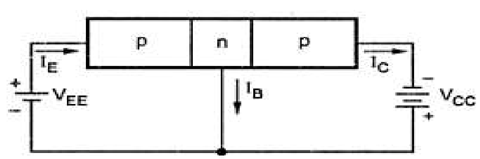
Operation of pnp transistor



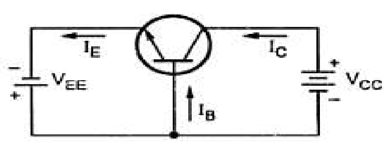
Current directions



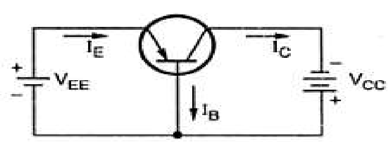
(a)



(b)



(c)

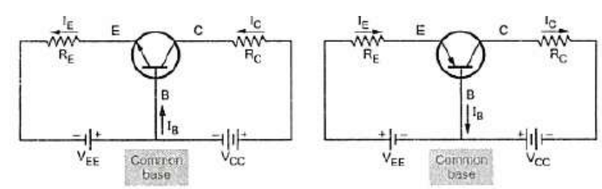


(d)

$$I_E = I_C + I_B \qquad \alpha_{d.c.} = \alpha \approx \frac{I_C}{I_E} \qquad \beta_{d.c.} = \beta = \frac{I_C}{I_B}$$

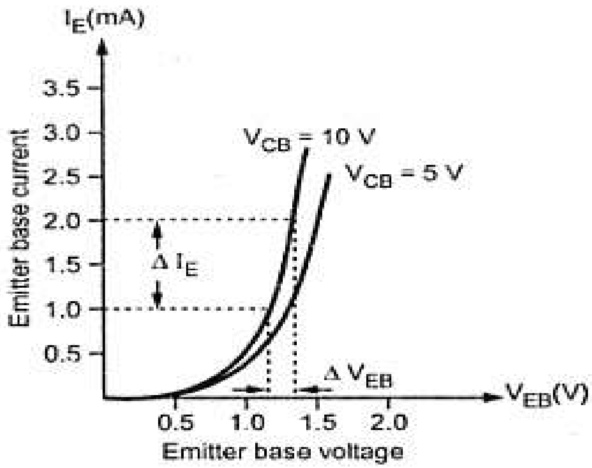
$$\beta_{d.c.} = \frac{\alpha_{d.c.}}{1-\alpha_{d.c.}}$$

Common base Configuration

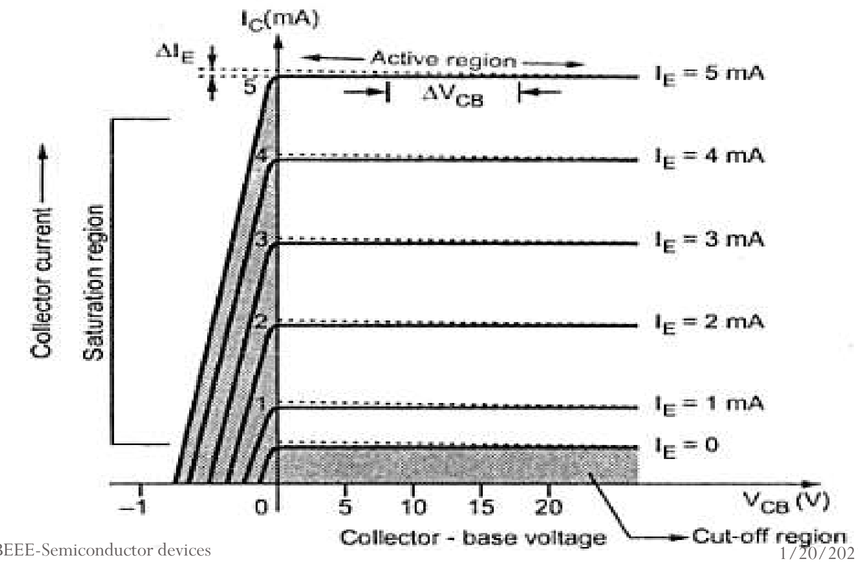


- Characteristics
  - Input characteristics
  - Output characteristics

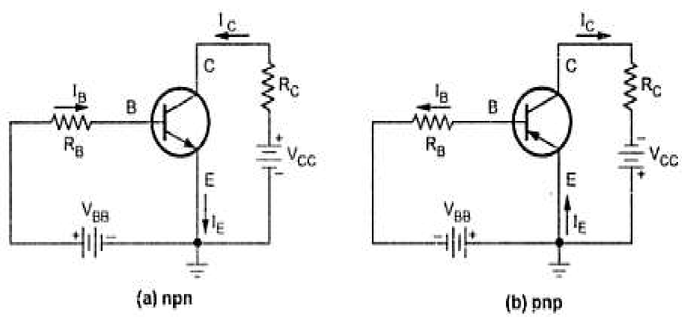
Input characteristics of CB confg.



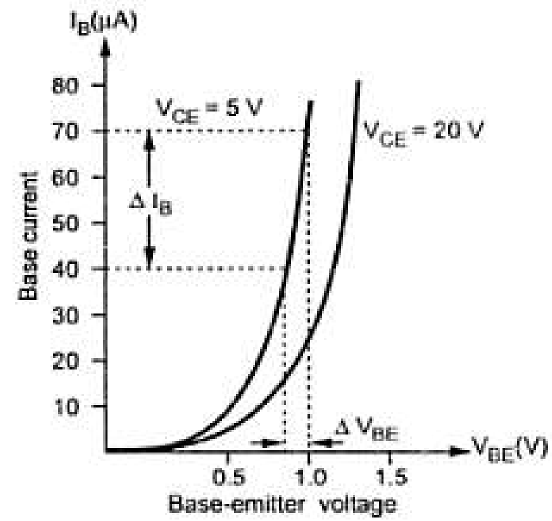
Output characteristics of CB confg.



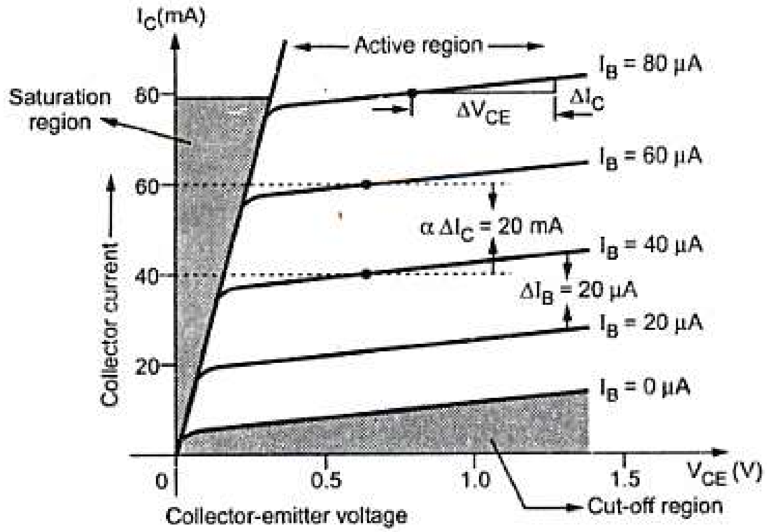
Common Emitter configuration



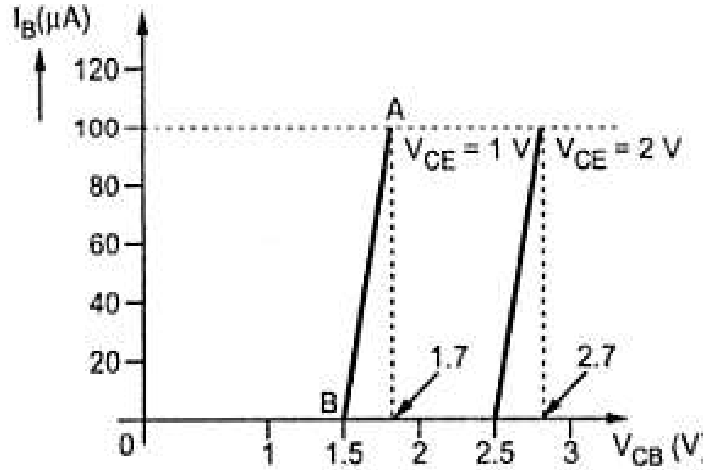
Input characteristics of CE confg.



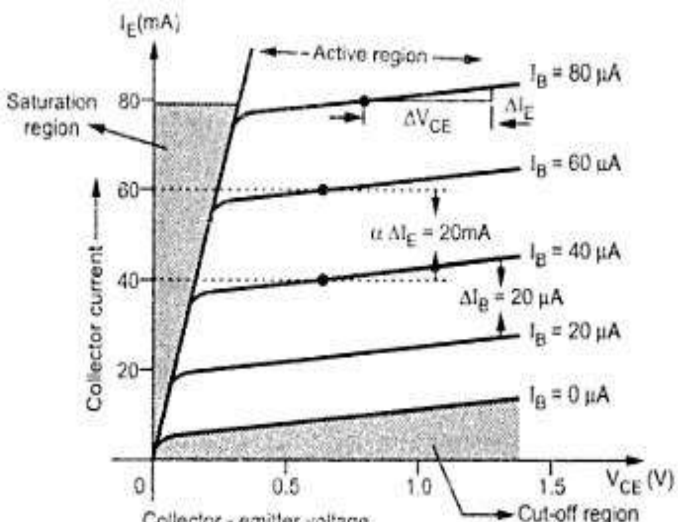
Output characteristics of CE confg.



Common Collector Configuration
Input characteristics of CC confg.



Output characteristics of CC confg.

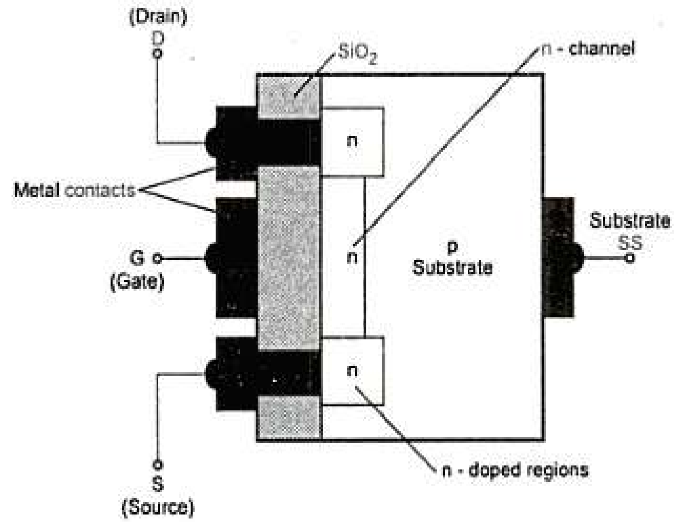


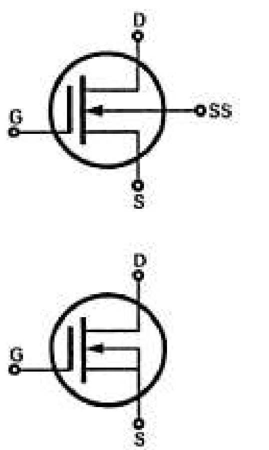
- CE configuration is widely used in Amplifier circuits because it provides both current gain and voltage gain greater than unity and hence greater power gain which is a product of voltage gain and current gain.
- CE configuration is ideal for coupling between stages as the ratio of output resistance to the input resistance is small. (Range 10 ohms to 100 ohms).

MOSFET

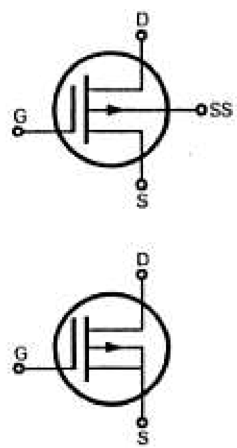
- MOSFET – Metal Oxide Semiconductor Field Effect Transistor
- Gate of the MOSFET is insulated from the channel by a silicon dioxide layer
- Types
  - Depletion type MOSFET
    - N channel
    - P Channel
  - Enhancement type MOSFET
    - N Channel
    - P Channel

N channel Depletion type MOSFET

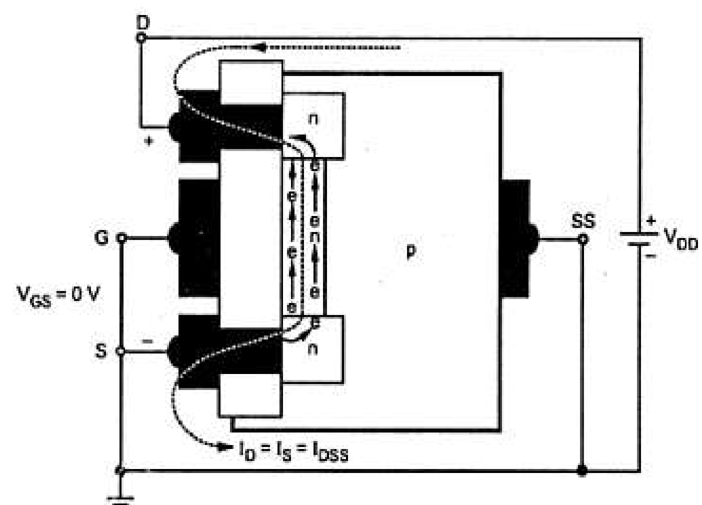




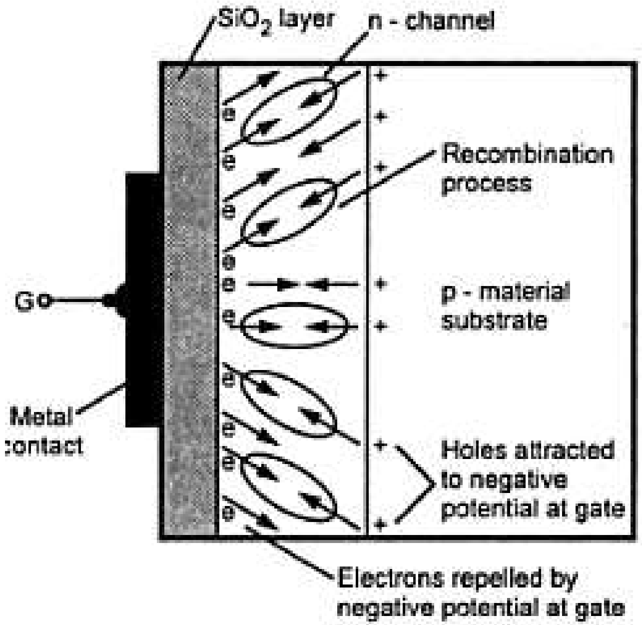
(a) Symbols for n-channel depletion type MOSFETs



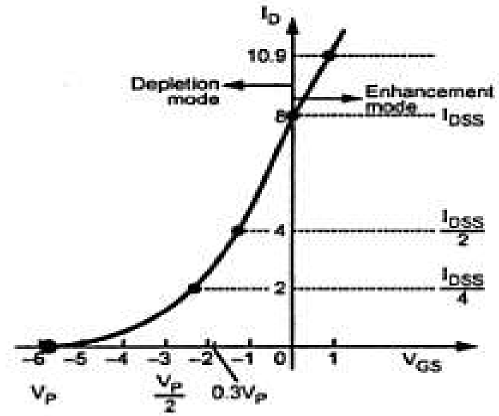
(b) Symbols for p-channel depletion type MOSFETs



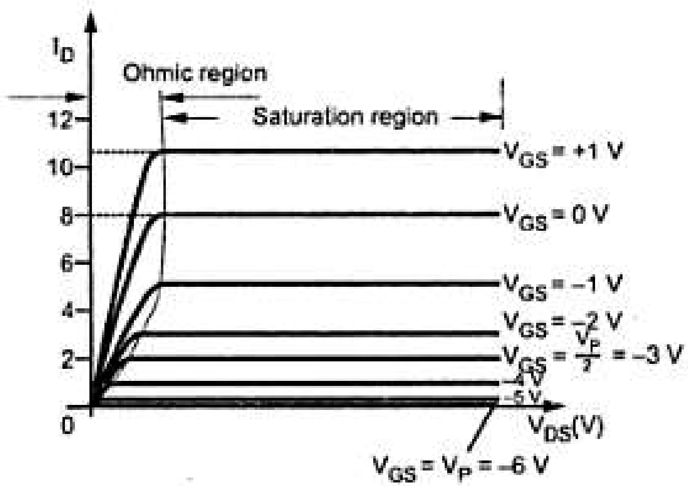
N-channel depletion-type MOSFET with V_{GS}= 0V and an applied voltage V_{DD}



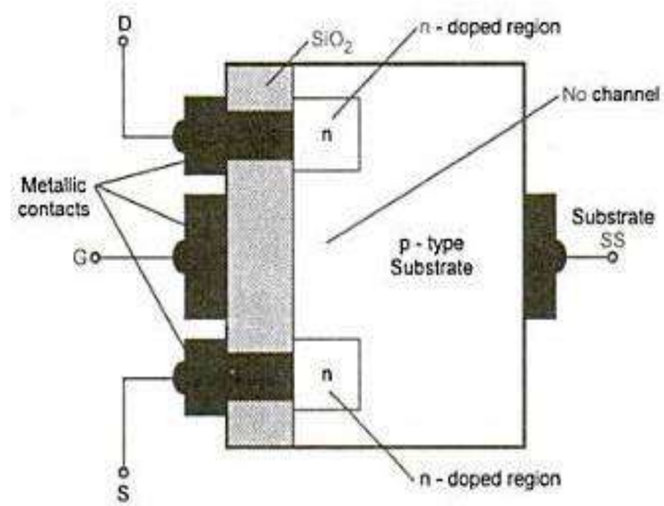
Transfer Characteristics



Drain characteristics

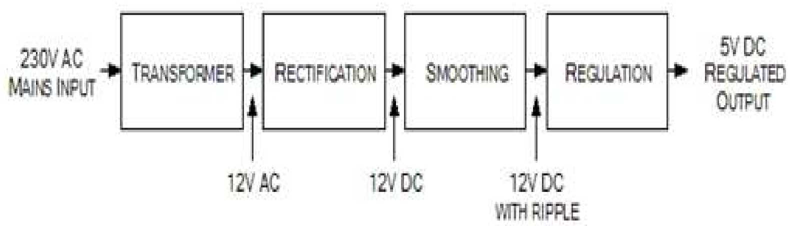


Enhancement MOSFET



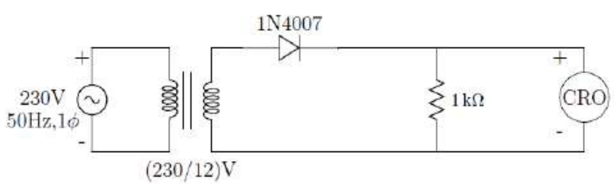
Applications of Diodes

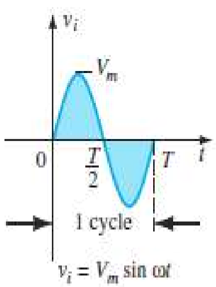
- Electronic circuits needs a dc voltage for their operation – DC is derived from the available single phase AC mains supply.
- RPS – Regulated power supply

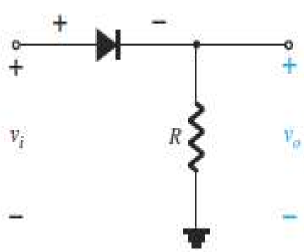


- Rectification:
  - Process of converting the alternating voltage (Bidirectional) in to the corresponding dc quantity (unidirectional) – Electronic device used for conversion -Rectifier
- Rectifiers :
  - HWR
  - FWR – center tapped transformer
    - Bridge rectifier

Half wave rectifier (HWR)

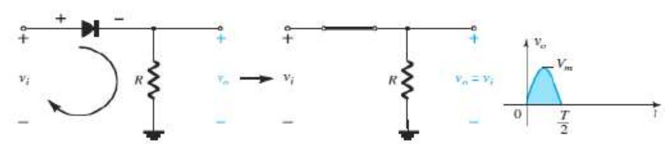




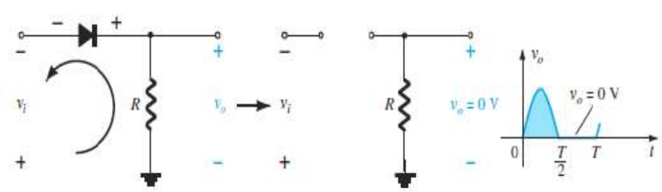


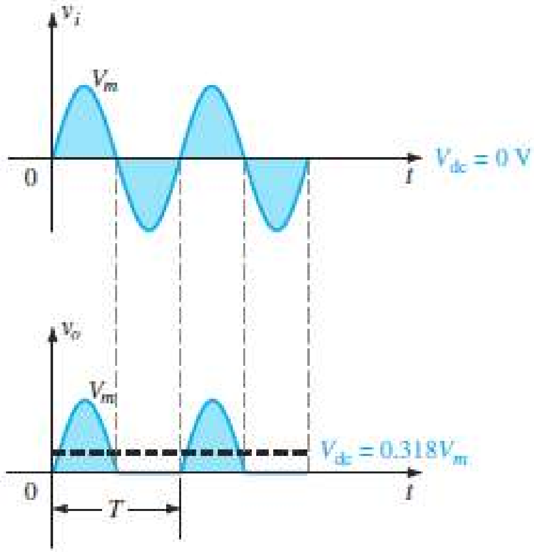
Operation of HWR:

- Positive half cycle:

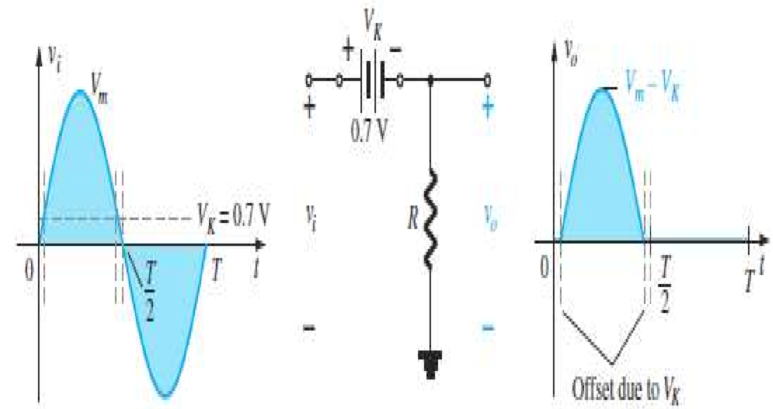


- Negative half cycle:





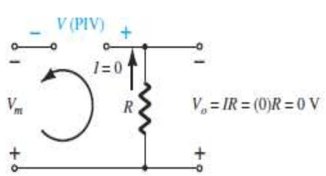
$\boxed{V_{dc} = 0.318\ V_m}$ half-wave



$\boxed{V_{dc} \cong 0.318(V_m - V_K)}$

Peak Inverse Voltage (PIV)

- It is the voltage rating that must not be exceeded in the reverse-bias region or the diode will enter the Zener avalanche region.

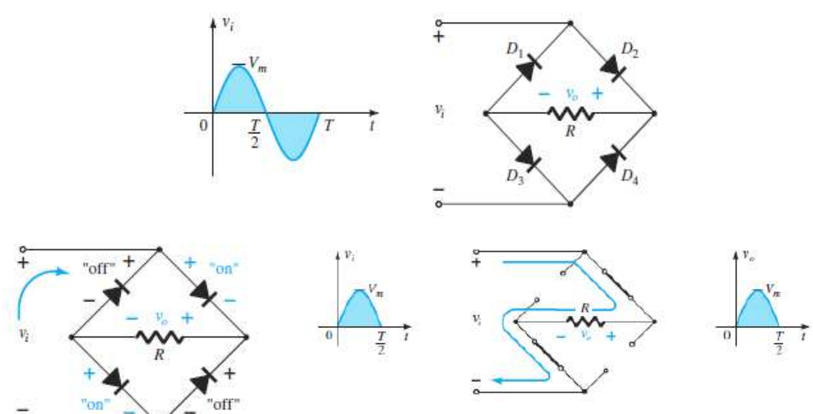


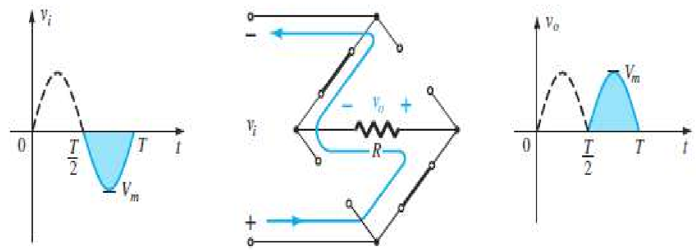
- Applying Kirchhoff's voltage law, it is obvious that the PIV rating of the diode must equal or exceed the peak value of the applied voltage.

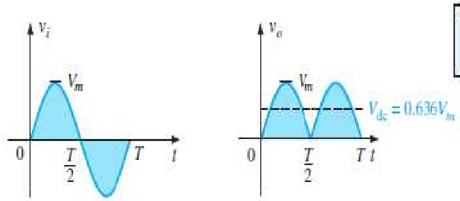
$\boxed{\text{PIV rating} \geq V_m}$ half-wave rectifier

Full Wave Rectifier – Bridge rectifier

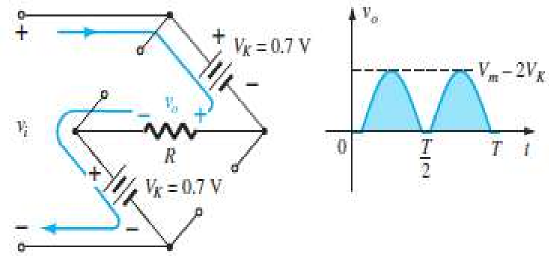
- The dc level obtained from a sinusoidal input can be improved 100% using a process called *full-wave rectification*







$$\boxed{V_{dc} = 0.636\, V_m}$$ full-wave



$$v_i - V_K - v_o - V_K = 0$$

$$v_o = v_i - 2V_K$$

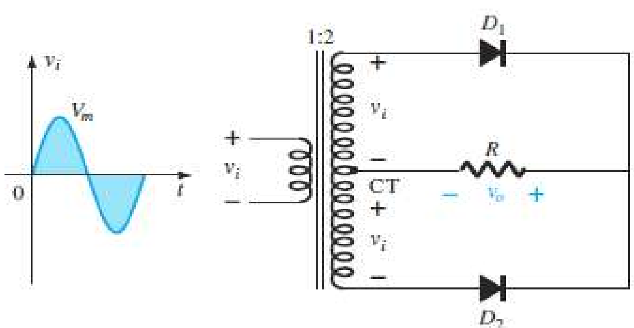
- For situations where $V_m >> 2V_K$, the following equation can be applied for the average value with a relatively high level of accuracy.

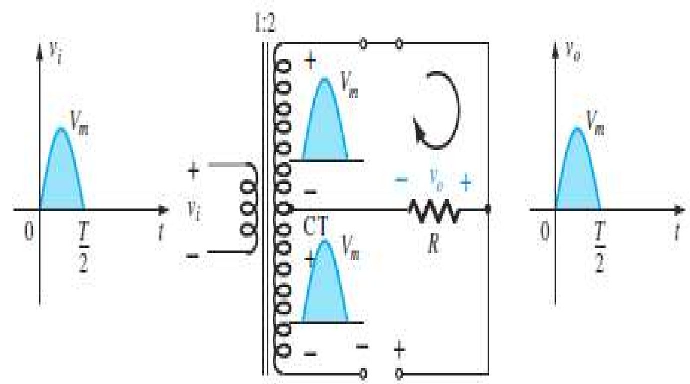
$$\boxed{V_{dc} \cong 0.636(V_m - 2V_K)}$$

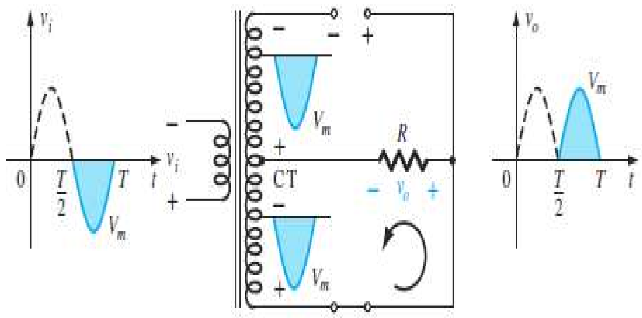
$$\boxed{\mathrm{PIV} \geq V_m}$$ full-wave bridge rectifier

FWR – with center tapped transformer

- FWR- with only two diodes but requiring a center-tapped transformer to establish the input signal across each section of the secondary of the transformer

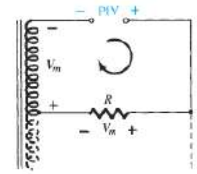






- PIV = *V*secondary + *VR*
- = *Vm* + *Vm*

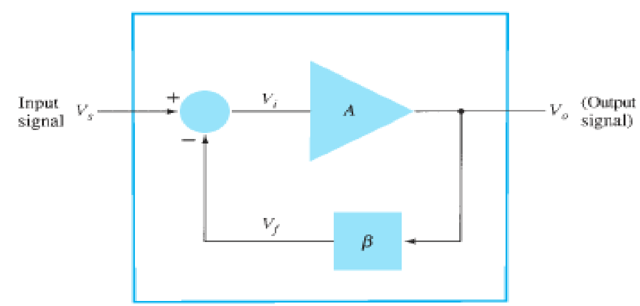
$\boxed{\text{PIV} \geqq 2V_m}$ CT transformer, full-wave rectifier



Feedback concept

- Depending on the relative polarity of the signal being fed back into a circuit, one may have negative or positive feedback.
- Negative feedback results in decreased voltage gain, for which a number of circuit features are improved.
- Positive feedback drives a circuit into oscillation as in various types of oscillator circuits.

- The input signal *Vs* is applied to a mixer network, where it is combined with a feedback signal *V f* .
- The difference of these signals *Vi* is then the input voltage to the amplifier.
- A portion of the amplifier output *Vo* is connected to the feedback network (β), which provides a reduced portion of the output as feedback signal to the input mixer network.



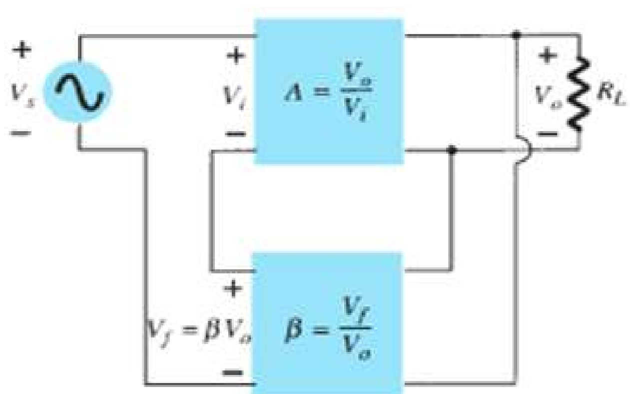
Feedback amplifier

Negative feedback

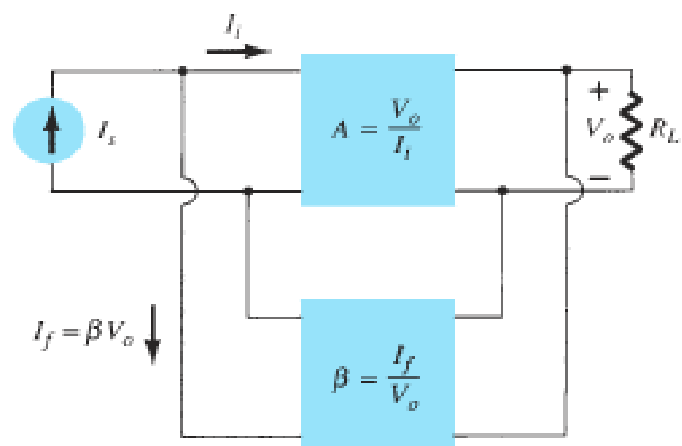
- If the feedback signal is of opposite polarity to the input signal, negative feedback results.
- Although negative feedback results in reduced overall voltage gain, a number of improvements are obtained.
  1. Higher input impedance.
  2. Better stabilized voltage gain.
  3. Improved frequency response.
  4. Lower output impedance.
  5. Reduced noise.
  6. More linear operation.

- There are four basic ways of connecting the feedback signal. Both *voltage* and *current* can be fed back to the input either in *series* or *parallel*.
  1. Voltage-series feedback
  2. Voltage-shunt feedback
  3. Current-series feedback
  4. Current-shunt feedback

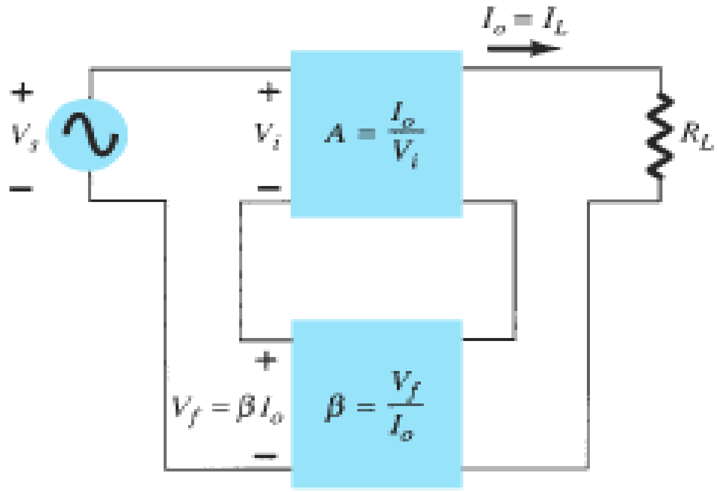
Voltage-series feedback



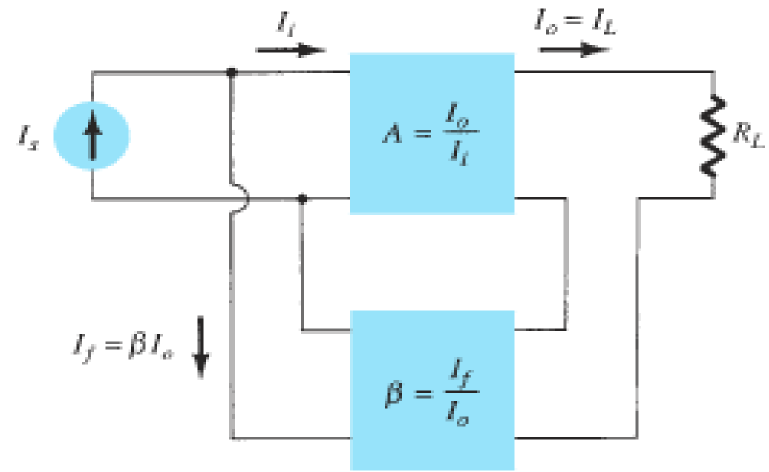
Voltage-shunt feedback



Current-series feedback



Current-shunt feedback



Feedback

- Series feedback connections tend to *increase* the input resistance, whereas shunt feedback connections tend to *decrease* the input resistance.
- Voltage feedback tends to *decrease* the output impedance, whereas current feedback tends to *increase* the output impedance.
- Typically, higher input and lower output impedances are desired for most cascade amplifiers.
- Both of these are provided using the voltage-series feedback connection.

Summary of Gain, Feedback, and Gain with Feedback

		Voltage-Series	Voltage-Shunt	Current-Series	Current-Shunt
Gain without feedback	A	$\frac{V_o}{V_i}$	$\frac{V_o}{I_i}$	$\frac{I_o}{V_i}$	$\frac{I_o}{I_i}$
Feedback	β	$\frac{V_f}{V_o}$	$\frac{I_f}{V_o}$	$\frac{V_f}{I_o}$	$\frac{I_f}{I_o}$
Gain with feedback	A_f	$\frac{V_o}{V_s}$	$\frac{V_o}{I_s}$	$\frac{I_o}{V_s}$	$\frac{I_o}{I_s}$