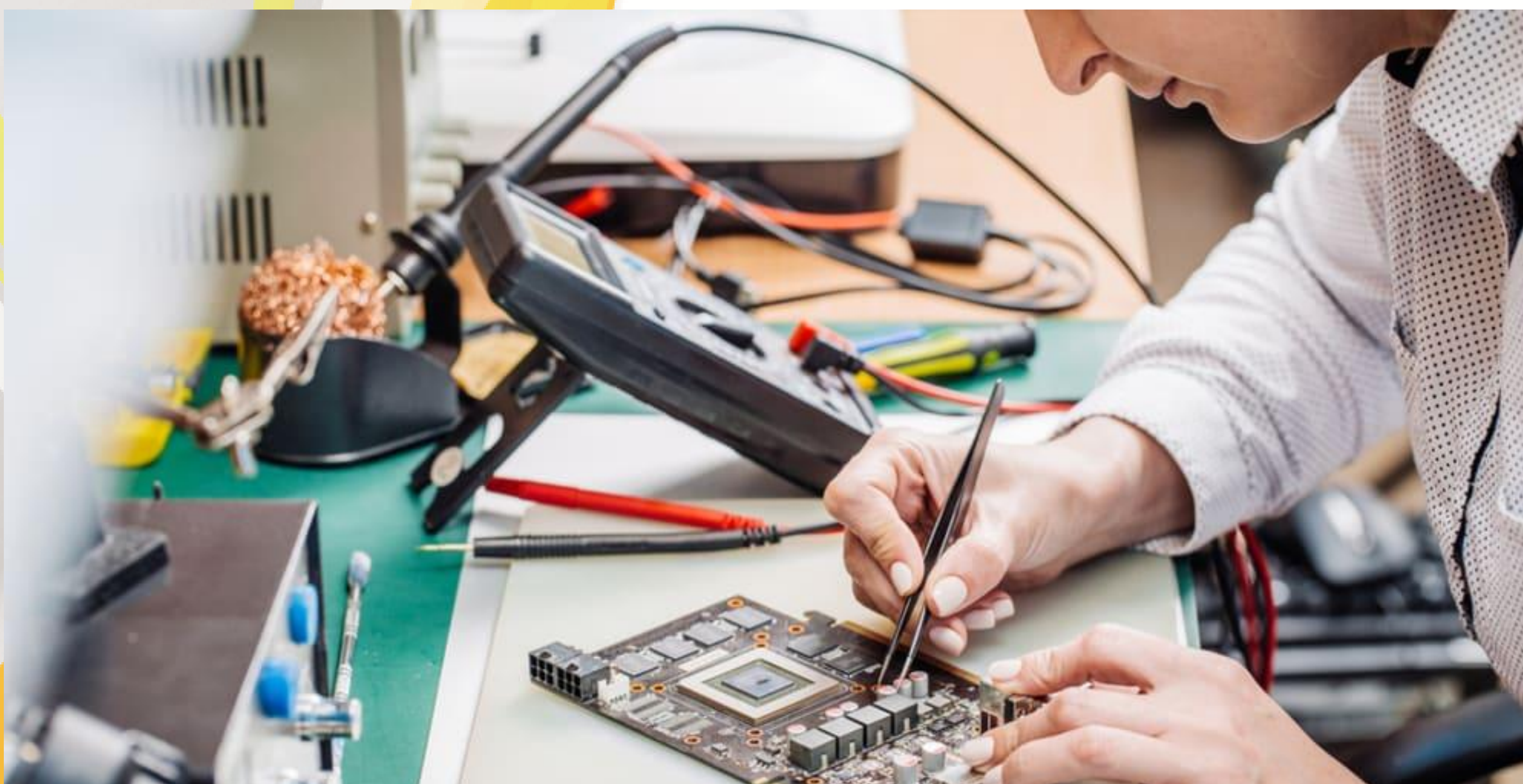
Electrical Engineering



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ELECTRICAL ENGINEERING

Course Developer

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Lesson 1

INTRODUCTION TO CIRCUITS

1.1 Introduction

Electrical engineering is a field of engineering that generally deals with the study and application of electricity, electronics and electromagnetism. Electrical energy is an important utility in a dairy processing plant for operating the equipments, instruments, control systems etc. Electrical engineering as a subject will give an understanding of A.C. fundamentals, A.C. circuits, transformers, alternators, motors, electrical measuring instruments and electrical power economics.

1.2 Important Terms

1.2.1 Electricity

Electricity is a form of energy which involves flow of electrons in a closed circuit to do work.

1.2.2 Electric current (I)

Flow of electron in an electric circuit is called electric current (I) and its unit is ampere (A).

1.2.3 Potential difference

When two bodies are changed to different electric potential, these exists a potential difference between the two bodies. Unit: Volt (v)

1.2.4 Resistance

The opposition offered to flow of electrons or current by a conductor / material is known as resistance. Unit: Ohm (Ω)

1.3 Law of Resistance

The resistance of a wire depends on the following function:

(a) Resistance (R) is directly proportional to the length of wire (L).

$$R \propto L$$

(b) Resistance (R) is inversely proportional to the cross sectional area of wire (a).

$$R \propto 1/a$$

(c) Resistance (R) depends on the temperature of the conducting wire.

(d) Resistance (R) depends on the atomic structure of the material.

1.3.1. Ohm's law

Ohm's law states that the current (I) flowing between two points in a circuit is directly proportional to the potential difference (V). This condition is applicable when temperature is constant.

$$I \propto V$$

$$\frac{V}{I} = constant$$

$$V = IR$$

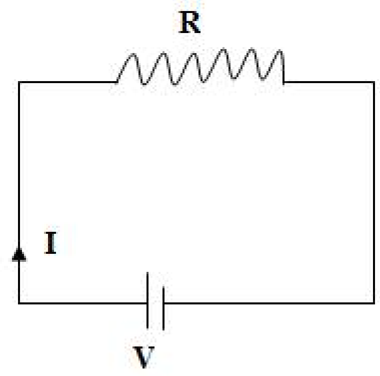


Fig. 1.1 Electric circuit

Numerical:

1. Calculate the current flowing in a circuit if voltage applied by the battery is 12 V and R = 5Ω.

Solution

V = IR
I=V/R
= 12/5
= 2.4 A

2. Calculate the current flowing in a A.C circuit at 220 V. Take value of R = 100 Ω.

Solution

V = IR
I = V/R
= 220/100
= 2.2 A

1.3.2 Effect of temperature on resistance

The value of resistance (R_T) at any temperature T°C is given as:

$R_T = R_o(1+a_rT)$

R_T = Resistance at temperature T , Ohm

R_0 = Resistance at 0°C,Ohm

a_r = Temperature co-efficient of resistance at 0°C.

1.4 Electrical Circuit

The electrical circuit can be kindly classified as:

a) D.C. Circuit
b) A.C. Circuit. (will be covered in Module 2)

1.5 D.C. circuits

A circuit based on direct current (D.C.) is known as D.C. circuit. Circuits can further be classified as:

- Series circuit

- Parallel circuit
- Series parallel circuit.

1.5.1 Series circuit

A circuit in which load (resistors) are connected in series so that same current flows through them is called series circuit.

Here three resistance R_1 ,R_2 & R_3 are connected in series across a voltage of V volts.

Let V_1 , V_2 & V_3 be the voltage across resistor R_1 ,R_2 & R_3 resistivity.

$V = V_1 + V_2 + V_3$

$IR = IR_1 + IR_2 + IR_3$

Where

$R = R_1 + R_2 + R_3$

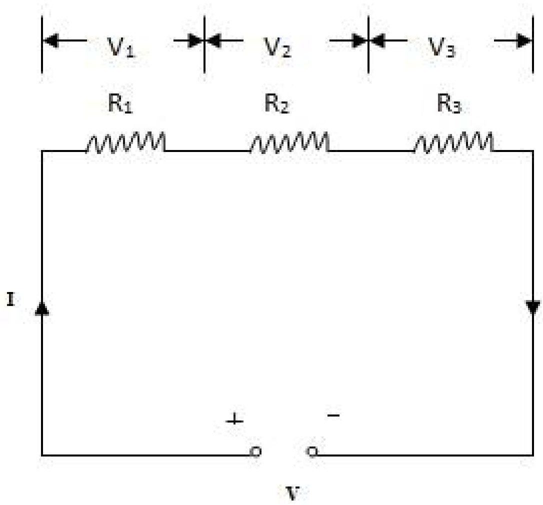


Fig. 1.2 Series circuit

1.5.2 Parallel circuit

A circuit in which load (register) are connected in parallel so that different current through them is called parallel circuit.

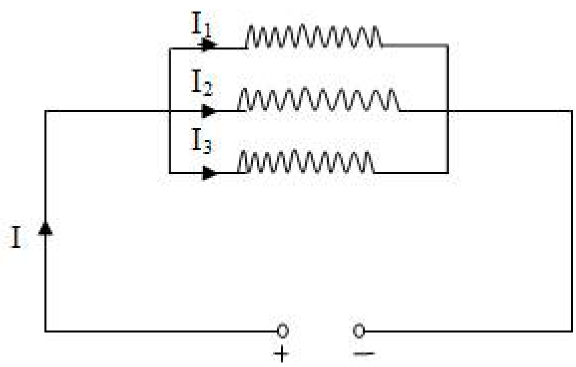


Fig. 1.3 Parallel Circuit

Here three resistances I_1, $I_2$and I_3 are connected in parallel across supply voltage of V volt. Note that the voltage V across each resister in same. The current flowing through R_1, R_2 and R_3 are I_1, I_2 and I_3 respectively.

$$I = I_1 + I_2 + I_3$$

Or

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

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

$$R = \frac{R_1R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

Where

R = Total resistance

$$V = IR = I_1R_1 = I_2R_2 = I_3R_3$$

$$I_1R_1 = IR$$

$$I_1R_1 = I\frac{R_1R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

$$I_1 = I\frac{R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

Similarly

$$I_2 = I\frac{R_1R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

$$I_3 = I\frac{R_1R_2}{R_1R_2 + R_2R_3 + R_3R_1}$$

1.6 Kirchhoff's Laws

1.6.1 First law: Kirchhoff's current law (KCL)

The algebraic sum total of all the currents (I_1, I_2, I_3,….I_n) meeting at a point is zero.

$$\sum I = 0$$

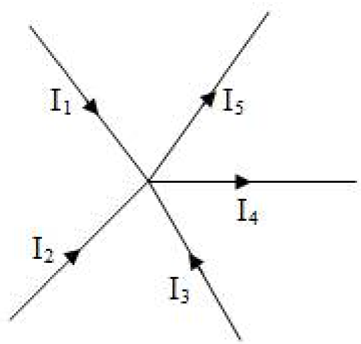


Fig. 1.4 Currents at a point

Taking incoming current at a point as +ve and outgoing current as –ve.

$$I_1 + I_2 + I_3 - I_4 - I_5 = 0$$

Or

$$I_1 + I_2 + I_3 = I_4 + I_5$$

1.6.2 Second law: Kirchhoff's voltage law (KVL)

(Also known as Kirchhoff's mesh law)

The algebraic sum total of all the emf and all the voltage drops is zero in a closed circuit or mesh.

$$\sum E + \sum V = 0$$

Rules for algebraic sum:

- Rise in potential is considered +ve and fall in potential is considered –ve
- Taking following circuit as example

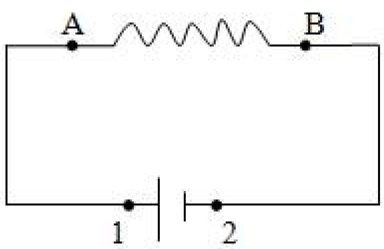


Fig. 1.5 Electric circuit

Voltage drop

- Tracing branch from A to B. V is negative (-v) i.e. fall is potential
- Tracing branch from B to A. V is positive

Emf

- Tracing branch from 1 to 2 E is negative
- Tracing branch from 2 to 1 E is positive

1.7 Superposition Theorem

The superposition theorem for electrical circuits states that for a linear system having two emf source in any branch of a bilateral linear circuit, the current flowing through any section is the algebraic sum of all the currents caused by each independent emf source acting alone, while all other independent sources are replaced by their internal resistances. Consider a circuit (Fig. 1.6) with two emf source.

Let r1 and r2 be internal resistance of emf source E1 and E2. Applying superposition theorem to the given electrical circuit:

- Case 1: considering first emf source E1 (Fig. 1.7). E2 is replaced by the internal resistance r2.
- Case 1: considering second emf source E2 (Fig. 1.8). E1 is replaced by the internal resistance r1.

Considering Fig. 1.6-1.8, the currents in different branches can be given as:

I1 = I1' – I1"

I2 = I2' – I2"

I3 = I3' + I3"

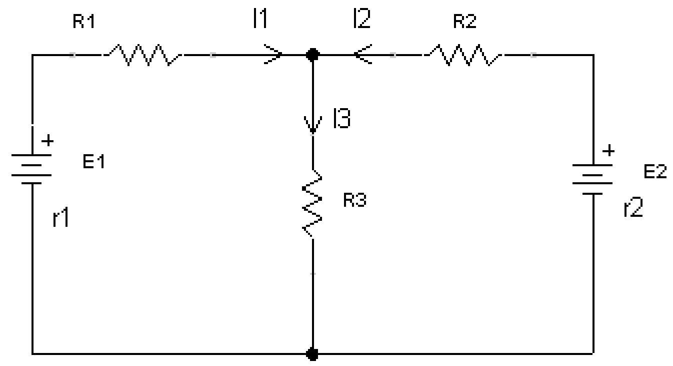


Fig. 1.6 Electric circuit with two emf source

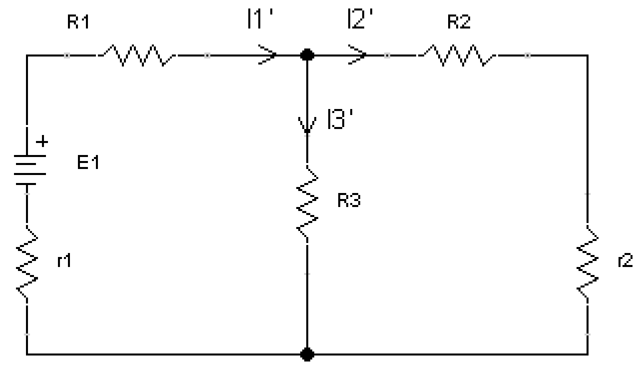


Fig. 1.7 Electric circuit considering first emf source

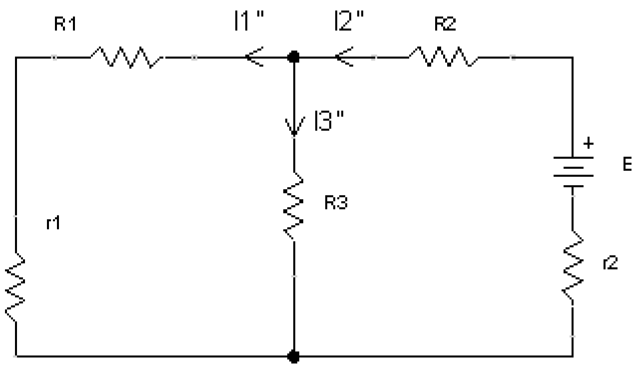
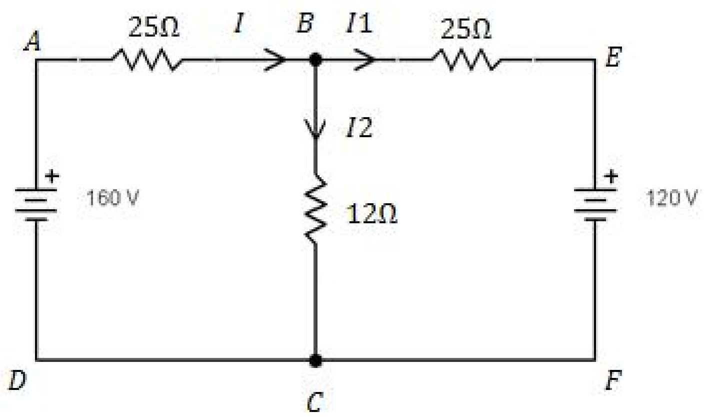


Fig. 1.8 Electric circuit considering second emf source

1.8 Numerical

1. For the circuit shown below calculate the current and power in 12 Ω resistor.



Solution

For mesh A B C D A applying K V L

- $25 (I_1 + I_2) – 12 I_2 + 160 = 0$
- $25 I_1 – 37 I_2 + 160 = 0$

$25 I_1 + 37 I_2 = 160$ -----------------(1)

For mesh B E F C B Applying K V L

$10 I_1 + 12 I_2 - 120 = 0$

$- 10 I_1 + 12 I_2 = 120$

Multiplying above equation by 2.5

$- 25 I_1 + 30 I_2 = 300$ ---------------(2)

Adding equ (1) & (2)

$(25 I_1 + 37 I_2 = 160) + (- 25 I_1 + 30 I_2 = 300) = 67 I_2 – 460$

$67 I_2 = 460$

$I_2 = 6.86$ A

Power $p = I_2^2 R_2$

$P = 6.86^2 * 12$

$= 564.7$ w

2. Find the branch current by superposition theorem in the following circuit.

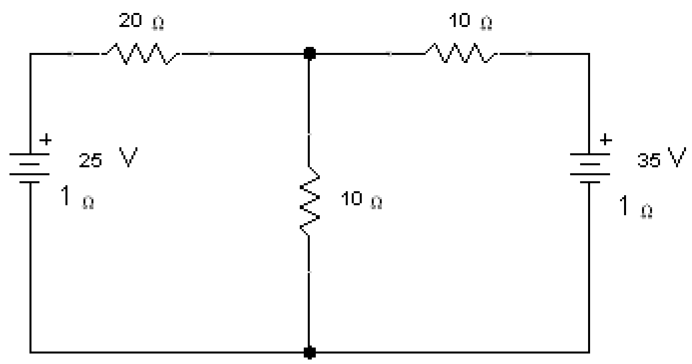


Fig. 1.9 Electric circuit with two emf source

Solution

The internal resistance of e.m.f can be denoted as follows:

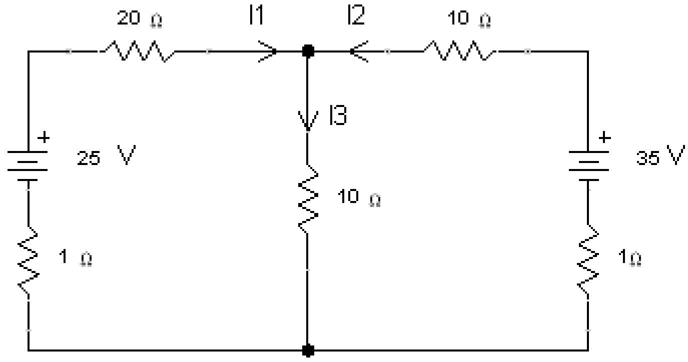


Fig. 1.10 Resistance of emf denoted in the circuit

By replacing 35v battery with internal resistance of 1Ω. Total resistance across 25 v.

$$20 + 1 + \frac{10 \times (10 + 1)}{10 + (10 + 1)} = 26.23\ \Omega$$

Current $11' = \frac{25}{26.23} = 0.95\ A$

Current $12' = 0.95\ \frac{10}{10+10+1} = 0.45\ A$

$$13' = 0.95\ \frac{11}{10 + 10 + 1} = 0.49\ A$$

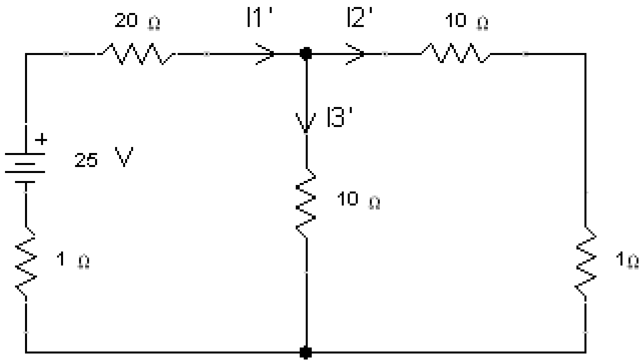


Fig. 1.11 Electric circuit considering first emf source

Now replace 25v battery by internal resistance as shown in the following fig.

Total resistance across 35 v battery

$$= 10 + 1 + \frac{21 \times 10}{21 + 10} = 17.77\ \Omega$$

$$I_2'' = \frac{35}{17.77} = 1.96\ A$$

$$I_1'' = 1.96 \times \frac{10^{10}}{10 + 21} = 0.63\ A$$

$$I_3'' = 1.96 \times \frac{21}{10 + 21} = 1.32\ A$$

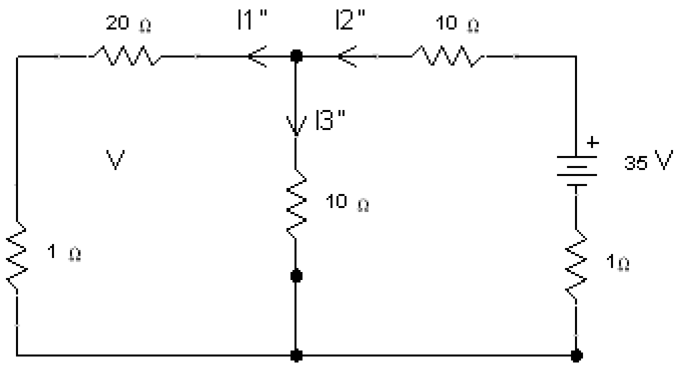


Fig. 1.12 Electric circuit considering second emf source

1.9 Thevenin Theorem

Thevenin theorem states that current flowing through a load resistance RL connected across any two terminals of a network by an equivalent circuit with voltage Eth and resistance Rth.

Where,
Eth = Thevenin voltage or open circuit voltage between two terminals of the network
Rth = Equivalent resistance of the network known as Thevenin resistance

Steps to apply Thevenin theorem

- Load resistance is removed to create an open circuit (Fig. 1.14)
- Find out the open circuit voltage between points A and B which is also known as thevenin voltage.

$$Eth = \left(\frac{E}{r + R1 + R2}\right) R2$$

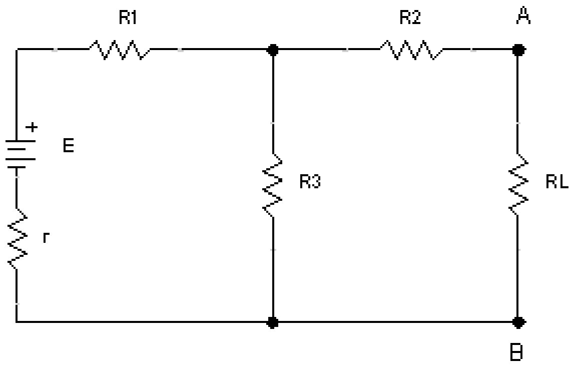


Fig. 1.13

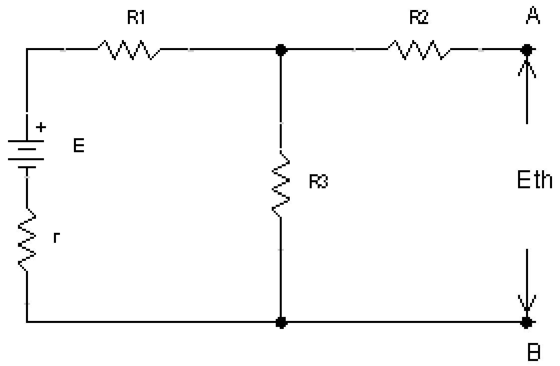


Fig. 1.14

- Resistance across points A and B is determined by replacing emf E by internal resistance r (Fig. 1.15). This resistance is known as Thevenin resistance.

$$Rth = \left(\frac{(r + R1)R2}{(r + R1) + R2}\right) + R2$$

- The network is replaced by Thevenin voltage Eth, internal resistance Rth and load resistance RL (Fig. 1.16).
- Current flowing through load resistance RL is calculated as:

$$I = \frac{Eth}{Rth + RL}$$

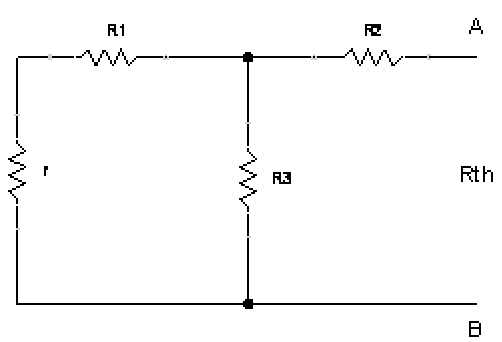


Fig. 1.15

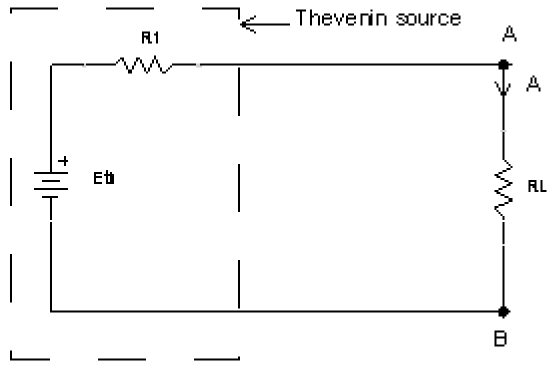


Fig. 1.16

2.0 Maximum Power Transfer Theorem

Maximum power transfer theorem states that power output of a network is maximum when load resistance RL is equal to internal resistance Rth i.e. RL = Rth

Software: Open source software Tiny CAD was used to draw the circuit diagrams. It is free software useful for electrical engineering teachers and students. The software can be downloaded from the following link:

http://sourceforge.net/apps/mediawiki/tinycad/index.php?title=TinyCAD

Lesson 2

ELECTROMAGNETIC INDUCTION AND MAGNITUDE OF INDUCED E.M.F. -I

2.1 Introduction

Before proceeding to the chapter of electro-magnetic induction, we need to know few things about magnetism and electromagnetism. The first part of the lesson will be a revision of what you have already studied in +2 level physics.

2.2 Magnetic Poles

When a bar magnet is dipped into iron filling, it is observed that large cluster of iron filling are formed at the two ends have highest magnetic effects and are called poles of the magnet, one is North Pole (N) and other is South Pole (S).

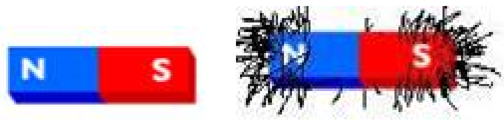


Fig. 2.1 Poles of a magnet

A simple experiment is described here to observe the distribution of magnetic field. Place a card board on the top of a bar magnet and sprinkle iron filling over it. When the cardboard is slightly tapped, the iron fillings get aligned in curved pattern as shown in figure 2.2. This arrangement is due to the magnetic force or field around the magnet.

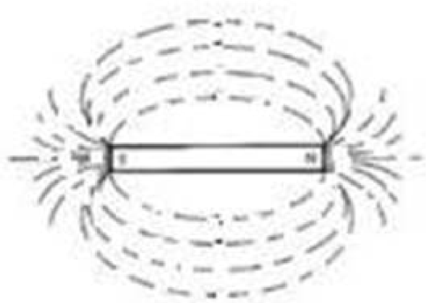


Fig. 2.2 Magnetic field around a magnet

2.3 Magnetic Field

It is the region around the magnet where the forces of attraction or repulsion act on magnetic poles. The magnetic field is strongest near the poles and its strength decreases with increasing distance from the poles.

2.4 Magnetic Flux

In the above experiment, the curved lines formed by the iron filings represent the magnetic lines of force and is known as magnetic flux.

Flux: The word Flux in dictionary means flow through a unit area, here it refers to magnetic lines of forces.

Magnetic flux may be quantified as the total number of magnetic lines of force produced by a magnet or an electromagnet. Magnetic flux is denoted by ϕ and its SI unit is weber (Wb)

$$1 \text{ Wb} = 10^8 \text{ magnetic lines of force} = 10^8 \text{ Maxwell}$$

If magnetic flux of a bar magnet is 1 Wb, there will be 10^8 magnetic lines of force joining north and south pole of the bar magnet.

2.4.1 Characteristics of lines of magnetic flux

1. The lines of magnetic flux are imaginary and represent the density and distribution of magnetic field.
2. In non-magnetic medium like air around the magnet, the line of magnetic flux has north to south direction.
3. In magnetic medium like inside a magnet the line of magnetic flux has south to north direction.
4. Thus, lines of magnetic flux form a closed loop (fig. 2.3)
5. The lines of magnetic flux do not intersect each other.
6. Lines of magnetic flux act like stretched cords, always trying to shorten themselves.
7. Parallel lines of magnetic flux which are in the same direction tend to repel each other.
8.

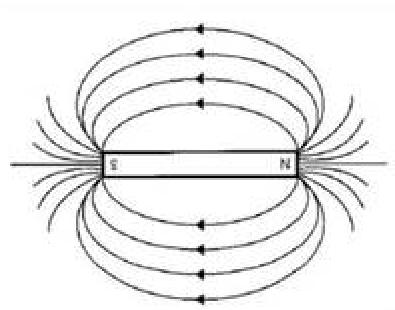


Fig. 2.3 Lines of magnetic flux form a closed loop

2.4.2 Magnetic flux density

The magnetic flux density is the flux per unit area at right angle to the flux at a point.

$$\text{Flux density, } B = \phi/A$$

Wb/m^2 or Tesla (T) where, ϕ = magnetic flux (Wb), A = area (m^2).

2.4.3 Permeability

Permeability is the ability of a material to conduct magnetic flux through it. Permeability is expressed as absolute and relative Permeability and is denoted as μ.

2.4.3.1 Absolute permeability (μ)

It is the actual permeability of a material. Air or vacuum has a poor permeability for magnetic flux and its value is given as:

$$\mu_o = 4\pi \times 10^{-7} \text{ H/m, where } \mu_o = \text{permeability air or vacuum.}$$

2.4.3.2 Relative permeability (μ_r)

Relative Permeability is the ratio of the absolute permeability of a material (μ) to the absolute permeability of air or vacuum (μ_o).

μ_r = absolute permeability of a material / absolute permeability of air or vacuum = μ / μ_o

#Relative permeability of air or vacuum = $\mu / \mu_o = 1$

#Relative permeability of all non magnetic material = 1

Table 2.1 Relative permeability of some materials

Material	Relative permeability
Aluminium	1.00002
Air/Vacuum	1
Soft iron	8000
Steel	100000
Nickel	100.600
Mu Metal (Nickel, 15% iron + copper + molybdenum)	50,000
Metglass Magnetic Alloy 2714A	10,00,000
Hydrogen a pure iron- N 5 grade	1,60,000
Permeability (nickel iron magnetic alloy) 20% iron & 80% nickel content	8,000

Magnetic material such as soft iron, steel etc have high relative permeability. Therefore it is used for making cores of electromagnet equipments. In fig 2.4 ii soft iron core is placed between the two magnets to increase the conductance of magnetic flux. The lines of magnetic flux pass completely through the soft iron ring. It results in a higher flux density in soft iron ring compared to air (Fig 2.4). Since result in a higher flux density in soft iron is 8000 times the flux density of air.

Fig. 2.4 Two magnets without and with soft iron core (Click for Animation)

Direction of magnetic field due to current passing through a horizontal coil and circular coil is shown in fig 2.5 and fig 2.6 respectively. The magnetic flux in the coil can be classified as useful and leakage flux (Fig. 2.7)

Fig. 2.5 Direction of magnetic field due to current passing through a horizontal coil (Click for Animation)

Fig. 2.6 Direction of magnetic field due to current passing through a circular coil (Click for Animation)

Fig. 2.7 Useful and leakage flux (Click for Animation)

2.5 Electromagnetic Induction

Electromagnetic Induction is a phenomenon by which an e.m.f. can be induced in a conductor by changing the flux linking with the conductor. If the conductor is connected through a closed circuit current will flow in it. The flow of current will take place as long as the flux linking the conductor is changing. Let us consider two cases:

Case 1

The bar magnet is stationary and the flux linking to coil is not changing.

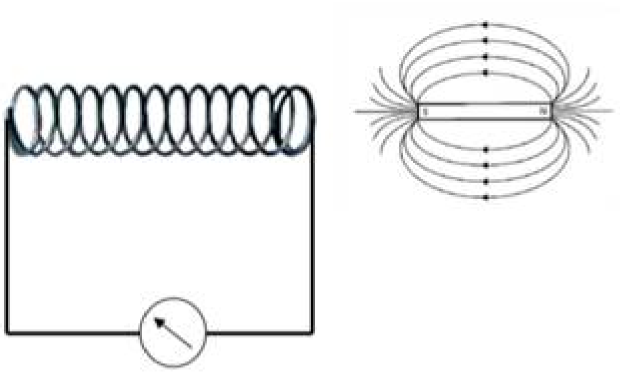


Fig. 2.8 Condition when flux linking the conductor is not changing

Case 2

The bar magnet is moved. The magnet is moved at a rapid pace into & from the coil

- The flux linking to coil changes.
- Magnetic induced emf i.e., voltage generated in coil equal to the rate of change of flux linkages.

Fig. 2.9 Condition when flux linking the conductor is changing (Click for Animation)

These observations were summed up into two laws known as Faraday's laws of electromagnetic induction.

First law

E.m.f (voltage) is induced in a coil or conduction when there is a change in magnetic flux linking the conductor.

Second Law

Magnitude of the induction e.m.f is equal to the rate of change of flux linkages.
In a coil of N turns, the flux linking the coil increases from ϕ_1 to ϕ_2 during the time period the second.

Initial flux linkages = N ϕ_1

Final flux linkages = N ϕ_2

According to second law, if e is the induced emf in the coil, it is given by the following equation.
e = rate of change of flux linkages

$$e = N\frac{(\phi_2 - \phi_1)}{t}$$

$$or\ e = N\frac{d\phi}{dt} Volts$$

$$or\ e = -N\frac{d\phi}{dt}$$

Here (-) ve sign shows that the voltage is induced in a direction such as to oppose the cause that produces it. Direction of magnetic field due to current passing through a conductor (Fig. 2.10) is given by right hand screw rule (Fig. 2.11)

Fig. 2.10 Magnetic field around a conductor (Click for Animation)

Fig. 2.11 Right hand screw rule (Click for Animation)

When a conductor is placed between two magnets and current is passed through it (Fig. 2.12), direction of current will determine whether the conductor will be pulled towards magnets (Fig. 2.13 i) or will be repelled

(Fig. 2.13 ii).

Fig. 2.12 Conductor placed between two magnets (Click for Animation)

Fig. 2.13 Direction of current will determine force on the conductor (Click for Animation)

Two conductors are placed side by side. Direction of current will determine whether the conductors will be pulled inwards (Fig. 2.14) or will be repelled (Fig. 2.15).

Fig. 2.14 Two conductors pulled inwards (Click for Animation)

Fig. 2.15 Two conductors repelled outwards (Click for Animation)

Numerical 1: Consider a coil of 75 turns. A magnet is moved close to the coil in such a way that the rate of change of flux linkages is 15 mWb/s. Calculate the e.m.f induced in the coil.

Given: N = 75

$$\frac{d\phi}{dt} = 15\frac{mWb}{s}$$

$$e = N\frac{d\phi}{dt} = 75 \times 15 \times 10^{-3} = 1.125\ V$$

Numerical 2: Consider a coil with 500 turns. If the flux linking the coil increase from 0.5 mWb to 1.5mWb in 1 sec, Calculate the induced emf.

Given:

N = 500

ϕ_1= 0.5 mWb

ϕ_2 = 1.5 mWb

t = 1 sec

$$e = N\frac{d\phi}{dt} = N\frac{(\phi_2 - \phi_1)}{t}$$

$$= \frac{500\ (1.5 - 0.5) \times 10^{-3}}{1} = 0.5\ Volt$$

Numerical 3: Flux of 5 mWb is linked with coil of 600 turns. If the flux is reversed in every 2s, Calculate the e.m.f induced in the coil.

Change in flux $d\phi$ = 5 – (-5) = 10 mWb [Since current is reversed]

Time period dt = 2 s.

Rate of change of flux = $\frac{d\phi}{dt} = \frac{10}{2} = 5$ mWb/s

Emf induced = e = N $\frac{d\phi}{dt}$ = $600 \times 5 \times 10^{-3} = 3\ Volt$

Numerical 4: A 6-pole d.c generator consists of 6 fields with coils connected in series. Each coil is of 1500 turns. When the generator is started, there is a magnetic flux of 0.05 Wb/pole. The rotor rotates at such a speed that the value of residual flux becomes 0.005 Wb/pole in 1 sec. Calculate the e.m.f induced in by the generator.

Given:

No. of poles = 6

No. of field windings = 6

No. of turns in each coils = 1500

Total no. of turns = 6×1500 = 9000

Total initial flux = 0.05 × 6 = 0.3 Wb

Total residual or final flux = 0.005 ×6 = 0.03 Wb

Time required for change between initial & final flux = 1 sec.

e.m.f induced

$$(e) = N\frac{d\phi}{dt} = \frac{9000 \times (0.3 - 0.03)}{1} = 2430V$$

Numerical 5: A coil having 1000 turns has flux linkage of 10 mWb. If this flux is reversed in 5ms, Calculate the e.m.f induced in the coil.

$$\text{Induced e.m.f (e)} = N\frac{d\phi}{dt}$$

N = 1000 turns

$d\phi$= 10-(-10) = 20 mWb

dt = 5×10^{-3}sec.

$$e = \frac{1000 \times 20 \times 10^{-3}}{5 \times 10^{-3}} = 4000V = 4KV$$

Lesson 3

ELECTROMAGNETIC INDUCTION AND MAGNITUDE OF INDUCED E.M.F.-II

3.1 Direction of Induced E.M.F

There are two methods of determining the direction of induced e.m.f.

1. Lenz's Law
2. Fleming's Right hand rule

3.1.1 Lenz's law

Lenz's law states that the direction of electro-magnetic induced current will be in such a direction so as to oppose the very cause which produces it. By the term "cause" we mean that the change in flux linking the coil is the cause of production of current. Therefore the flow of induced current will be in such a direction that the magnetic field created will oppose the change in the flux which is responsible in producing the induced current.

When N- pole of a bar magnet is brought close to a coil, an e.m.f. is induced in the coil. The direction of the current will be such that 'B' side of the coil attains north polarity, So as to oppose the change in the original flux.

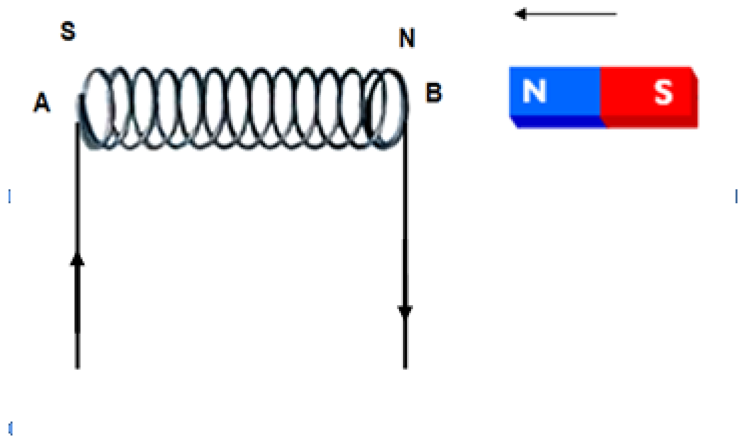


Fig. 3.16 E.m.f. induced in the coil by moving a magnet to and fro

3.1.2 Fleming's right hand rule

Keep forefinger, middle finger and thumb of your right hand in a position that they are at right angles to each other (Fig. 3.17 a, and b). If the:

a. First finger of the right hand is pointed in the directing magnetic flux.
b. Thumb is pointed in the direction of motion of the conductor.
c. Then the second finger will point in the direction of induced current.

Fig. 3.17 (a) Fleming right hand rule

[Fig. 3.17 (b) Fleming right hand rule (Click for Animation)]

3.1.3 Fleming's left hand rule

Fleming's left-hand rule is used for electric motors, while Fleming's right-hand rule is used for electric generators. Separate hands need to be used for motors and generators because of the differences between cause and effect. In an electric motor, the electric current and magnet field exist (which are the causes), and they lead to the force that creates the motion (which is the effect), and so the left hand rule is used. In an electric generator, the motion and magnetic field exist (causes), and they lead to the creation of the electric current (effect), and so the right hand rule is used.

[Fig. 3.17 (c) Fleming left hand rule (Click for Animation)]

3.2 Magnitude of Induced E.M.F.

Induced e.m.f. can be classified as:

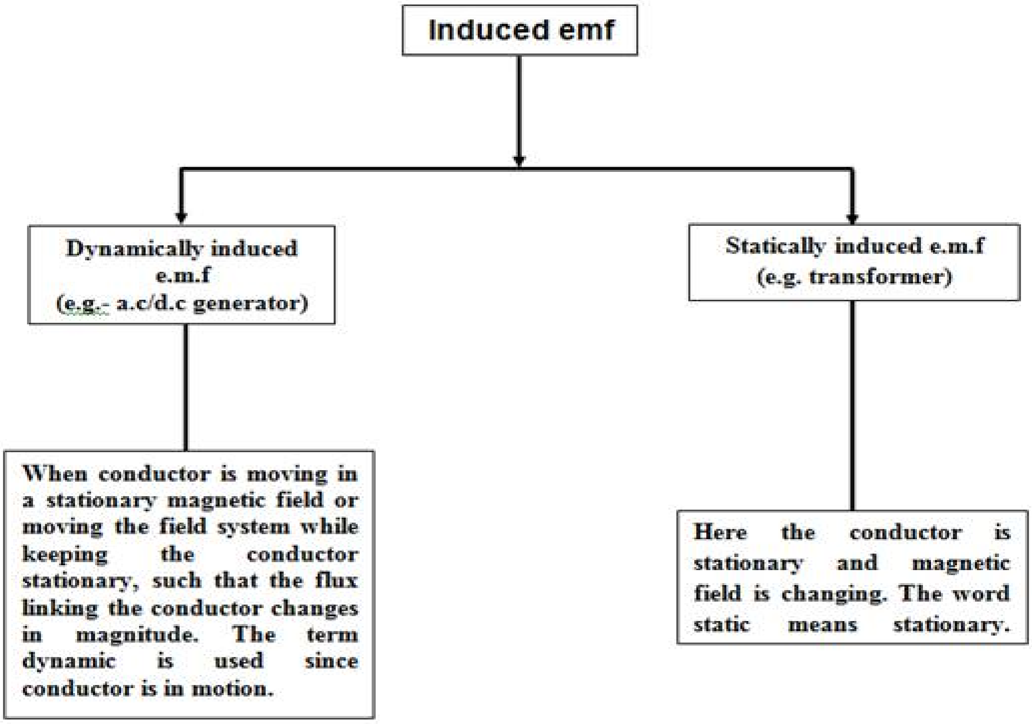


Fig. 3.18 Classification of induced e.m.f.

3.2.1 Dynamically induced e.m.f.

It can occur in two cases:

1. When conductor is moving in stationary magnetic field.
2. Or moving the entire field system while keeping the conductor stationary.

In both the above cases magnetic flux is cut by the conductor to induce e.m.f. in the conductor.

Consider a conductor of length l meters is placed in the magnetic field of magnetic flux density B Wb/m^2. The conductor is moving at right angles to the field at velocity v m/s (Fig. 3.19 a).

[Fig. 3.19 (a) Conductor moving at right angles to the field (Click for Animation)]

If the conductor moves a small distance dx in dt seconds. Then area swept by the conductor is = l ×dx.

Flux cut by conductor $d\phi$ = Flux density × area swept

$= B \times l.dx$ Wb

$d\phi = Bldx$ Wb……………….eqn. 1

According to Faraday's laws of electromagnetic induction, e.m.f (e) induced in the conductor is given by:

$$e = N\frac{d\phi}{dt}$$

Since N = 1,

$$e = \frac{d\phi}{dt} \dots\dots\dots\dots\dots eqn.\,2$$

From equations 1 & 2.

$$e = Bl\frac{dx}{dt}$$

$$e = Blv\ volt$$

Where,

$$v = \frac{dx}{dt} = velocity$$

If the conductor is moved at an angle θ with the direction of magnetic field at a velocity v m/s, as shown in figure 3.19 (b), then:

Area swept by the conductor, $A = l \times dx \sin\theta$

Flux cut by conductor $d\phi$ = Flux density × Area swept

$d\phi = Bldx \sin\theta$

$$\text{Induced e.m.f.}\ (e) = \frac{Bldx\ Sin\ \theta}{dt} = Blv\ Sin\ \theta$$

Fig. 3.19 (b) Conductor is moved at an angle θ with the direction of magnetic field (Click for Animation)

Unsolved numerical

Numerical 1: A wire of length 60 cm is at right angles to a uniform magnetic field having flux density 2 Wb/m^2. The velocity of the conductor is 50 m/s. Calculate the induced e.m.f. if conductor moves at an angle 70^0 to the field. (Ans: 46.43 V)

Numerical 2: A conductor of length 30 cm moves with a velocity of 50 m/s in a uniform magnetic field (flux density 2.5 Wb/m^2) Calculate the e.m.f. induced in the conductor when the direction of motion is:

(a) 90^0 to the magnetic field. (Ans 33.52 V)

(b) Inclined at 30^0 to the direction of field. (Ans 37.05 V)

3.2.2 Statically induced E.M.F

Here the conductor/ coil and magnetic field system both are stationary.

3.2.2.1 Self induced e.m.f

The e.m.f induced in a coil due to flux change linking with its own turn is known as self induced e.m.f. When current flows through a coil, a magnetic field is established through the coil. If the current flowing in the coil also changes. Due to change in flux linkage an e.m.f will be induced in the coil. According to Lenz's law the direction of induced e.m.f is such that it opposes the cause which produces it. Thus the direction of this induced e.m.f is toward change of current in the coil.

$$The\ magnitude\ of\ self\ induced\ e.m.f\ (e) = N\frac{d\phi}{dt}$$

When current in the coil is varied, the induced e.m.f. opposes the change of current in the coil. This oppose caused by induced e.m.f delays the change of current in the coil.

Fig. 3.20 Self induced e.m.f (Click for Animation)

3.2.3 Mutually induced e.m.f

If two coils are placed such that change in current in one coil induces e.m.f in the adjoining coil, it is known a mutually induced e.m.f. Consider two coils A and B is placed side by side as shown in the figure 3.21. When current is passed through coil A links to coil B. The flux common to both the coils (linking A to B) is called mutual flux (ϕ_m). Varying current in coil A, varies the mutual flux leading to e.m.f induction in both the coils. Now there are two types of induced e.m.f in the two coils A & B.

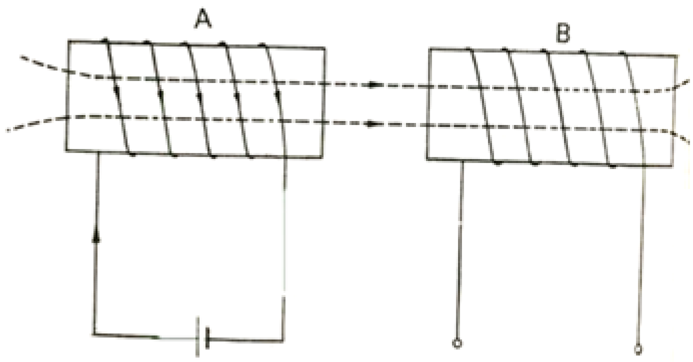


Fig. 3.21 Mutual Inductance

In Coil A: Self-induced e.m.f

Coil B: Mutually induced e.m.f

Characteristics of mutually induced e.m.f.

1. Magnitude of mutually induced e.m.f

   $$e_m = N_m\frac{d\phi m}{dt}$$

   where

   N_m = number of turns in coil B.

   $$\frac{d\phi m}{dt} = rate\ of\ change\ of\ mutual\ flux.$$

2. According to Lenz's law, the direction of mutually induced e.m.f is as to oppose the very cause producing it. The direction of induced current in coil B due to mutual induced e.m.f will be such that the flux linking coils A & B.
3. The characteristic of two coils such that voltage can be induced in one coil by changing current in the other coil is called mutual inductance.
4. Mutually induced e.m.f in coil B will exists as long as the current in coil A is being changed. If the magnitude of current in coil A comes to a constant value, the mutual flux no longer changes and mutually induced e.m.f (in coil B) drops to zero.

3.3 Coefficient of Self Inductance (L)

Self inductance of the coil may be defined as the property of a coil due to which it opposes the change of current flowing through itself. This property of self inductance is attained by a coil is due to the self induced e.m.f produced in the coil itself by the changing current. The principle of self inductance can be understood taking two cases (Table 3.1):

Table 3.1 Cases for the direction of self induced e.m.f.

	Current in the coil	Direction of self induced e.m.f.
Case 1	Increasing	Is such to oppose the rise of current (and opposite to applied voltage)
Case 2	Decreasing	Is such to oppose the decrease of current (and of same direction as the applied voltage)

Now we should understand that self inductance does not prevent the current from changing, but only causes delay to the change.

3.3.1 Inductance of the coil depends on the following factors:

1. Number of turns in a coil and its shape.
2. Relative permeability (μ_r) of the material which surrounds the coil.
3. The rate of change of magnetic field. (It can also be said as rate of change of flux linkage).

Self inductance L = Nϕ/I henry.

Where

N = Number of turns in the coil.

ϕ = flux linking with the coil.

I = Current flowing through the coil.

Nϕ= Flux linkages.

3.4 Coefficient of Mutual Inductance

It may be defined as the characteristic of coil due to which it opposes the change of current in the neighbouring coil.

$$\text{Mutually induced e.m.f } (e_m) = -M\frac{di_1}{dt}$$

where,

$$M = \frac{N_1 N_2 \mu_0 \mu_r a}{l}$$

i_i = current flowing through coil 1.

N_1= Number of turns on core of length l meters.

a = area of cross section.

μ_r= relative permeability.

N_2 = Number of turns in coil 2.

3.5 Coefficient of Coupling

Consider two coils placed adjacent to each other such that flux produced in one coil links to the other. The fraction of magnetic flux produced by the current in one coil linking to other coil is known as co-efficient of coupling (K).

Coefficient of coupling $K = \frac{M}{\sqrt{L_1 L_2}}$

Where,

L_1 & L_2 are inductance of coil 1 and 2 respectively.

M = Mutual inductance between them.

Numerical: A coil having 1000 turns has flux linkage of 10 mWb. If this flux is reversed in 5ms, Calculate the e.m.f induced in the coil.

Induced e.m.f (e) = $N\frac{d\phi}{dt}$

N = 1000 turns

$d\phi = 10-(-10) = 20$ mWb

$dt = 5\times10^{-3}$sec.

$$e = \frac{1000 \times 20 \times 10^{-3}}{5 \times 10^{-3}} = 4000V = 4KV$$

Lesson 4

FUNDAMENTALS OF ALTERNATING CURRENT

4.1 Introduction

In an A.C. system; the voltage acting in the circuit changes polarity (+ve & -ve) at regular time interval and therefore the current also changes direction accordingly. A.C systems are more widely used than D.C. system due to following reasons:

1. For large scale power generation, transmission and distribution ac systems are used to reduce transmission losses. Transformers are used to step up or step down alternating voltage efficiently. Thus handling alternating current is easier than D.C. system.
2. A.C. motors known as induction motors are simple in construction and also are cheaper compared to d.c motor.

The switch gears like switches, circuit breaker etc for A.C. system is simpler than D.C. system.

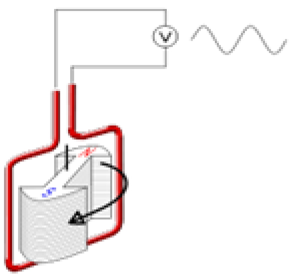
4.2 Generation of Alternating Voltage and Currents

An alternating voltage may be generated by

a) Rotating a coil in a uniform magnetic field.

b) Rotating a magnetic field within a stationary coil.

Fig. 4.1 Rotating a coil in a uniform magnetic field (Click for Animation)



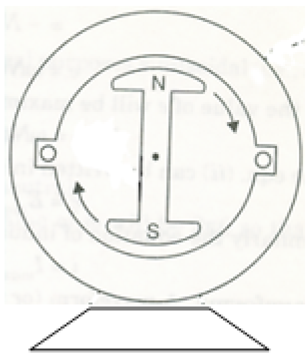


Fig. 4.2 Rotating a magnetic field within a stationary coil.

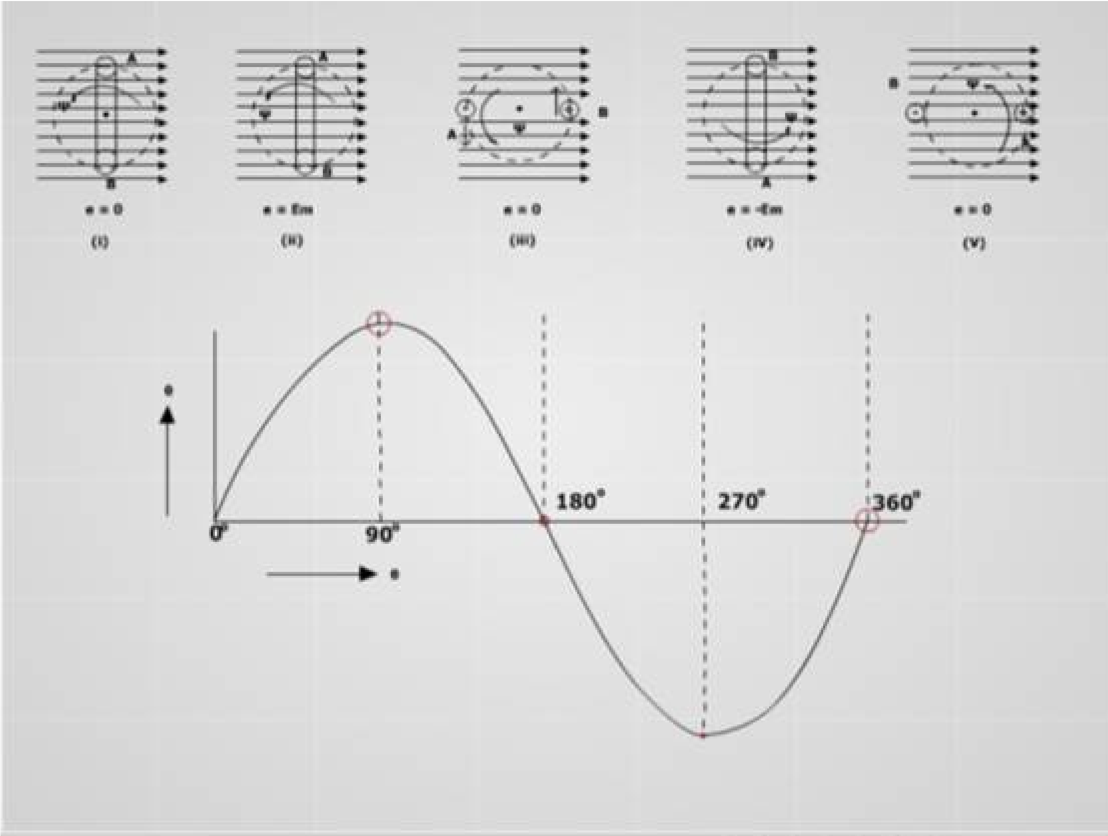


Fig. 4.3 Generation of A.C.

The alternating voltage generated by any of the above methods will be of sinusoidal waveform (i.e sine wave). The magnitude of generated voltage depends upon the speed of rotation, number of turns of coil and the strength of magnetic field. The equation for alternating voltage is given by:

$$e = E_m \text{ Sin } \omega t$$

Where,

e = Instantaneous voltage at any time t.

E_m = Maximum value of alternating voltage.

ω = Angular velocity of coil.

Alternating voltage in Sine waveform will produce sinusoidal current. There can be different types of alternating wave forms (Fig. 4.4).

[Fig. 4.4 Different waveforms (Click for Animation)]

Among different types of wave forms, sinusoidal wave is preferred over ramp, triangular or square wave because of following reasons:

- In A.C. system like induction motor and transformer, sinusoidal wave has lower losses with higher efficiency.
- Sinusoidal waves produce less noise or disturbance.

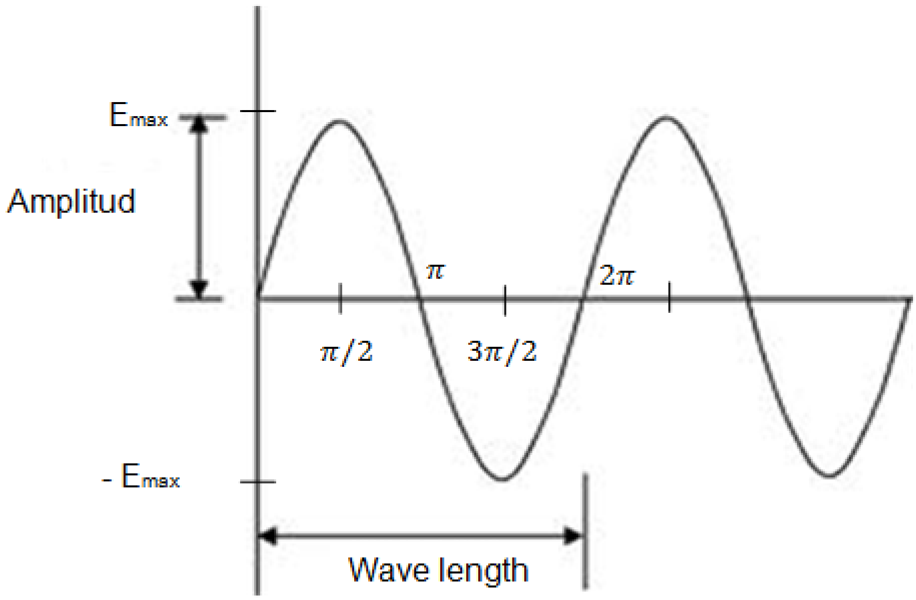


Fig. 4.5 A.C. sine wave

4.3 A.C. Terms

1. **Wave form:** Also known as wave shape is the shape of the curve obtained by plotting the instantaneous value of voltage or current in y-axis vs time in x-axis.
2. **Cycle:** an alternating quantity either voltage or current when completes one set of positive and negative values. One cycle is equal to 2π radian or 360^0 electrical degree.
3. **Alternation:** One half cycle of alternating quantity either –ve or +ve half is called an alternation.
4. **Instantaneous value:** The value of an alternating quantity (voltage or current) at any instant is called instantaneous value.
5. **Time period:** The time required to complete one cycle of an alternating quantity is known as Time period. It is denoted by T and its unit is in second.
6. **Frequency:** The number of cycles per second of an alternating quantity is known as time period. Its unit is cycles/sec or Hertz (Hz). It is denoted by f.

   $$Frequency\ f = \frac{1}{Time\ period} = \frac{1}{T}$$

   Unit per second (1/s)
7. **Amplitude:** The maximum positive or negative value of alternating quantities is known as peak value or amplitude. It is denoted by E_{max} or I_{max}.
8. **Angular velocity (ω):** Angular velocity of rotating coil is given as:

   $$Angular\ velocity\ \omega = \frac{Angle\ turned\ by\ coil}{Time\ taken} = \frac{2\pi}{T}$$

   $$\omega = 2\pi f$$

Note: In one revolution the coil undergoes rotation of 2 π radiations.

4.4 Magnitude of Alternating Voltage and Current

There are three ways to measure magnitude of alternating voltage and current.

1. Peak value.
2. Average or mean value.
3. R.M.S value.

4.4.1 Peak value

The maximum value attained by an alternating quantity either voltage or current during one cycle is called the peak value. It is also known as amplitude and denoted as E_{max} or I_{max}.

4.4.2 Average value

The arithmetic mean of all the instantaneous values of an alternating quantity over one cycle is known as average value.

$$Average\ value = \frac{Area\ under\ the\ curve}{Base\ length}$$

Since in symmetrical waves like sinusoidal current or voltage wave +ve half is equal to -ve half, the average value over a complete cycle is zero. Therefore, for alternating quantity average value is considered only for +ve half of the cycle.

$$Average\ value = \frac{Area\ of + ve\ half}{Base\ length}$$

4.5 Average Value of Sinusoidal Current

Consider an elementary area of width dθ in the +ve half of an alternating current. If i is the mid ordinate of the strip, then area of strip:

Area of strip = idθ

$$\text{Area of half cycle} = \int_0^{\pi} id\theta \ldots\ldots\ldots\ldots.(1)$$

Equating an alternating current

$$i = I_m \text{ Sin } \theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

From equation (1) & (2):

$$Area\ of\ half\ cycle = \int_0^{\pi} I_{max} Sin\ \theta\ d\theta$$

$$= I_{max}[-Cos\ \theta]_0^{\pi} = 2I_{max}$$

$$Average\ value\ I_{ave} = \frac{Area\ of\ half\ cycle}{Base\ length\ of\ half\ cycle} = \frac{2\ I_{max}}{\pi}$$

$$I_{ave} = 0.637\ I_{max}$$

Similarly for alternating voltage, average value of voltage is given as:

$$E_{ave} = 0.637\ E_{max}$$

4.6 R.M.S Value (Root mean Square value)

The R.M.S value of an alternating current is the steady current or direct current which when flows through a known resistance for a given time produces the same amount of heat when the alternating current is flowing through the same resistance for the same time.

Consider the +ve half cycle of a non-sinusoidal alternating current I, flowing through a resistance R ohms for t seconds. Let divide the entire area into n equal parts as shown in the figure 4.6.

Fig. 4.6 Dividing wave into n equal parts (Click for Animation)

Let us consider that heat produced in the resistance R by current I is same as produced by direct current I flowing through resistance R for the same duration t seconds.

We know, heat produced in a resistance is given has:

Heat produced (q) = Current^2×Resistance ×Time

$q = i^2Rt$

$$Heat\ produced\ by\ i_1 = {i_1}^2R\frac{t}{n}$$

$$Heat\ produced\ by\ i_2 = {i_2}^2R\frac{t}{n}$$

$$Similarly\ heat\ produced\ by\ i_n = {i_n}^2R\frac{t}{n}$$

$$Total\ Heat\ produced = ({i_1}^2R + {i_2}^2R + \cdots \ldots + {i_n}^2R)\frac{t}{n} \ldots \ldots \ldots \ldots \ldots (1)$$

According to assumption heat produced by direct current I flowing through R for the same time is:

$$q_{dc} = I^2Rt \qquad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (2)$$

As the heat produced in both the cases is same we can equate equation (1) and (2):

$$I^2Rt = \left(\frac{{i_1}^2R + {i_2}^2R + \cdots \ldots + {i_n}^2R}{n}\right)t$$

$$I^2Rt = \left(\frac{{i_1}^2 + {i_2}^2 + \cdots \ldots + {i_n}^2}{n}\right)Rt$$

$$I^2 = \left(\frac{{i_1}^2 + {i_2}^2 + \cdots \ldots + {i_n}^2}{n}\right)$$

$$I = \sqrt{\frac{{i_1}^2 + {i_2}^2 + \cdots \ldots + {i_n}^2}{n}}$$

$$= \sqrt{mean\ value\ of\ i^2}$$

I = Square root of mean of squares of instantaneous values.

= Root-mean-square (r.m.s) value.

$$r.m.s\ value = \sqrt{\frac{Area\ of\ half - cycle\ wave\ squared}{Base\ of\ half\ cycle}}$$

4.7 R.M.S Value of Sinusoidal Current

The equation for sinusoidal alternating current is given by:

$i = I_{max}$ Sin θ……………………..(1)

The bold line in the figure shows sinusoidal current wave and the shaded line denotes i^2 value of the sinusoidal wave.

Fig. 4.7 i^2 value of the sinusoidal wave (Click for Animation)

In the previous section we have already seen the formula for r.m.s value of current (I_{rms}):

$$I_{rms} = \sqrt{\frac{Area\ of\ half\ cycle\ squared\ wave}{Base\ of\ half\text{-}cycle}} \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

Consider an elementary area of width dθ in the +ve half cycle of the i^2 current wave.

Area of Strip = i^2 dθ

$$Area\ of + ve\ half\ cycle\ of\ the\ squared\ wave = \int_0^{\pi} i^2 d\theta$$

From equation (1):

$$= \int_0^{\pi} I^2{}_{max} Sin^2\theta \; d\theta$$

$$= I^2{}_{max} \int_0^{\pi} Sin^2\theta \; d\theta$$

$$= I^2{}_{max} \int_0^{\pi} \frac{1 - Cos2\theta}{2} \; d\theta$$

$$= \frac{I^2{}_{max}}{2} \int_0^{\pi} (1 - Cos2\theta\,) d\theta$$

$$= \frac{I^2{}_{max}}{2} \left[\theta - \frac{Sin\;2\theta}{2}\right]_0^{\pi}$$

$$= \frac{I^2{}_{max}}{2} \left[(\pi - 0) - \frac{Sin\;2\pi - Sin\;0}{2}\right]$$

Area of +ve half cycle of the squared wave:

$$\frac{\pi\, I^2{}_{max}}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Base of half cycle = Π ……… (4)

Placing values from equation 3 and 4 in equation 2:

$$I_{rms} = \sqrt{\frac{\pi\, I^2{}_{max}}{\pi\; 2}} = \frac{I^2{}_{max}}{\sqrt{2}}$$

$I_{rms} = 0.707\ I_{max}$

Similarly for sinusoidally alternating voltage r.m.s value can be given as:

$E_{r.m.s} = 0.707\ E_{max}$

4.8 Form Factor

The ratio of r.m.s value to average value of an alternating quantity is known as form factor:

$$Form\ factor = \frac{I_{rms}}{I_{ave}}$$

$$or, Form\ factor = \frac{E_{rms}}{E_{ave}}$$

$$Form\ factor = \frac{I_{rms}}{I_{ave}}$$

$$= \frac{I_{max}/\sqrt{2}}{2I_{max}/\pi}$$

$$= \frac{\pi I_{max}}{2\sqrt{2}I_{max}}$$

Form factor = **1.11**

4.9 Peak Factor

Peak factor is the ratio of maximum value to r.m.s value of an alternating quantity is known as peak factor.

$$Peak\ factor = \frac{I_{max}}{I_{rms}}$$

$$or, Peak\ factor = \frac{E_{max}}{E_{rms}}$$

$$Peak\ factor = \frac{I_{max}}{I_{rms}} = \frac{I_{max}}{I_{max}/\sqrt{2}} = \sqrt{2} = \mathbf{1.414}$$

4.10 Numerical

Q.1. Calculate the frequency and angular velocity of an alternating quantity if the time period = 0.5 sec.

Sol. Frequency $f = \frac{1}{time\ period(T)}$

$= \frac{1}{0.5}$

= 2 Hz or 2 cycles per sec

Angular velocity w = 2πf radians/sec

= 2π×2

= 2× 3.14 ×2

= 12.14 radian/ sec.

Q.2 For an alternating quantity, I = 100 sin125t calculate

a. Maximum value of current

b. r.m.s value

c. Average value

d. Frequency

e. value of current after 0.005 sec.

Solution:

a. We know $i = I_m \sin\omega t$

$\mathbf{I_m = 100A}$

b. $I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{100}{\sqrt{2}} = \mathbf{70.70}$

c. $I_{ave} = 0.637\ I_m$

$= 0.637 \times 100$

= 63.7 A

d. $\sin\omega t = \sin 125t$

$\omega = 2\pi f$

$\sin 2\pi f t = \sin 125t$

$2\pi f t = 125$

$f = \frac{125}{2\pi} = 19.9$

≅20 Hz

e. From the ques i = 100 sin 125t

i = 100sin125×0.005

i = **10.88 A**

Q.3 For an alternating current i=75 sin 68t determine:

a. Maximum value

b. r.m.s value

c. Average value

d. Form factor

e. Frequency

Sol: a. we know for an alternating quantity.

$i = I_{max} \sin\omega t$

$I_{max} = \mathbf{75\ A}$

b. $I_{rms} = \frac{Imax}{\sqrt{2}}$

$= \frac{75}{\sqrt{2}} = \mathbf{53.03A}$

c. $I_{ave} = 0.637\ I_{max}$

$= 0.637 \times 75$

$= \mathbf{47.77\ A}$

d. form factor $= \frac{I_{rms}}{I_{ave}}$

$= \frac{53.03}{47.77}$

$= \mathbf{1.11}$

Q.4 Find the instantaneous value (equation) for alternating, voltage of 230v at 50 Hz for domestic supply.

Sol: Equation for alternating voltage:

$V = V_m \sin\omega t$

$V_{rms} = \frac{V_m}{\sqrt{2}}$

$V_m = \sqrt{2} \times 230$

$= 325.26$

$\omega = 2\pi f$

$= 2\pi 50$

$= 314.15$ radian/ sec

$V = 325.26 \sin 314.15t$

Q.5 Calculate the term required by the current to obtain values of 25, 50 and 75 A. for a sinusoidal alternation current having maximum value of 150 A and frequency 50 Hz.

Sol: we know

$i = I_{max} \sin\omega t$

$I_{max} = 150A$

a. Time for attaining 25 A

$25\ m = 150 \sin (2\pi 50t)$

$\sin 2\pi 50t = \frac{25}{150}$

$2\pi 50t = \sin^{-1} 0.166$

$2 \times 180° \times 50 \times t = 9.55^0$

$$t = \frac{9.55°}{2×180°×50}$$

= 0.00053 sec.

b. Time for attaining 50 A.

$$50 = 150 \sin(2\pi 50t)$$

$$\text{Sin}(2\pi 50t) = \frac{50}{150}$$

$$2 \times 180 \times 50 \times t = \sin^{-1} 0.33$$

$$t = \frac{19.26°}{2×180×50}$$

= 0.00107 sec.

c. time for attaining 75 A

$$75 = 150 \sin(2\pi 50t)$$

$$\text{Sin}(2\pi 50t) = \frac{75}{150}$$

$$2 \times 180 \times 50 \times t = \sin^{-1} 0.5$$

$$t = \frac{30}{2×180×50}$$

= 0.00166 sec

Lesson 5

PHASE RELATIONS AND VECTOR REPRESENTATION

5.1 Introduction

Sinusoidal varying alternating quantity (Current or Voltage) may be represented in following three ways:

a. Graphically represented by wave form.
b. Mathematical equation of instantaneous value of an alternate quantity.
c. Phasor Diagram: Phasor is a line of definite length to represent an alternating quantity. The length of this line is equal to the maximum value of the alternating quantity. It rotates in anti-clockwise direction at angular velocity ω radians/ second.

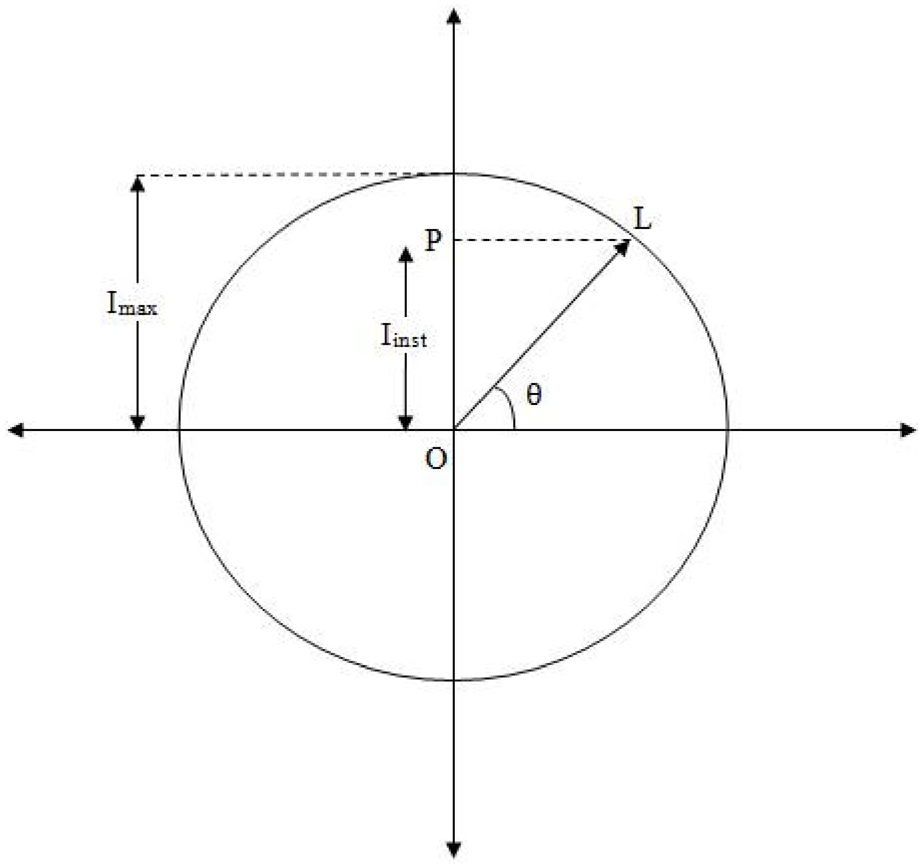


Fig. 5.1 Phasor for alternating current

Let us consider an alternating current $i = I_{max}$ Sin ωt. The phasor is shown in fig. 5.1.

- The phasor OL rotating in anti-clockwise direction is representing the alternate current.
- The horizontal dotted projecting phasor OP on Y-axis gives the value of the current at that instant (I_{inst}).
- The lengthy phasor (i.e OL) gives the maximum value of current, I_{max}.
- The angle of the phasor with the horizontal x-axis represent the angle of the alternating current θ. This angle θ is also known as phase of the alternating quantity.
- I is the value of current at that instance and is given by equation:
  $i = i_{max}$ Sin ωt (Where θ = ωt)
- The angular velocity of phasor is ω radian/ sec about point O.

5.2 Phasor Diagram of Similar Alternating Quantity

Let us consider two alternating currents of same frequency of magnitude I_{m1} and I_{m2}. Two alternating quantities having same frequency but having different zero points are said to have a phase difference.

As shown in figure 5.2, the angle between the zero points of two alternating current is called phase angle or angle of phase difference ϕ. Phase angle can be measured as degrees or radians.

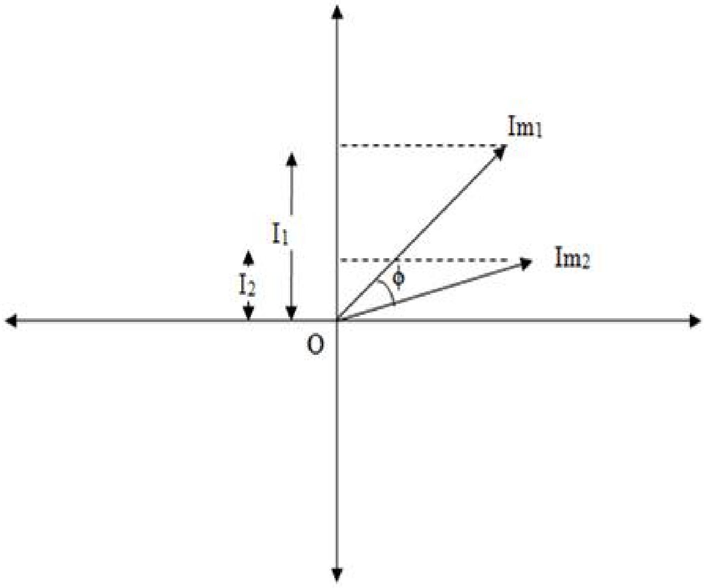


Fig. 5.2 Phasor Diagram of similar alternating quantity

5.2.1 The concept of leading and lagging

Alternating quantities with different zero points have a phase difference generally measured as angle ϕ.
Leading: The quantity which attains zero point earlier than the other quantity is known as leading quantity.
Lagging: The quantity which attains zero point later than the leading quantity is known as lagging quantity.

In figure 5.2 I_1 is the leading current w.r.t I_2, And I_2 is the lagging current w.r.t. I_1. The phase difference between them is ϕ.

5.3 Phasor Diagram of Different Alternating Quantity

In case of two alternating quantities e.g. current & voltage, let us consider following assumptions:

1. Two alternating quantities voltage V and current I of same frequency.
2. Voltage is leading w.r.t current by phase difference of ϕ angle.
3. These alternating quantities can be shown by phasor diagram (Fig. 5.3).
4. The phasor V_m and I_m rotate at the same angular velocity ω radian / sec.
5. Due to same angular velocity the phase difference ϕ between two phasors V_m and I_m remains constant.

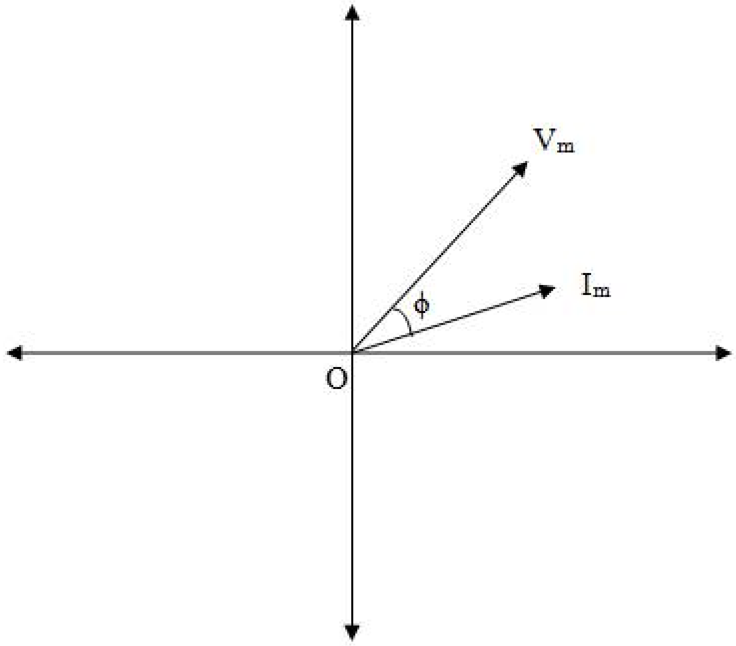


Fig. 5.3 Phase difference ϕ between two phasors V_m and I_m

5.4 Addition and Subtraction of Alternating Quantities

5.4.1 Addition of alternating quantities

There are certain rules for addition of alternating quantities:

a) Alternating quantities like voltage and currents can be represented as phasor.
b) These phasor can be added in the same manner as forces are added.
c) Only alternating quantities of similar types can be added. Either voltages can be added or currents can be added. Voltage cannot be added to current.

Alternating voltage or current can be added by any of the following methods:

i. Parallelogram method.
ii. Method of components.

5.4.1.1 Parallelogram method

This technique is used for addition of two phasors at a time. The two alternating quantities are denoted by phasor diagram. The two phasors are arranged as the adjacent sides of a parallelogram. The diagonal of the formal parallelogram gives the resultant value of the two phasors. The following diagram shows phasor diagram of a.c parallel circuit:

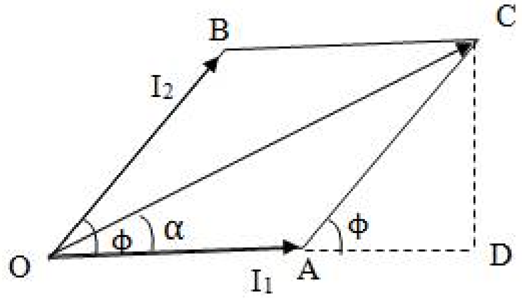


Fig 5.4 Phasor diagram of a.c parallel circuit

The two currents flowing in the circuit are given as:

$i_1 = I_{m1} \text{Sin } \omega t$

$i_2 = I_{m2} \text{ Sin } (\omega t + \phi)$

i_r = resultant current

I_{m1} and I_{m2} are the maximum value of currents i_1 and i_2 respectively. Here i_1 is leading w.r.t i_2 or in other words i_2 is lagging w.r.t i_1. The phase difference between i_1 and i_2 is ϕ^o.

$$OC = \sqrt{(OD)^2 + (DC)^2}$$

$$= \sqrt{(OA + AD)^2 + (DC)^2}$$

$$I_{mr} = \sqrt{(I_{m1} + I_{m2} Cos\ \phi)^2 + (I_{m2} Sin\ \phi)^2}$$

$$= \sqrt{I_{m1}{}^2 + I_{m2}{}^2 (Sin^2\phi + Cos^2\phi) + 2 I_{m1} I_{m2} Cos\ \phi}$$

$$= \sqrt{I_{m1}{}^2 + I_{m2}{}^2 + 2 I_{m1} I_{m2} Cos\ \phi}$$

$$tan\ \alpha = \frac{y}{x} = \frac{CD}{OD}$$

$$Phase\ angle\ \alpha = tan^{-1} \frac{CD}{OD}$$

$$= tan^{-1} \frac{I_{m2} Sin\ \phi}{I_{m1} + I_{m2} Cos\ \phi}$$

The equation for instantaneous value of resultant current i_r is given as:

$i_r = I_{mr} \text{ Sin } (\omega t + \alpha)$

5.4.1.2 Method of components

This method can be used to add two or more phasors. The steps are as follows:

- Draw the phasor diagram for each alternating quantity.
- Resolve each phasor into horizontal and vertical components.
- Add all the horizontal components algebraically to obtain the resultant horizontal component I_x.
- The entire vertical component algebraically to obtain the resultant vertical component I_y.
- The resultant value of the alternating quantity will be calculated as:

$$I_R = \sqrt{(I_x)^2 + (I_y)^2}$$

5.5 Subtraction of Alternating Quantities

The steps for subtraction of alternating quantities are described below:

1. Draw phasor diagram for the two alternating quantities.
2. One of the phasor is traced and drawn in reverse direction.
3. Now it can be solved by parallelogram method or method of component.

Two similar alternating quantities i.e current i_1 and i_2 is given by phasor OA and OB.

The subtraction can be given by = OA –OB

= phasor OC

Lesson 6

A.C. SERIES AND PARALLEL CIRCUITS

6.1 A.C. Circuit

When an alternating current flows in closed loop or a path, it is called an a.c. circuit. Different elements of an a.c. circuit may be any or in combination of following:

1. Resistance: An electrical element which causes opposition to the passage of an electric current through that element.
2. Inductance: In electromagnetism and electronics, inductance in the circuit "induces" (creates) a voltage (electromotive force) in both the circuit itself (self-inductance) and any nearby circuits (mutual inductance). Inductance is typified by the behaviour of a coil of wire in resisting any change of electric current through the coil.
3. Capacitance: Capacitance is the ability of a body to store an electrical charge. Any element or structure that is capable of being charged, either with static electricity or by an electric current exhibits capacitance.

If the voltage applied to an a.c. circuit in sinusoidal, the resulting alternating current is sinusoidal. Also the frequency of the alternating current will be equal to that of applied voltage. The opposition to the flow of current in an a.c. circuit may be due to:

1. Resistance R
2. Inductive reactance ($X_L = \omega L$)
3. Capacitive reactance ($X_C = \frac{1}{\omega C}$)

Different types of A.C. Circuit can be listed as follows:

1. A.C. Circuit with only one element
   a) Resistance
   b) Inductance
   c) Capacitance
2. A.C. Series Circuit
   a) R-L Series Circuit
   b) R-C Series Circuit
   c) R-L-C Series Circuit
3. A.C. Parallel Circuit

6.2 A.C. Circuit with Only One Element

6.2.1 A.C. Circuit with only one element-resistance

The figure 6.1 shows an a.c. circuit with a pure resistance of R Ω

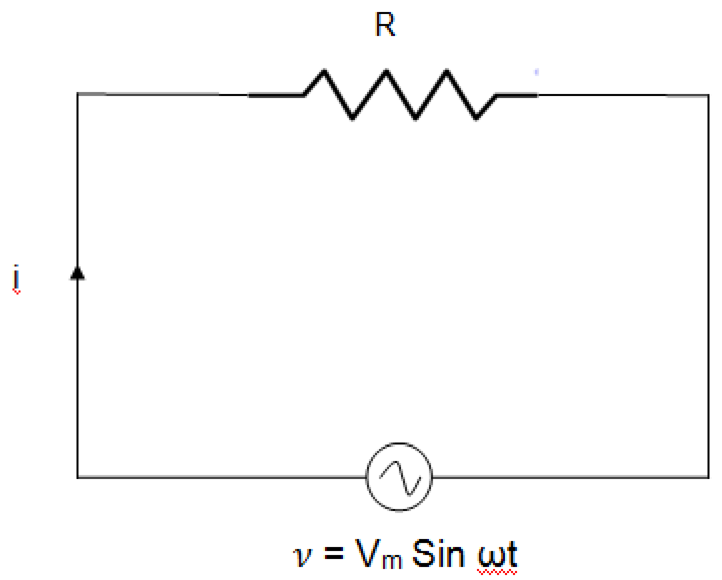


Fig. 6.1 A.C. Circuit with only one element-Resistance

The current in the circuit is i= ν/R.................(1)

The instantaneous value of alternating voltage is given by:

$$\nu = V_m Sin\ \omega t \dots\dots\dots\dots..(2)$$

From equation (1) and (2)

$$i = \frac{V_m \sin \omega t}{R} \dots\dots\dots\dots\dots..(3)$$

The value of current will be maximum when Sin ωt=1

$$I_m = \frac{V_m}{R} \dots\dots\dots\dots..(4)$$

From equation (3) and (4)

$$i = I_m Sin\ \omega t \dots\dots\dots..(5)$$

In an a.c. circuit having resistance as any element, the phase difference between voltage and current is zero. In other words it can be said that current is in phase with the voltage power.

We know instantaneous power p= ν i

From equation (2) and (5) we have

$$p = (V_m Sin\ \omega t)(I_m Sin\ \omega t)$$

$$= V_m I_m Sin^2 \omega t$$

$$= \frac{V_m I_m (1 - Cos\ 2\ \omega t)}{2}$$

$$= \frac{V_m I_m}{2} - \frac{V_m I_m Cos\ 2\ \omega t}{2}$$

Considering average power

$$p = \frac{V_m I_m}{2}$$

$$[\text{Average value of } \frac{V_m I_m\ Cos\ 2\ \omega t}{2} = 0\ ]$$

$$P = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}$$

$$P = V_{rms}\ I_{rms}$$

p = ν i where V = rms voltage, I = rms current

6.2.2 A.C. Circuit with only one element-inductance

Figure 6.2 shows an a.c. circuit with pure inductance of L Henry

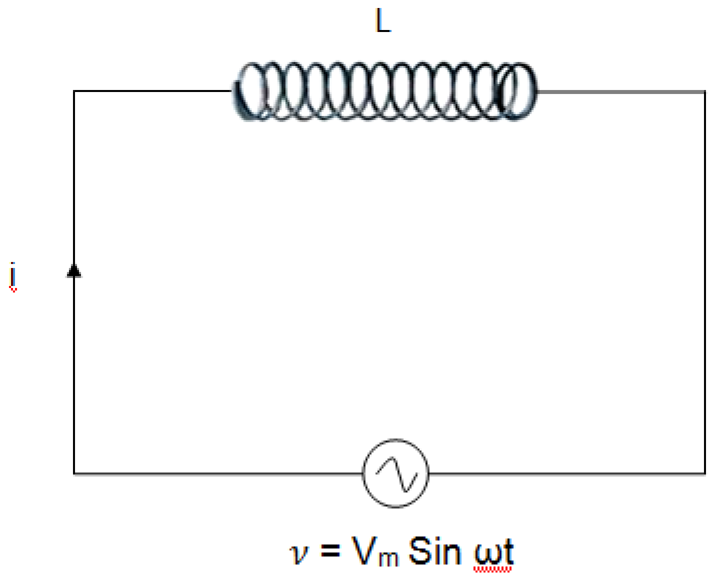


Fig. 6.2 A.C. Circuit with only one element-Inductance

The sinusoidal voltage can be given as

$$\nu = V_m Sin\ \omega t$$

The e.m.f in the coil due to the current I flowing in the circuit can be given as

$$E = L\frac{di}{dt} \ldots \ldots (2)$$

The induced e.m.f is also called e.m.f opposes the change of current in the coil .Back e.m.f. induced in the coil is equal and opposite of the applied voltage. Thus equation

$$L\frac{di}{dt} = V_m Sin\ \omega t$$

Integrating

$$i = \frac{V_m}{L}\int Sin\ \omega t\ dt$$

$$= \frac{V_m}{\omega L}\ (-\cos\ \omega t)$$

$$i = \frac{V_m}{\omega L}\sin\left(\omega t - \frac{\pi}{2}\right) \ldots \ldots \ldots \ldots \ldots . . (3)$$

i will be maximum when value of $(\sin \omega t - \frac{\pi}{2})$ is one $[\sin\left(\omega t - \frac{\pi}{2}\right) = 1]$

$$I_m = \frac{V_m}{\omega L} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

$$\omega L = \frac{V_m}{I_m}$$

In the above equation

ωL is also known as inductive reactance X_L of the coil.

ω =angular velocity
f =frequency in hertz
L =inductance in henry
X_L=inductive reactance in Ω (ohms)

Note: X_L is the opposition offered by pure inductance to the flow of an alternating current

From equation (3) and (4) we have

$$i = I_m \sin\left(\omega t - \frac{\pi}{2}\right) \dots\dots\dots\dots\dots\dots\dots (5)$$

From equation (1) and (5) it can be seen that current in a inductive circuit lags behind the voltage by $\frac{\pi}{2}$ radians or 90^c.It is well represented in the phasor diagram shown in fig. 6.3

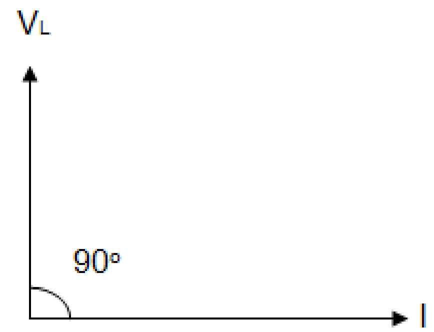


Fig. 6.3 Phasor diagram for current and voltage in an inductive circuit

Power

Instantaneous power p = v i

$$= V_m Sin\ \omega t \times I_m Sin(\omega t - \frac{\pi}{2})$$

$$= V_m I_m Sin\omega t . Cos\omega t$$

$$p = \frac{V_m I_m}{2} \text{Sin } 2\ \omega t$$

Average power consumed over one cycle

$$p = average\ of\ \frac{V_m I_m}{2} \sin 2\ \omega t$$

$$p = 0$$

This shows that power absorbed in a circuit having only inductance element is zero

6.2.3 A.C. circuit with only one element- capacitance

Fig. 6.4 Shows a circuit with capacitance C farads

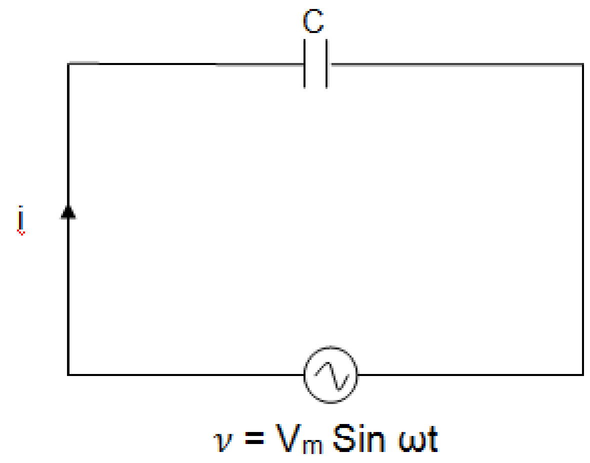


Fig. 6.4 Circuit with capacitance C farads

The value of alternating voltage is given as

$\nu = V_m Sin\ \omega t$

The charge on the capacitor q=c ν

$$= CV_m Sin\omega t$$

The current in the circuit is

$$i = \frac{d(q)}{dt}$$
$$= \frac{d(C\ V_m \sin\ \omega t)}{dt}$$

$$= \omega CV_m Cos\ \omega t$$

$$i = \frac{1}{\omega C} V_m Sin\left(\omega t + \frac{\pi}{2}\right)$$

$\frac{1}{\omega c}$ *can be written as capacitive reactance. It measures in ohms*

$i = \frac{1}{Xc} V_m\ Sin\left(\omega t + \frac{\pi}{2}\right) \dots \dots \dots . (1)$

The value of the current will be maximum when sin $(\omega t + \frac{\pi}{2}) = 1$

$I_m = \frac{V_m}{Xc}$

From equation (1)

$i = I_m Sin(\omega t + \frac{\pi}{2})$

This equation shows that in a circuit with capacitance as an only element, the current leads the voltage by 90° (Fig. 6.5)

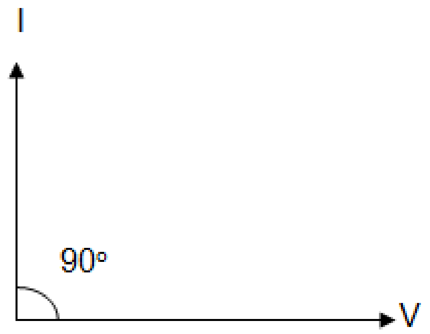


Fig. 6.5 Current leads the voltage by 90° in a circuit with capacitance

Power

Instantaneous power is given by

$$p = v\, i$$

$$= V_m Sin\ \omega t \times I_m Sin\left(\omega t + \frac{\pi}{2}\right)$$

$$= V_m I_m Sin\omega t . Cos\omega t$$

$$p = \frac{V_m I_m}{2}\ Sin\ 2\ \omega t$$

The average power over one complete cycle is p = Zero

The power absorbed in a circuit with pure capacitance is zero.

6.3 A.C. Series Circuit

There are three major types of circuit as follows

1. R-L Series Circuit
2. R-C Series Circuit
3. R-L-C Series circuit

6.3.1 R-L series circuit

Figure 6.6 shows a pure resistance and inductance connected in series

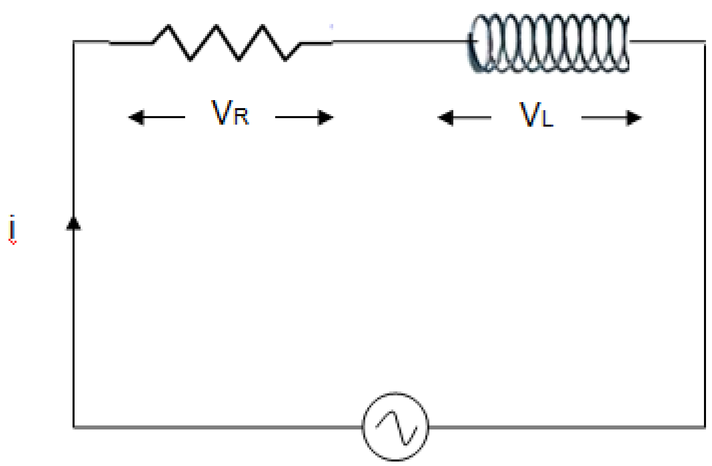


Fig. 6.6 A.C. circuit with series resistance and inductance

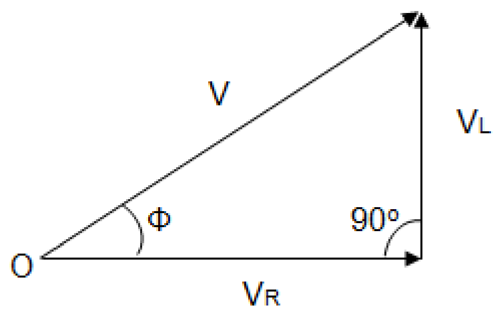


Fig. 6.7 Phasor diagram for a.c. series circuit

From the phasor diagram

$$V^2 = (V_R)^2 + (V_L)^2$$

$$V = \sqrt{V_R^2 + V_L^2}$$

$$= \sqrt{(IR)^2 + (IX_L)^2}$$

$$= I\sqrt{R^2 + X_L^2}$$

$$V = I.Z$$

Here,

V = r.m.s value of applied voltage

I = r.m.s. value of current

V_R = voltage drop across R = IR

V_L = voltage drop across L = IX_L

Z = Impedance of the circuit and it is measured in Ω ohms

$$tan\ \phi = \frac{V_L}{V_R}$$

$$\tan \phi = \frac{IX_L}{IR} = \frac{X_L}{R}$$

$$\phi = tan^{-1}\frac{X_L}{R}$$

Here ϕ is known as phase angle

Voltage leads current by ϕ angle. In other words it can be said that current lags voltage by ϕ angle. Figure 6.8 shows the impedance triangle

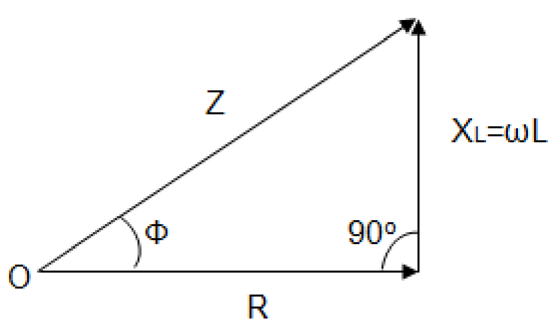


Fig. 6.8 Impedence triangle for a.c. series circuit

Impedance $Z = \sqrt{R^2 + X_L^2}$

$$Power\ factor = \cos\phi = \frac{R}{Z}$$

Here, Z = Impedance and R = Resistance

X_L=Inductive reactance

ϕ = Phase angle

Cos ϕ = power factor of the circuit

Power P= VI Cos ϕ

= (Z.I) ICos ϕ

$$= ZI^2\frac{R}{Z}$$

$P = I^2R$

In a series R-L Circuit power is consumed in resistance only. Inductance consumes zero power. The unit of power is watt.

6.3.2 R-C series circuit

Fig. 6.9 shows a pure resistance and capacitance connected in series.

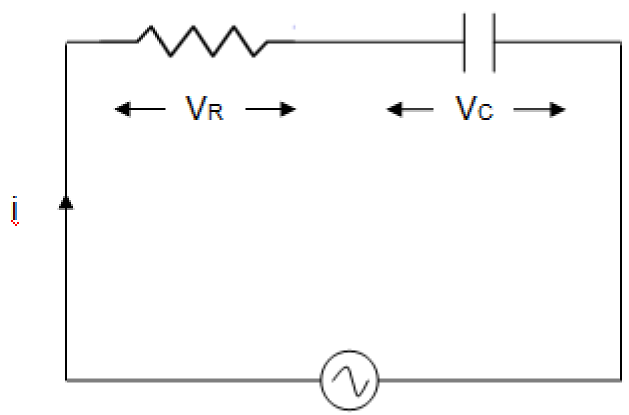


Fig. 6.9 A.C. circuit with series resistance and capacitance

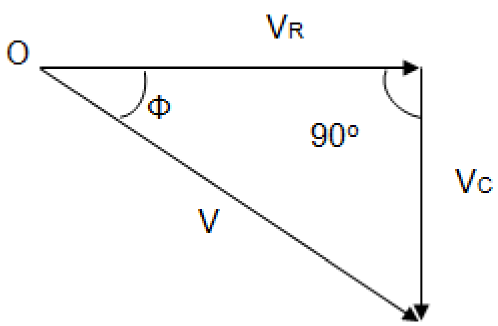


Fig. 6.10 Phasor diagram for a.c. series resistance and capacitance circuit

From the phasor diagram figure 6.10

$V^2 = (V_R)^2 + (-V_C)^2$

$$V = \sqrt{V_R^2 + V_C^2}$$
$$= \sqrt{(IR)^2 + (IX_C)^2}$$
$$= I\sqrt{R^2 + X_c^2}$$
$$V = I.Z$$

Here,

V = r.m.s value of applied voltage

I = r.m.s. value of current

V_R = Voltage drop across R = IR

V_C = Voltage drop across C = IX_C

Z = Impedance of the circuit and it is measured in ohms

$$tan\ \phi = \frac{V_C}{V_R}$$
$$\tan\phi = \frac{IX_C}{IR} = \frac{X_C}{R}$$
$$\phi = tan^{-1}\frac{X_C}{R}$$

Here ϕ is known as phase angle.

Current leads voltage by ϕ angle. In other word can be said that voltage lags current by ϕ angle. The figure 6.11 shows the impedance triangle.

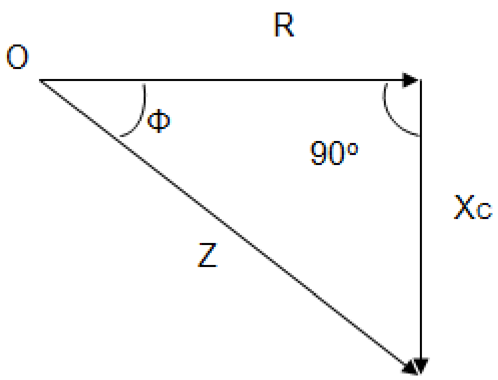


Fig. 6.11 Impedance triangle for a.c. series circuit

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

Power factor = $\cos\phi = \frac{R}{Z}$

Here, Z = Impedance and R=Resistance

X_C = Capacitive reactance

$Cos\ \phi$ = Power factor of circuit

C = Capacitance

$X_C = \frac{1}{\omega C}$ = Capacitive reactance

Power P = VICosϕ

Here,

V = r.m.s value of applied voltage

I = r.m.s. value of current

$Cos\ \phi$ = Power factor of circuit

6.3.3 R-L-C series circuit

When a pure resistance R ohms, pure inductance L Henry and pure capacitor of capacitance C farad are connected in series it is known as R-L-C Series Circuit.

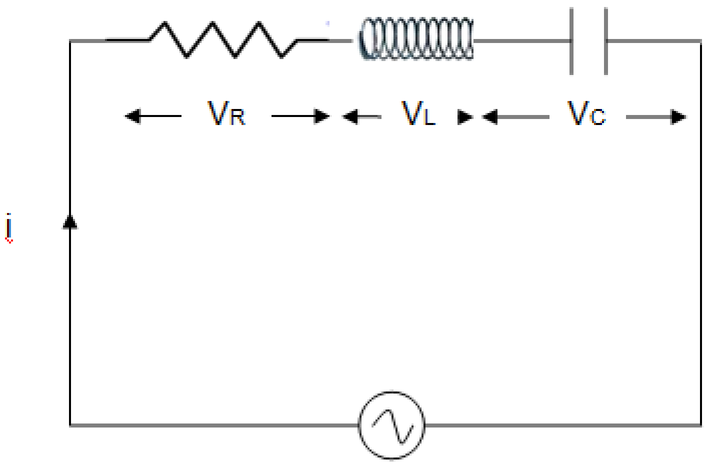


Fig. 6.12 A.C. series circuit for resistance, inductance and capacitance

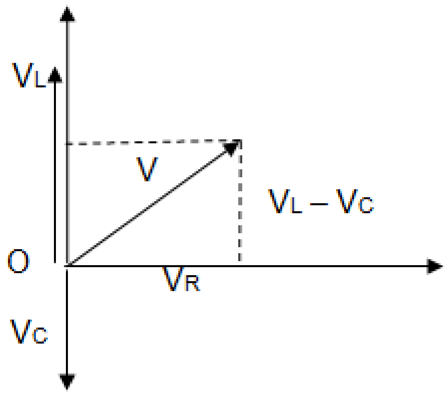


Fig. 6.13 Phasor diagram for resistance, inductance and capacitance series circuit

The voltage drop across each element is given as:

a) Resistance (R) = V_R = IR (in phase with current I)

b) Inductance (L) = $V_L = IX_L$ (leads current by 90°)

c) Capacitance (C) = $V_C = I.X_C$(lags current by 90°)

In the phasor diagram V_L is leading current I by 90° and V_C is lagging current by 90°. So it is evident that V_L and V_C are at 180° to each other. In technical terms it is said to be 180° out of phase with each other. The circuit will behave like inductive or capacitive manner depending upon voltage drop V_L or V_C w.r.t current I.

From the phasor diagram:

$$V = \sqrt{V_R^2 + (V_L - V_C)^2}$$

$$= \sqrt{(IR)^2 + (IX_L - IX_C)^2}$$

$$= I\sqrt{R^2 + (X_L - X_C)^2}$$

$$V = I.Z$$

Where

Z = Impedance of the circuit which offers opposition to current flow

Phase Angle

Again from the phasor diagram

$$\tan\phi = \frac{V_L - V_C}{V_R}$$

$$\tan\phi = \frac{X_L - X_C}{R}$$

$$\phi = \tan^{-1}\frac{X_L - X_C}{R}$$

Power factor:

$$\cos\phi = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + (X_L - X_C)^2}}$$

Three cases of R-L-C Series Circuit

The equation for impedance is given as:

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

Case 1: When $X_L > X_C$

- The term (X_L-X_C) is positive.
- The circuit works as an R-L Series Circuit.
- Current lags behind voltage.
- Phase angle is positive.
- Power angle is positive.
- Power factor is lagging.
- Current flowing in circuit i,

$$i = I_m Sin(\omega t - \phi)$$

Case 2: When $X_C > X_L$

- The term (X_L-X_C) is negative.
- The circuit works as an R-C Series Circuit.
- Current leads over voltage.
- Phase angle is negative.
- Power factor is negative.

- The current flowing in the circuit i,

$$i = I_m Sin(\omega t + \phi)$$

Case 3: When $X_L = X_C$

- The term $(X_L - X_C) = 0$.
- The circuit works as pure resistance.
- Current is in phase with voltage.
- Phase angle is Zero.
- Power factor = 1.
- The current flowing in the circuit i,

$$i = I_m Sin\ \omega t$$

6.4 True Power and Reactive Power

Table 6.1 Power in the electrical circuit

		Formula	**Units**
1. True power	• Power consumed by watt meter • Is the useful work and the current is in phase with the voltage • Is the power consumed by resistance • It is also known as active power	$P_{True} = V \times I\ Cos\phi$	Watts
2. Reactive power	• Power consumed in L or C in a circuit is zero but the circulating power is termed as reactive power • Does no useful work and current is 90^o out of phase with voltage. • Reactive power cannot be measured by wattmeter.	$P_{Reac} = V \times I\ Sin\phi$	VAR
3. Apparent power	• It is defined as the product of Voltage and Current	$P_{apparent} = VI$	VA

6.5 Power Triangle

Figure 6.14 shows the power triangle for an A.C. circuit.

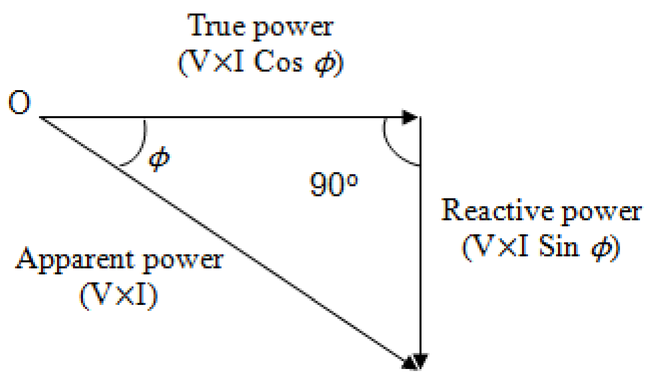


Fig. 6.14 Power triangle for an A.C. circuit

True power $P_{True} = V \times I \cos \phi$

Reactive Power $P_{Reac} = V \times I \sin \phi$

Apparent power $P_{app} = VI$

$$P_{app}^2 = P_{True}^2 + P_{reac}^2$$

From power triangle

$$Cos\ \phi = \frac{\text{True power}}{\text{Apparent power}}$$

6.6 A.C. Parallel Circuits

In a.c. circuits R, L and C are connected in parallel. Voltage across each element is same but the current flowing through it is different. Equipments, lights and circuits are connected and operated in parallel. Parallel connection gives advantage that each equipment, appliance or device can be operated independently having separate switches for on/off. Parallel circuits are analysed using following methods:

1. Phasor diagram
2. Admittance method
3. Symbolic methods

Numerical

1. A coil of R = 100 ohm and L = 125 milli Henry is connected across alternating voltage e = 250 sin 100πt. Determine:

a. Impedance
b. Current through the coil

Solution:

$2\pi ft = 100\pi t$

$f = 50$ Hz

Inductive reactance $X_L = \omega L$

$= 2\pi fL$

$= 2\pi 50 \times 125 \times 10^{-3}$

$= 39.25$ ohm

Impedance Z = $\sqrt{R^2 + X_L^2}$

$$Z = \sqrt{100^2 + 39.25^2}$$

Z = 107. 42 ohm

Current through coil I = e_m/Z

= 250/107.42 = 2.32 A

2. A resistance of 50 ohm and capacitor of 200 µF are connected across 220 V, 50 Hz voltage supply. Determine:

a. **Impedance**
b. **Current through the coil**
c. **Power factor**

Capacitive reactance = $X_C = \frac{1}{\omega C} = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 200 \times 10^{-6}}$ = 15.92 ohm

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

$$Z = \sqrt{50^2 + 15.92^2}$$

Z = 52. 47 ohm

Current I = V/Z = 220/52.47 = 4.19 A

Power factor Cos ϕ = R/Z = 50/52.47 = 0.953 leading

3. A resistance of 50 ohm, inductance 75 mH and capacitor of 25 µF are connected across 220 V, 50 Hz voltage supply. Determine:

a. **Impedance**
b. **Current through the coil**
c. **Power factor**

Inductive reactance $X_L = \omega L$

$= 2\pi fL$

$= 2\pi x50x75x\ 10^{-3}$

= 23.55 ohm

Capacitive reactance = $X_C = \frac{1}{\omega C} = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 25 \times 10^{-6}}$ = 127.38 ohm

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

$Z = \sqrt{50^2 + (127.38 - 23.55)^2}$

Z = 115.24 ohm

Current I = V/Z = 220/115.24 = 1.9 A

Power factor Cos $\phi = R/Z = 50/115.24 = 0.433$ leading

Lesson 7

CONCEPT OF RESONANCE

7.1 Introduction

An RLC circuit (or LCR circuit) is an electrical circuit consisting of a resistor, an inductor, and a capacitor, connected in series or in parallel. The RLC part of the name is due to those letters being the usual electrical symbols for resistance, inductance and capacitance respectively. The circuit forms a harmonic oscillator for current and will resonate at resonant frequency.

7.2 Concept of Resonance in Series Circuit

The resonance frequency is defined as the frequency at which the impedance of the circuit is at a minimum. Equivalently, it can be defined as the frequency at which the impedance is purely real (that is, purely resistive). This occurs because the impedance (reactance) of the inductor and capacitor at resonance are equal but of opposite sign and cancel out. Thus in a R-L-C series circuit, when the value of the inductance is equal to the capacitance i.e. $X_L = X_C$, the circuit is said to be in resonance. For a circuit the value of X_L and X_C is given as follows:

$$X_L = 2\pi fL$$

Where

f = frequency

L = Inductance Units Henry

$$X_C = \frac{1}{2\pi fc}$$

where

f = frequency

C = Capacitance unit Farad

At resonant frequency (f_r) $X_L = X_C$

i.e., $2\pi f_r L = \frac{1}{2\pi f_r C}$

$$\text{Resonant frequency} = \frac{1}{2\pi\sqrt{LC}}$$

7.2.1 Resonance curve

Resonance curve is plotted between current and frequency. For R-L-C series circuit current approaches maximum value at the resonant frequency (f_r) and declines abruptly on either side at that point. It is so due to following reason (Table 7.1):

Table 7.1 Variation in current with frequency

Condition		Circuit Impedance (Z)	

Frequency < Resonating frequency	$X_C > X_L$	Z > R	Rapid decrease in current
Frequency > Resonating frequency	$X_L > X_C$	Z > R	Rapid decrease in current
Frequency = Resonating frequency	$X_L = X_C$	Z ≈ R Z is minimum	Rapid increase in current

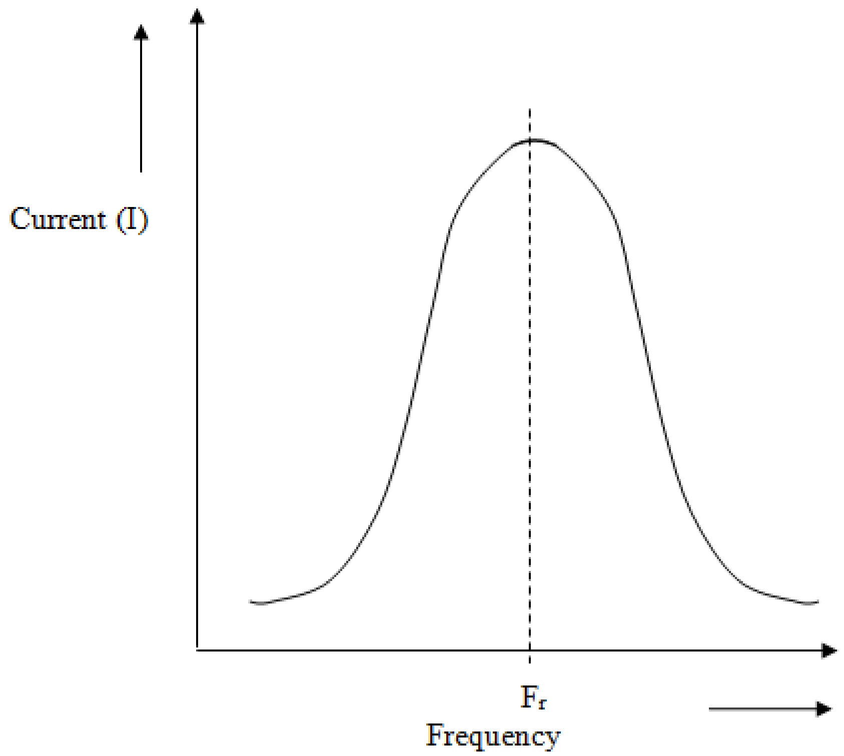


Fig 7.1 Resonance curve

The resonance curve has a shape of dome because magnitude of circuit current decreases rapidly as the frequency varies from the resonant frequency.

Sharpness of resonance: The narrowness of the frequency band around the resonance at which the response of an electric circuit exceeds an arbitrary fraction of its maximum response, often 70.7%.

Selectivity: The selectivity of the circuit is a measure of its ability to reject any frequencies either side of these points. A more selective circuit will have a narrower bandwidth whereas a less selective circuit will have a wider bandwidth. The selectivity of a series resonance circuit can be controlled by adjusting the value of the resistance only, keeping all the other components the same.

7.2.2 Q-factor

Q-factor gives the degree of current change with frequency above and below resonance. A R-L-C circuit is used to discriminate between frequencies. In other words Q-factor or quality factor is the ability to discriminate different frequencies.

$$Q - \text{Factor} = \frac{\text{Voltage across L or C}}{\text{Applied voltage}}$$

$$Q - \text{factor} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Resonant circuits are used to respond selectively to signals of a given frequency while discriminating against signals of different frequencies. If the response of the circuit is more narrowly peaked around the chosen frequency, we say that the circuit has higher "selectivity". A "quality factor" Q, as described below, is a measure of that selectivity, and we speak of a circuit having a "high Q" if it is more narrowly selective.

An example of the application of resonant circuits is the selection of AM radio stations by the radio receiver. The selectivity of the tuning must be high enough to discriminate

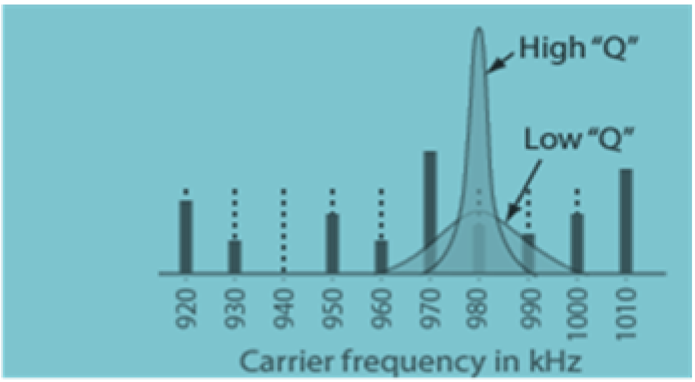


Fig 7.2 Q-factor

Q-factor depends entirely upon design of coil (i.e. R-L part of the R-L-C circuit) because resistance arises in this rather than in a capacitor.

7.3 Concept of Resonance in Parallel Circuit

"Parallel resonant circuit" comprises of a capacitor (C) connected in parallel with an inductive coil having a resistance R and inductance L which in combination is connected across an a.c. supply.

Consider a parallel resonant circuit with following elements:

a. L = Coil Inductance
b. R = Coil resistance. (usually very small and is neglected compared to other impedances)
c. C = Capacitance (assumed to be loss less)
d. Variable frequency a.c. source

Here a coil (L) and capacitor (C) are connected in parallel with an AC power supply. Let R be the internal resistance of the coil. When X_L equals X_C, the reactive branch currents are equal and opposite. Hence they cancel out each other to give minimum current in the main line. Since total current is minimum, in this state the total impedance is maximum. Resonant frequency given by:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

If R is negligible then,

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Note that any reactive branch current is not minimum at resonance, but each is given separately by dividing source voltage (V) by reactance (Z). Hence I=V/Z, as per Ohm's law.

- At f_r, line current is minimum. Total impedance is maximum. In this state a circuit is called a *rejector circuit*.
- Below f_r, circuit is inductive.
- Above f_r,circuit is capacitive.

Like series resonant circuit, the resonance in a parallel resonant circuit will occur, when the power factor of the entire circuit becomes unity.

7.4 Comparison of Series and Parallel Resonant Circuits

Table 7.2 Comparison of series and parallel resonant circuits

		Series Circuit	Parallel Circuit
1.	Connection	R-L-C series connection across a.c. supply	R-L and C connected in parallel across a.c. supply.
2.	Circuit current at resonance	Maximum	Minimum
3.	Impedance at resonance	Minimum (Z = R)	Maximum (Z=L/CR)
4.	Magnification	Voltage	Current
5.	Power factor at resonance	Unity	Unity

7.5 Application of R-L-C Circuit

1. They are used in many different types of oscillator circuit.
2. Variable tuned circuits: A very frequent use of these circuits is in the tuning circuits of analogue radios. Adjustable tuning is commonly achieved with a parallel plate variable capacitor which allows the value of C to be changed and tune to stations on different frequencies.
3. Signal Filters: Can be used to filter a signal by blocking certain frequencies and passing others.
4. Voltage multiplier
5. Pulse discharge circuits

7.6 Applications of Resonance Effect

1. Most common application is tuning. For example, when we tune a radio to a particular station, the LC circuits are set at resonance for that particular carrier frequency.
2. A series resonant circuit provides voltage magnification.
3. A parallel resonant circuit provides current magnification.
4. A parallel resonant circuit can be used as load impedance in output circuits of RF amplifiers. Due to high impedance, the gain of amplifier is maximum at resonant frequency.
5. Both parallel and series resonant circuits are used in induction heating.

Numericals

1. Calculate the resonant frequency for a R-L-C series circuit having L = 25 mH and C = 30μF.

$$\text{Resonant frequency} = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{25\times10^{-3}\times30\times10^{-6}}} \qquad = 184 \text{ Hz}$$

2. Calculate the resonant frequency for a R-L-C series circuit having L = 30 mH and C = 50 μF. Also calculate band width of the circuit if Q-factor is 50.

$$\text{Resonant frequency} = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{30\times10^{-3}\times50\times10^{-6}}} \qquad = 130 \text{ Hz}$$

Q = fr/BW

BW = fr/Q = 130/50 = 2.6 Hz

Lesson 8

POLYPHASE ALTERNATING CURRENT CIRCUITS

8.1 Introduction

In domestic supply line comprise mostly of single phase electricity. Home appliances like T.V., refrigerator, washing machines are designed to be operated by single phase alternating current. But for individual use where heavy duty machines have to be operated single phase current is not sufficient. There polyphase a.c. is needed to run in plant and machinery. Polyphase means a.c. will have two or more than two phases. Generally 3 phase (also denoted as 3ϕ) alternating systems are employed in the industry.

8.2 Polyphase Systems

8.2.1 Single phase

A generator with one armature winding involves a single phase alternating current. The instantaneous value of emf induced in the eq. is given as

$$e_{a1a2} = E_m.\ \text{Sin}\ (\omega t)$$

8.2.2 Two phase

A two phase alternative (generator) has two windings and the angle between them is 90^o. As a result the phase difference between the two alternating voltages is 90^o. And since the number of turns in the two windings are same the magnitude of e.m.f generated and frequency is same in both the windings. The instantaneous value of e.m.f induced in the two coils is given as:

$$e_{a1a2} = E_m\ \text{Sin}\ \omega t$$

$$e_{a1a2} = E_m \sin(\omega t - 90^o) \text{ or } Em \sin(\omega t - \pi/2)$$

8.2.3 Three phase

A three phase system has three windings in the alternator. The windings are placed such that the angle between them is 120^o (Fig. 8.1). Since the windings are identical the magnitude and frequency of alternating voltage is same for all the three windings. The instantaneous value of e.m.f. indicates in the three windings are given as:

$$e_{a1a2} = E_m\ \text{Sin}\ \omega t$$

$$e_{b1b2} = E_m\ \text{Sin}\ (\omega t - 120^o) \text{ or } E_m\ \text{Sin}\ (\omega t\text{-}\ 2\pi/3)$$

$$e_{c1c2} = E_m\ \text{Sin}\ (\omega t\text{-}240^o) \text{ or } E_m\ \text{Sin}\ (\omega t\text{-}\ 4\pi/3)$$

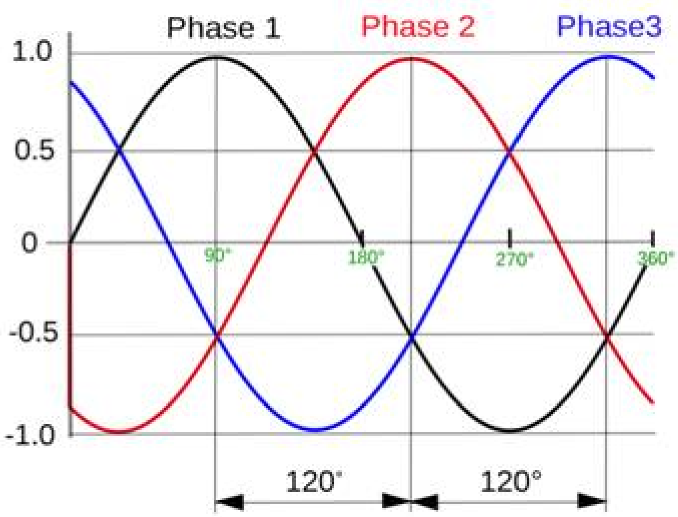


Fig. 8.1 Wave form of three phase system

8.3 Comparison of Three phase and Single Phase System

Table 8.1 Comparison of three phase and single phase system

		3ϕ System	**Single ϕ System**
1.	Transmission line distribution and voltage regulation	Better	Poor
2.	Transmission line conductor (wire) requirement for distribution	Less (Only 75% of what is received for single ϕ system)	More
3.	Vibration due to electrical loads (e.g. motors)	Low	High
4.	Electrical Machine (e.g. motors, generators, transformers etc.)		
	a. Size	Small	Bulky
	b. Construction	Simple	Complex
	c. Performance	Better	Average
	d. Cost	Cheaper	Expensive than 3ϕ
	e. Efficiency	High	Low
	f. Power factor of motor	High (0.7 to 0.8)	Low (0.5)
	g. Starting of motors	Self Starting	Not self starting

8.4 Power Sequence

In a poly phase system, the order in which the phases attain the maximum voltages (emf) is called as phase sequence. Maximum voltage or emf is attained in the phase sequence of $a_1a_2 \rightarrow b_1b_2 \rightarrow c_1c_2$. If the direction notation is reversed then the new phase sequence will be $c_1c_2 \rightarrow b_1b_2 \rightarrow a_1a_2$.

Note: In 3ϕ induction motor, the direction of rotation depends on phase sequence of the applied voltage. Direction of the rotation can be reversed by interchanging any two lines.

8.5 Numbering of Phases

The phases can be numbered in three methods according to the phase sequence of system.

a) By numbering 1, 2, 3

b) By alphabetically a, b, c

c) Colour code (R, Y, B) where R = Red, Y = Yellow, B = Blue

+ ve phase sequence = RYB

- ve phase sequence = RBY or BYR or YRB

8.6 Double Subscript Notation

Voltages in the 3ϕ systems can be denoted using two subscripts. The two subscripts are the two points between which the voltage or current is being considered. The sequence of subscript gives the direction in which voltage is denoting or current is flowing.

Example

V_{RY} – It denotes the voltage between points RY and the positive direction of voltage from R to Y.

I_{RY} – It denotes the current flowing from point R towards point Y.

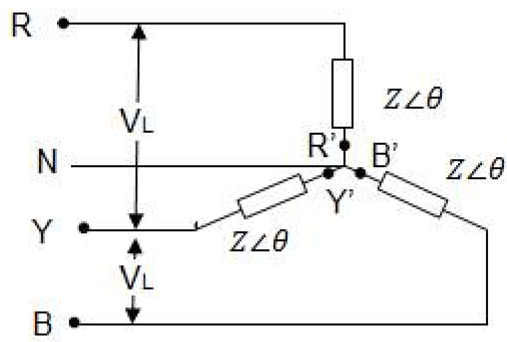
8.7 Inter Connection of Three Phases

Let us first understand the construction of a 3ϕ alternator. It comprises of two main parts stator and rotor. Stator is the stationary part of the alternator. Stator have three windings. Winding has two terminal marked on start and finish. A total of six wires will be required to connect the alternator (two for each winding). The type of connection is very expensive and complex. Instead these six terminals are connected by any of the two methods.

1. Star or wye (Y) connection (Fig 8.2)
2. Mesh or delta (Δ) connection (Fig 8.3)

8.7.1 Star or wye (Y) connection

Here the similar ends (either start or finish) are connected at a point. This point is known as star or neutral point (N). Line conductors are commonly called by colour code R (Red), Y (Yellow) and B (Blue) and are shown in Fig 8.1. as RR′, YY′ and BB′. They can also be sequenced as a,b,c or 123.



8.2 Star or Y connection

- Neutral connection: - The wire joining neutral point N is known as neutral connection.
- Phase voltage: - As the name suggests it is the voltage measured between any line and Neutral (N) is known as phase voltage (V_{ph}). Since the coils are held at 120^0.
- Line voltage: - It is the voltage existing between any two phase winding or phases (V_{ph}).

$$\text{Line voltage} = \sqrt{3} \times \text{phase voltage}$$

- Phase current: - Current flowing through any winding or phase is known as phase current.

- Line current: - Current flowing through any line is known as line current.

For star connection line current = phase current

Note: Star connection is also known as 3 phase 4 wire system. In case neutral wire in not there, it may be called as $3\phi 3$ wire system.

Power

Output power per phase = $V_{ph}\ I_{ph}\ Cos\phi$

Total output power = 3 $V_{ph}\ I_{ph}\ Cos\phi$

since $V_L = \sqrt{3}\ V_{ph}$

$I_{ph} = I_L$

$\therefore$ Total output power = $\sqrt{3}\ V_L\ I_L\ Cos\phi$

Where

V_{ph} = Phase voltage

I_{ph} = Phase current

V_L = Line voltage

I_L = Line current

$Cos\phi$ = Power factor

P = Power

8.7.2 Delta or mesh connection

In delta or Mesh connection the three windings are connected in series pattern (Fig. 8.3). The connections are made in the following way:

Start of winding $a_1 \rightarrow$ Finish terminal of winding c_2

Start of winding $b_1 \rightarrow$ Finish terminal of winding a_2

Start of winding $c_1 \rightarrow$ Finish terminal of winding b_2

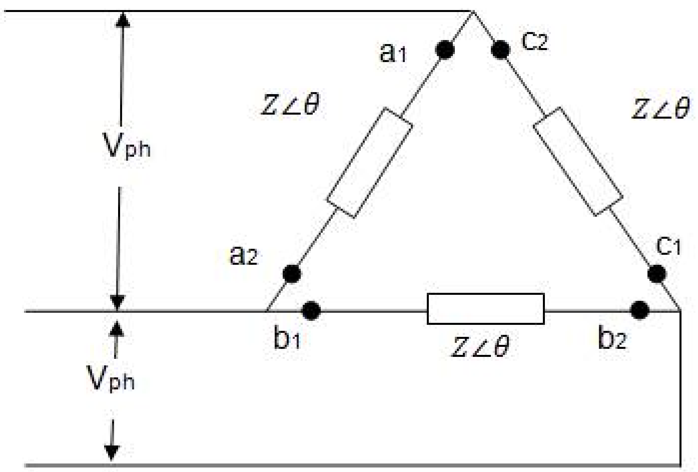


Fig. 8.3 Delta or mesh connection

- Phase voltage – The voltage measured in windings or phases is known as phase voltage.
- In Mesh or Delta Δ connection

Line voltage (V_L) = Phase voltage (V_{ph})

- Phase current – Is the current flowing through any winding or phase.
- Line current – Is the current flowing through any line. For Δ connection:

Line current (I_L) = $\sqrt{3}\, I_{ph}$

Where

I_{ph} = phase current

Power

Output power per phase = $V_{ph}\, I_{ph} \cos\phi$

For balanced load,

Total power $P = 3\, V_{ph}\, I_{ph} \cos\phi$

Since $V_{ph} = V_L$ and $I_L = \sqrt{3}\, I_{ph}$

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

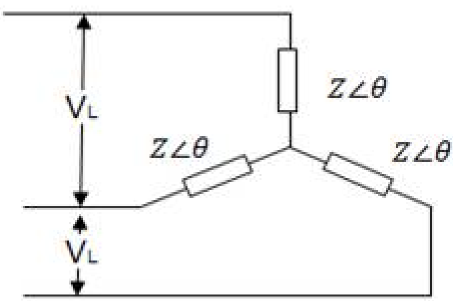
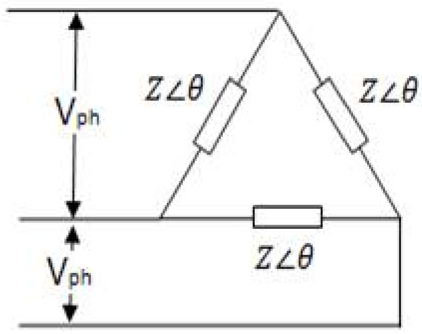
True power $P = \sqrt{3}\, V_L\, I_L \cos\phi$ units Watts (W) or kilowatts (kW)

Apparent power $P_{app} = \sqrt{3}\, V_L\, I_L$ units VA or kVA

Reactive power $P_{rec} = \sqrt{3}\, V_L\, I_L \sin\phi$ units VAR or kVAR

8.8 Differences Between Star(Y) and Delta(Δ) Connection

Table 8.2 Differences between star(Y) and delta (Δ) connection

Star (Y)	**Delta (Δ)**
1. Structure 	1. Structure 
2. Winding are connected by joining similar ends	2. Windings are connected by joining dissimilar ends
3. 3ϕ 4 wire system is possible	3. Only 3ϕ 3 wire system possible
4. Provision for neutral	4. No neutral wire
5. Line voltage $V_L = \sqrt{3}\, V_{ph}$ Where, V_{ph} = Phase voltage	5. Line voltage V_L = Phase voltage V_{ph}
6. Line current I_L = Phase current I_{ph}	6. Line current $I_L = \sqrt{3}\, I_{ph}$ Where, I_{ph} = phase current
7. Line voltage are at phase difference of 120^0	7. Lines current are at phase difference of 120^0.
8. Alternators are generally designed as 3 ϕ star system because of following	8. Alternators are not generally connected as Delta system.

reason i. Less insulation requirement ii. Require less number of turns in the winding	

Numericals

1. Calculate line voltage of Y-system if phase voltage is 340 V.

$V_L = \sqrt{3}\ V_{ph}$

$V_L = \sqrt{3}$ X 340

V_L = 588.89 V

2. Calculate line current of Δ-system if phase current is 25 A.

$I_L = \sqrt{3}\ I_{ph}$

$I_L = \sqrt{3}$ X 25

I_L = 43.3 A

3. Calculate total power in a Y-system if line voltage and line current is 440 V and 25 A respectively. Consider power factor as 0.65.

Total output power = $\sqrt{3}\ V_L\ I_L\ \text{Cos}\phi$

= $\sqrt{3}$ X 440 X 25 X 0.65

= 12.38 kW

4. For a star connected system calculate the line voltage and output power if phase voltage = 410 v and line current is 7.5 A. Take power factor as 0.86.

Solution

Given

V_{ph} = 410 v

I_L = 7.5 A

Cos Φ = 0.86

$V_L = \sqrt{3}\ V_{ph}$

$= \sqrt{3}\ V_{ph}$

= 710.14 v

Total outer power = $= \sqrt{3}\ V_L I_L \cos\emptyset$

$= \sqrt{3} \times 710.14 \times 7.5 \times 0.86$

= 7933 w

5. For a data connected system calculate the line current and output power if phase voltage is 440 v and phase current is 5A. Take power factor as 0.75. Also calculate the reactive power.

Solution

V_{ph} = 440 v

$I_L = 5$ A

Cos $\Phi = 0.76$

$I_L = \sqrt{3}\ I_{ph}$

$= \sqrt{3} \times 5$

$= 8.66$ A

Output power $p = 3\ V_{ph}\ I_{ph} \cos\Phi$

$= 3 \times 440 \times 5 \times 0.75$

$P = 4950$ w

Reactive power $p_{rec} = \sqrt{3}\ V_L I_L \sin \emptyset$

$p_{rec} = 3\ V_{ph}\ I_{ph}$ Sin Φ

Cos $\Phi = 0.75$

$\Phi = 41.40°$

Sin $\Phi = 0.661$

$P_{rec} = 3 \times 440 \times 5 \times 0.661$

$= 4362.6$ W

Lesson 9

STAR DELTA TRANSFORMATION

9.1 Transformations

Alternating voltage and current can be shown using phasor diagram. The problems can be analysed by using following two mathematical forms:

9.1.1 Rectangular form

Consider a voltage phasor V. The magnitude of the phasor is V and having θ angle from reference line OX.

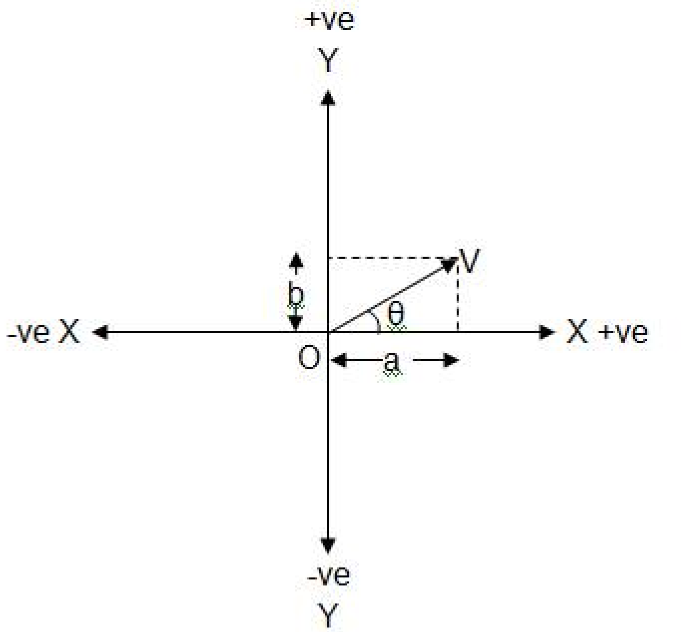


Fig. 9.1 Voltage phasor denoted by OV

Voltage phasor V = a + jb

Magnitude of phasor $V = \sqrt{a^2 + b^2}$

$\theta = \tan^{-1}(b/a)$

9.1.2 Polar form

In polar form the phasor can be represented by the magnitude and the angle with the reference axis.

$$V = V\angle\ \theta°$$

9.2 Conversion Methods

1. To convert Rectangular to polar form:

   Rectangular form V = a + jb

   $$V = \sqrt{a^2 + b^2}$$
   $$\theta = \tan^{-1}(b/a)$$

   Polar form = V ∠ θ°

2. To convert Polar to Rectangular form:

   Rectangular form = V ∠ θ°

   $$a = V\cos\theta$$

$b = V \sin\theta$

Polar form = a + jb

9.3 Numerical

Q.1 Convert 100 + j 50 to polar form:

Magnitude = $\sqrt{100^2 + 50^2}$

= 111.80

Phase angle = $\tan^{-1} 50/100$

= 26.56°

Polar form = 111.80∠ 26.56°

Q.2 Convert 100∠ 14.47° to rectangular form.

$a = V \cos\theta$

= 100 cos14.47°

= 96.82

$b = V \sin\theta$

=100 sin 14.47°

= 25

Rectangular form = 96.82 + j25

Q.3 Convert 200−j50 and −25−j20 into polar forms.

1. 200-j50 into polar

Magnitude = $\sqrt{200^2 + (-50)^2}$

= 206.15

Phase angle $= \tan^{-1} b/a$

$= \tan^{-1}(-50/100)$

= −14.03°

Polar form = 206.15∠−14.03°

2. −25−j20 into polar

Magnitude = $\sqrt{(-25)^2 + (-20)^2}$

= 32.01

Phase angle $= \tan^{-1}(-20/-25)$

= 38.65°

Polar form = 32.01∠38.65°

9.4 Adding and Subtraction of Phasors

The rectangular form is the simplest method for addition or subtraction of Phasors. If the phasors are represented in polar form, they should be first converted to rectangular form and then addition or subtraction be carried out.

(i) Addition: For the addition of phasors in the rectangular form, the real components are added together and the complex numbers (j components) are added together. Consider two voltage phasors:

$V_1 = a_1 + jb_1$; $V_2 = a_2 + jb_2$

Resultant Voltage $V = V_1 + V_2 = (a_1 + jb_1) + (a_2 + jb_2)$

$$= (a_1 + a_2) + j(b_1 + b_2)$$

Magnitude of resultant, $V = \sqrt{(a_1 + a_2)^2 + (b_1 + b_2)^2}$

Angle from OX-axis, $\theta = \tan^{-1}\frac{(b_1+b_2)}{(a_1+a_2)}$

(ii)Subtraction is done similar to what was done in phasor addition

$$V = V_1 - V_2 = (a_1 + jb_1) - (a_2 + jb_2)$$

$$= (a_1 - a_2) + j(b_1 - b_2)$$

Magnitude of resultant voltage, $V = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$

Angle from OX-axis, $\theta = \tan^{-1}\frac{(b_1-b_2)}{(a_1-a_2)}$

9.5 Multiplication and Division of Phasors

Multiplication and division of phasor is done in polar form as the method is simpler compared to what is done in rectangular form. Consider two phasor:

$$V_1 = a_1 + jb_1 = V_1\angle\theta_1$$

$$V_2 = a_2 + jb_2 = V_2\angle\theta_2$$

9.5.1 Multiplication

(i) Rectangular form,

$$V_1 \times V_2 = (a_1 + jb_1)(a_2 + jb_2)$$

$$= a_1a_2 + ja_1b_2 + ja_2b_1 + j^2b_1b_2$$

$$= (a_1a_2 - b_1b_2) + j(a_1b_2 + a_2b_1) \qquad (\text{as } j^2 = -1)$$

Magnitude of resultant $= \sqrt{(a_1a_2 - b_1b_2)^2 + (a_1b_2 + a_2b_1)^2}$

Angle w.r.t. OX-axis, $\theta = \tan^{-1}\left(\frac{a_1b_2+a_2b_1}{a_1a_2-b_1b_2}\right)$

(ii) Polar form. To multiply the phasors that are in polar form, multiply their magnitudes and add the angles (algebraically).

$$V_1 \times V_2 = V_1\angle\theta_1 \times V_2\angle\theta_2 = V_1V_2\angle\,\theta_1 + \theta_2$$

Multiplication of phasors becomes easier when they are expressed in polar form.

9.5.2 Division

(i) Rectangular form,

$$\frac{V_1}{V_2} = \frac{a_1 + jb_1}{a_2 + jb_2}$$

$$= \frac{a_1 + jb_1}{a_2 + jb_2} \times \frac{a_2 - jb_2}{a_2 - jb_2}$$

$$= \frac{(a_1a_2 + b_1b_2) + j(b_1a_2 - a_1b_2)}{a_2^2 + b_2^2}$$

$$= \frac{a_1a_2 + b_1b_2}{a_2^2 + b_2^2} + j\frac{(b_1a_2 - a_1b_2)}{a_2^2 + b_2^2}$$

(ii) Polar Form. To divide the phasors that are in polar form, the magnitude of phasors are divided and denominator angle is subtracted from the numerator angle.

$$\frac{V_1}{V_2} = \frac{V_1\angle\theta_1}{V_2\angle\theta_2} = \frac{V_1}{V_2}\angle\theta_1 - \theta_2$$

9.6 Transformation

9.6.1 Star to delta (Y/Δ) transformation

In any electrical system a star Y connection may be replaced by an equivalent Δ-connected system. A 3-phase star system having voltage V_L and line current I_L may be replaced by a Δ-connected system having phase voltage V_L and phase current $I_L/\sqrt{3}$. Y-connected load having branch impedances each of $Z\angle\emptyset$ may be replaced by an equivalent Δ-connected load having phase impedance is $3Z\angle\emptyset$ (Fig. 1.2).

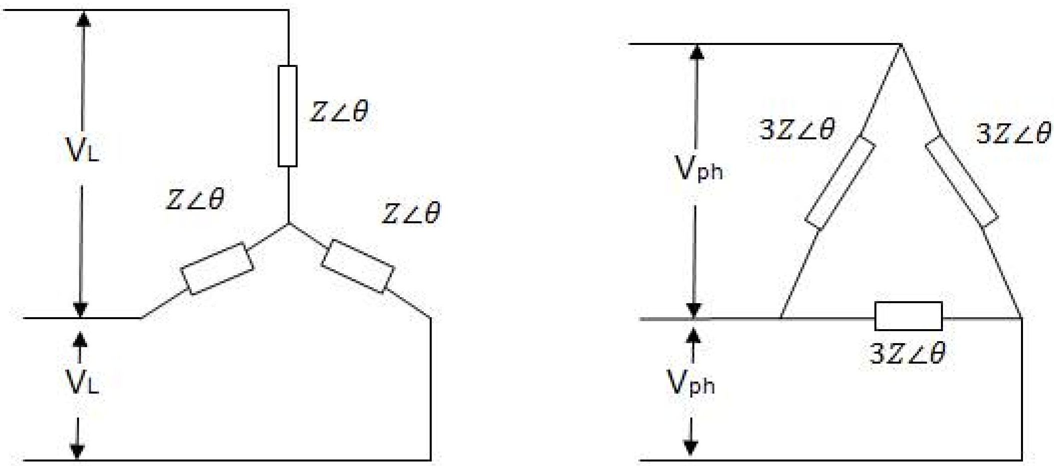


Fig. 9.2 Star to delta (Y/Δ) transformation

For a balanced star-connected load, let

V_L = line voltage;

I_L = line current;

$Z\angle\emptyset$ = impedance per phase

Then for an equivalent Δ-connected system,

Phase voltage $V_{ph} = V_L$

Phase current $I_{ph} = I_L / \sqrt{3}$

$Z_{ph} = 3Z\angle\emptyset$

$Z_Y = V_L / (\sqrt{3}\, I_L)$

9.6.2 Delta to star (Δ/Y) transformation

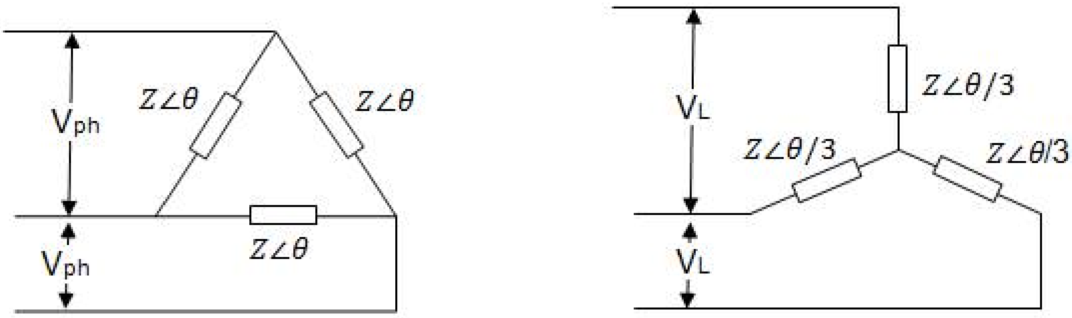


Fig. 9.3 Delta to star (Δ/Y) transformation

Now, in the equivalent Δ-connected systems, the line voltages and currents must have the same values as in the Y-connected system, hence we must have

$V_L = V_{ph}$

$I_{ph} = I_L / \sqrt{3}$

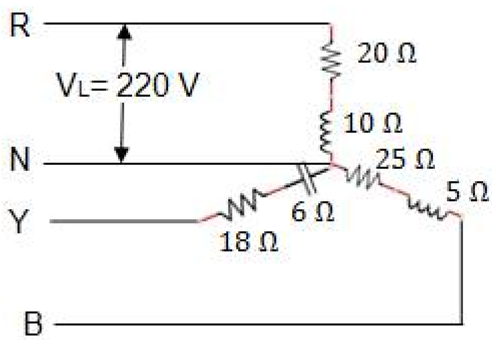
$Z_\Delta = V_L / (I_L / \sqrt{3}) = \sqrt{3}\ V_L / I_L = 3Z_Y$

$Z_\Delta \angle \emptyset = 3\ Z_Y \angle \emptyset$ $\qquad$ $(\because V_L / I_L = 3Z_Y)$

$Z_\Delta = 3\ Z_Y$ or $Z_Y = Z_\Delta / 3$

Numerical

1. A 220 V 3 phase Y connected load is shown in following diagram. The phase sequence is RYB. Calculate the line currents and neutral line current.



$Z_R = (20 + j10) = 22.36\angle 26.56^o$

$Z_Y = (18 + j6) = 18.97\angle 18.43^o$

$Z_Y = (25 + j5) = 25.49\angle 11.30^o$

Let line voltages with difference of phase angle 120^o

$V_{RN} = 220\angle 0^o$

$V_{YN} = 220\angle{-120^o}$

$V_{BN} = 220\angle{-240^o}$

Line currents:

$I_R = V_{RN}/Z_R = \frac{220\angle 0^o}{22.36\angle 26.56^o} = 9.83\angle{-26.56^o} = 8.79 - j4.39$ A

$I_Y = V_{YN}/Z_Y = \frac{220\angle{-120^o}}{18.97\angle 18.43^o} = 11.59\angle{-138.43^o} = -8.67 - j7.69$ A

$I_B = V_{BN}/Z_B = \frac{220\angle{-240^o}}{25.49\angle 11.30^o} = 8.63\angle{-251.3^o} = -2.76 + j8.17$ A

$I_N = I_R + I_Y + I_B$

$= 8.79 - j4.39 - 8.67 - j7.69 - 2.76 + j8.17$

$I_N = -2.64 + j4.87 = 5.53\angle 118.46^o$ A

2. Consider 75 ohm resistors are connected in star and then in delta. If line voltage V_L = 440 V calculate line and phase current in star and delta system.

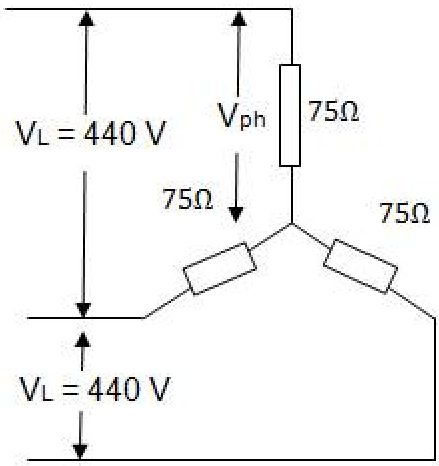
Solution

Star connection

Phase voltage $V_{ph} = V_L/\sqrt{3} = 440/\sqrt{3} = 254.03$ V

Phase current $I_{ph} = V_{ph} / Z_{ph} = 254.03/75 = 3.38$ A

Line current I_L = Phase current I_{ph} = 3.38 A



Delta connection

Phase voltage V_{ph} = Line voltage V_L = 440 V

Phase current $I_{ph} = V_{ph} / Z_{ph} = 440/75 = 5.86$ A

Line current $I_L = I_{ph} \times \sqrt{3} = 5.86 \times \sqrt{3} = 10.14$ A

Lesson 10

TRANSFORMER THEORY-I

10.1 Introduction

Transformer is used to increase or decrease the voltage. Transformer is an important electrical machine in a power system (Fig. 10.1). A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling.

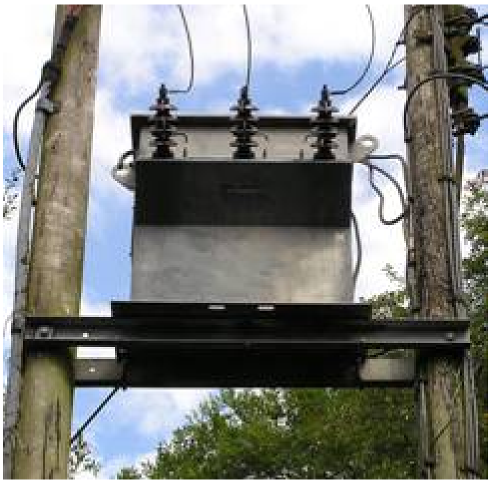


Fig. 10.1 A pole mount transformer

Electrical power is generated at power plant (Thermal/Hydel/Nuclear) generally at 11 kV. The voltage is stepped up to 220 kV or 400 kV for transmission to long distances. It is done to reduce loss and increase distribution efficiency. Transformer can be broadly classified as:

10.1.1 Step up transformer

When output voltage is greater than input voltage ($V_2>V_1$).

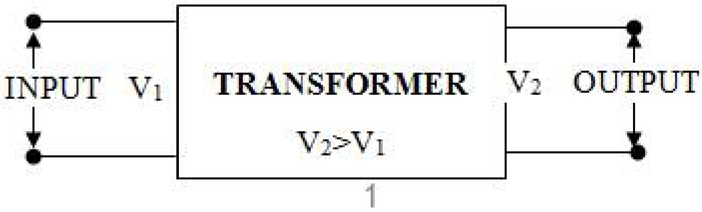


Fig. 10.2 Step up transformer

10.1.2 Step down transformer

When output voltage is less than input voltage ($V_2<V_1$).

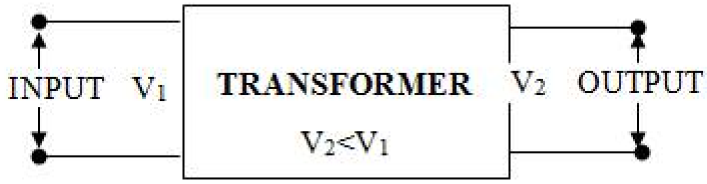


Fig. 10.3 Step down transformer

10.2 Principle of Operation

Transformer works on the principle of electromagnetic induction. The basic elements of a transformer are (Fig. 10.3):

1. Steel core: on which primary and secondary winding are done.
2. Primary winding: a.c. supply is connected.
3. Secondary winding: Load is connected.

When primary winding is connected to a.c. voltage V_1, an alternating flux is set up in the core. This alternating flux links with the secondary winding through the steel core. An e.m.f. is induced in the secondary winding known as mutually induced e.m.f. According to Lenz's law the direction of induced e.m.f. V_2 is opposite to the applied voltage V_1 (Fig.10.4).

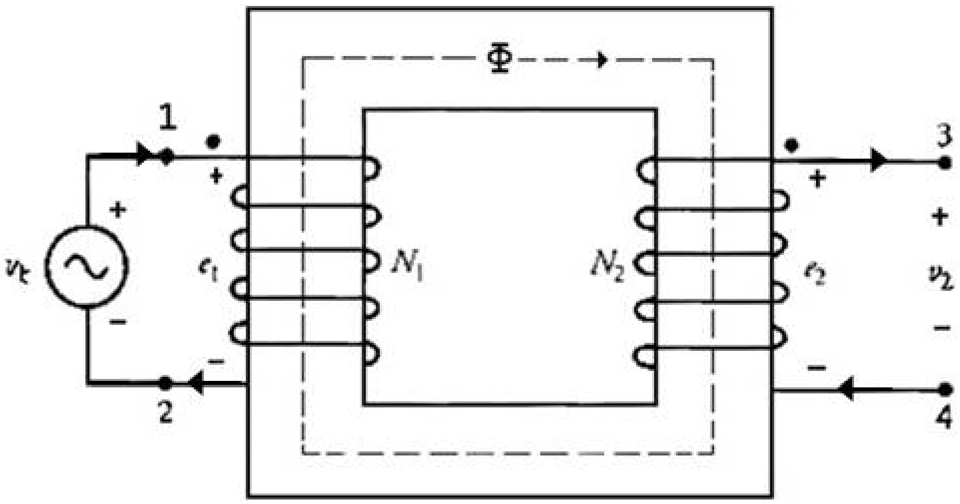


Fig. 10.4 Direction of induced emf in secondary coil is opposite to applied voltage

The primary and secondary windings are not connected but due to mutual flux emf is induced in the secondary coils.

10.3 E.m.f. Equation of a Transformer

Consider a transformer having

N_1 number of turns in primary side

N_2 number of turns in secondary side

The transfer is updated by a.c input of frequency f. Let Φ_m be the maximum flux in the transfer core.

$\Phi_m = B_m \times A$

Where

Φ_m = Maximum flux in core , Wb

B_m= Maximum flux density

A = area of core

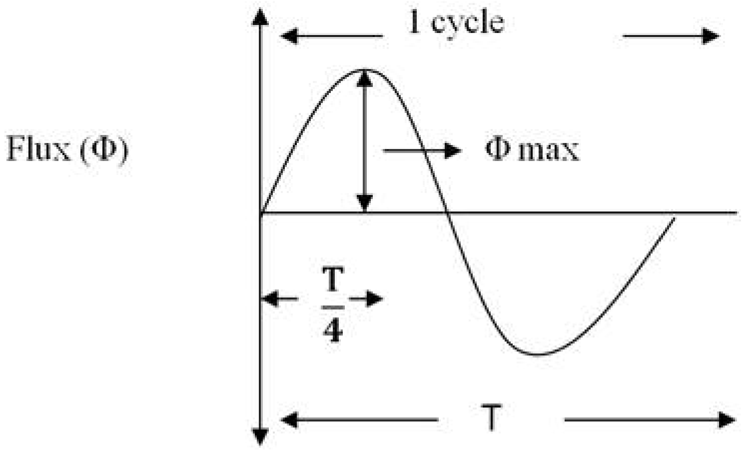


Fig. 10.5 Wave form of alternating flux

From above figure it is evident that flux increase from zero to the maximum value Φ_m in T/4 seconds.

$$\text{Average rate of change of flux} = \frac{\Phi_m}{T/4}$$

$$= \frac{4\Phi_m}{T}$$

$$Average \frac{emf}{turn} = 4\ f\ \Phi_m \frac{\text{Wb}}{s} \text{ or volts}$$ ------------(1) [Since T = 1/f]

We know,

Form factor = r.m.s. value/average value = 1.11

Or, r.m.s value = 1.11 × average value--------(2)

From eqn (1) & (2)

r.m.s value of e.m.f/ turn = 1.11 × 4 f Φ_m volts

= 4.44 f Φ_m volts/turn

r.m.s value of induced emf in primary winding having N_1 turns

E_1 =4.44 f Φ_m N_1 volts-------------(3)

r.m.s value of induced emf in secondary winding having N_2 turns

E_2 = 4.44 f Φ_m N_2 volts----------(4)

Dividing equation (4) & (5)

$$\frac{E_2}{E_1} = \frac{4.44\, f\, \emptyset_m N_2}{4.44\, f\, \emptyset_m N_1}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K ---------(5)$$

The ratio of secondary voltage (E_2) to primary voltage (E_1) is known as transformation ratio (K).

- Step up transformer $N_2 > N_1$ or $K > 1$
- Step down transformer $N_1 > N_2$ or $K < 1$

In case of an ideal transformer

Input power = output power

$$V_1 I_1 = V_2 I_2$$

or $$E_1 I_1 = E_2 I_2$$

$$\frac{E_2}{E_1} = \frac{I_1}{I_2} -----------(6)$$

From (5) & (6)

$$\frac{E_2}{E_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1} = K$$

10.3.1 Turn ratio

The ratio of secondary to primary turns is called turn ratio,
turn ratio= N_2/N_1.

If $N_2>N_1$ transformer is step-up transformer

If $N_2<N_1$ transformer is step-down transformer.

The relationship between transformation ratio and turn ratio is given as:

$$K = \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

10.4 Working

When an alternating voltage V_1 is applied to the primary, an alternating flux $\emptyset$ is set up in the core. The alternating flux links both the windings and induces e.m.f.s E_1 and E_2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E_1 is termed as primary e.m.f. and e.m.f. E_2 is termed as secondary e.m.f.

$$\text{Clearly, } E_1 = -N_1 \frac{d\emptyset}{dt} \quad \text{and} \quad E_2 = -N_2 \frac{d\emptyset}{dt}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitude of E_2 and E_1 depend upon the number of turns on the secondary and primary respectively. If $N_2>N_1$, then $E_2>E_1$ (or $V_2>V_1$) and we get a step-up transformer. On the other hand, if $N_2<N_1$, then $E_2<E_1$ (or $V_2<V_1$) and we get a step-down transformer. If load is connected across the secondary winding, the secondary e.m.f. E_2 will cause a current I_2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level. The following points may be noted carefully:

- The transformer action is based on the laws of electromagnetic induction.
- There is no electrical connection between the primary and secondary. The a.c. power is transferred from primary to secondary through magnetic flux.
- The transformer cannot work on d.c. power.
- There is no change in frequency i.e. output power has the same frequency as the input power.
- The losses that occur in a transformer are:
    a) Core losses-eddy current and hysteresis.
    b) Copper losses-in the resistance of the windings.

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

10.5 Application of Transformer

10.5.1 Power distribution

Big generating stations are located at hundreds or more km away from the load center (where the power will be actually consumed). Long transmission lines carry the power to the load centre from the generating stations. Generator is a rotating machines and the level of voltage at which it generates power is limited to several kilo volts only a typical value is 11 kV. To transmit large amount of power (several thousands of mega watts) at this voltage level means large amount of current has to flow through the transmission lines. The cross sectional area of the conductor of the lines accordingly should be large. Hence cost involved in transmitting a given amount of power raises many folds. Not only has that, the transmission lines had their own resistances. This huge amount of current will cause tremendous amount of power loss or I^2R loss in the lines. This loss will simply heat the lines and becomes a wasteful energy. In other words, efficiency of transmission becomes poor and cost involved is high. The above problems may address if we could transmit power at a very high voltage say, at 200 kV or 400 kV or even higher at 800 kV. But as pointed out earlier, a generator is incapable of generating voltage at these levels due to its own practical limitation. The solution to this problem is to use an appropriate step-up transformer at the generating station to bring the transmission voltage level at the desired value as depicted in figure 10.6 where for simplicity single phase system is shown to understand the basic idea.

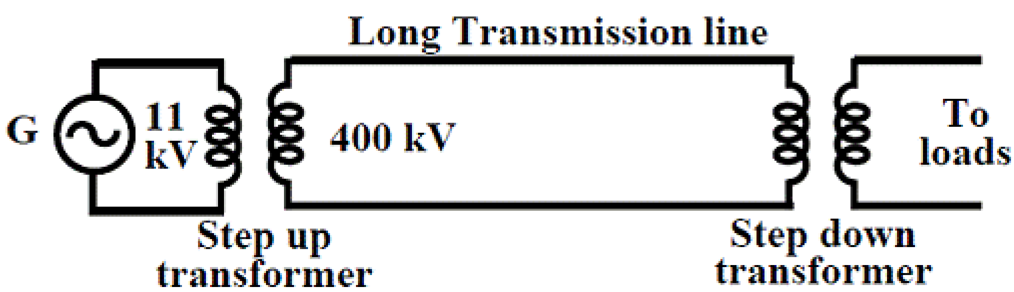


Fig. 10.6 Power transmission system

Obviously when power reaches the load centre, one has to step down the voltage to suitable and safe values by using transformers. Thus transformers are an integral part in any modern power system. Transformers are located in places called substations. In cities or towns you must have noticed transformers are installed on poles – these are called pole mounted distribution transformers. These type of transformers change voltage level typically from 3-phase, 6 kV to 3-phase 440 V line and then to 220 V line.

10.5.2 Domestic use

Small transformers are used in the mobile charger, emergency light etc to bring 220 V domestic supply to low voltage may be 4.5 V or 6 V.

10.6 Construction of Transformer

1. **Steel core:** Silicon steel in the form of thin laminations is used for the core material. The core is laminated to minimize the eddy current loss. These laminations are coated with a thin layer of insulating varnish, oxide or phosphate. The thickness of laminations ranges from 0.35 mm to 0.5 mm. The construction can be core type or shell type:

   a) Core type: In a core type construction the winding surrounds the core. The laminations are cut in L shape and are assembled in form of rectangular frame (Fig. 10.7). To prevent flux leakage primary and secondary windings are placed overlapping on the limbs of core.

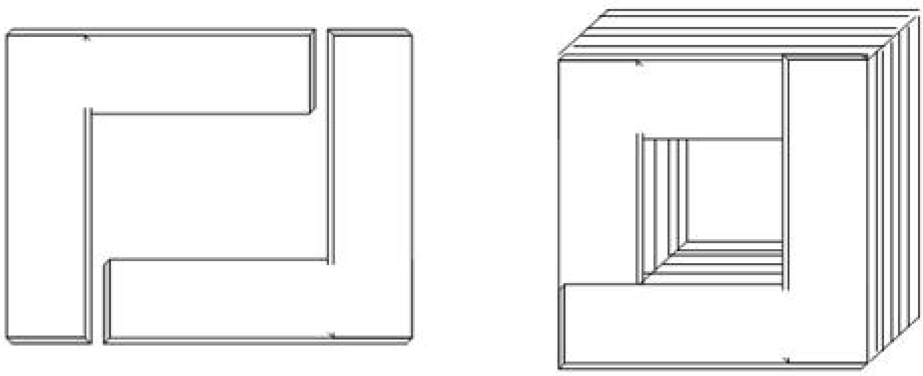


Fig. 10.7 Core type transformer

   b) Shell type: In case of shell-type transformer, individual laminations are cut in the form of long strips of E's and I's as shown in fig 10.8. In order to avoid high reluctance at the joints where the laminations are butted against each other, the alternate layers are stacked differently to eliminate continuous joints.

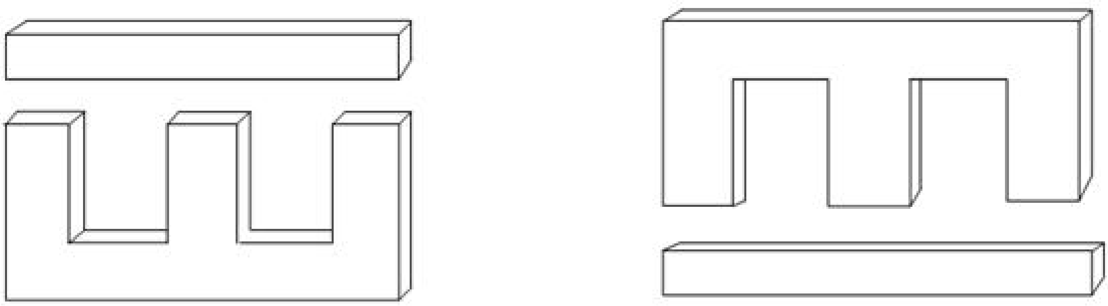


Fig. 10.8 Shell type transformer

   In a shell-type transformer, the core has three limbs, the central limb carries whole of the flux, where as the side limbs carry half of the flux. Therefore, the width of the central limb as about double to that of the other limbs. Both of the primary and secondary windings are placed on the central limb side by side or concentrically. The low voltage winding is placed nearer the core and the high voltage winding is placed outside the low voltage winding to reduce the cost of insulation placed between core and low voltage winding. In this case also the windings are form-wound in cylindrical shape and the core laminations are inserted later on.

2. **Windings:** Windings form another important part of transformers. In a two winding transformer two windings would be present. The one which is connected to a voltage source and creates the flux is called primary winding. The second winding where the voltage is induced by induction is called a secondary. If the secondary voltage is less than that of the primary the transformer is called a step down transformer. If the secondary voltage is more then it is a step up transformer. A step down transformer can be made a step up transformer by making the low voltage winding as its primary. Hence it may be more appropriate to designate the windings as High Voltage (HV) and Low Voltage (LV) windings. The winding with more number of turns will be a HV winding. The current on the HV side will be lower as V-I product is a constant and given as the VA rating of the machines. Also the HV winding needs to be insulated more to withstand the higher voltage across it. HV also needs more clearance to the core, yoke or the body. These aspects influence the type of the winding used for the HV or LV windings.

   a. Primary winding: a.c. supply is connected.
   b. Secondary winding: Load is connected.

3. **Container/tank:** It forms the outer covering and body of the transformer. It is filled with oil in case of oil cooled transformers.

4. **Bushings:** Are required for connecting the ends of the winding to the external circuit. Bushings are made of porcelain and it insulate the terminals from the transformer body. Two separate bushings are provided for High Voltage (HV) and Low Voltage (LV) connections (Fig. 10.9).

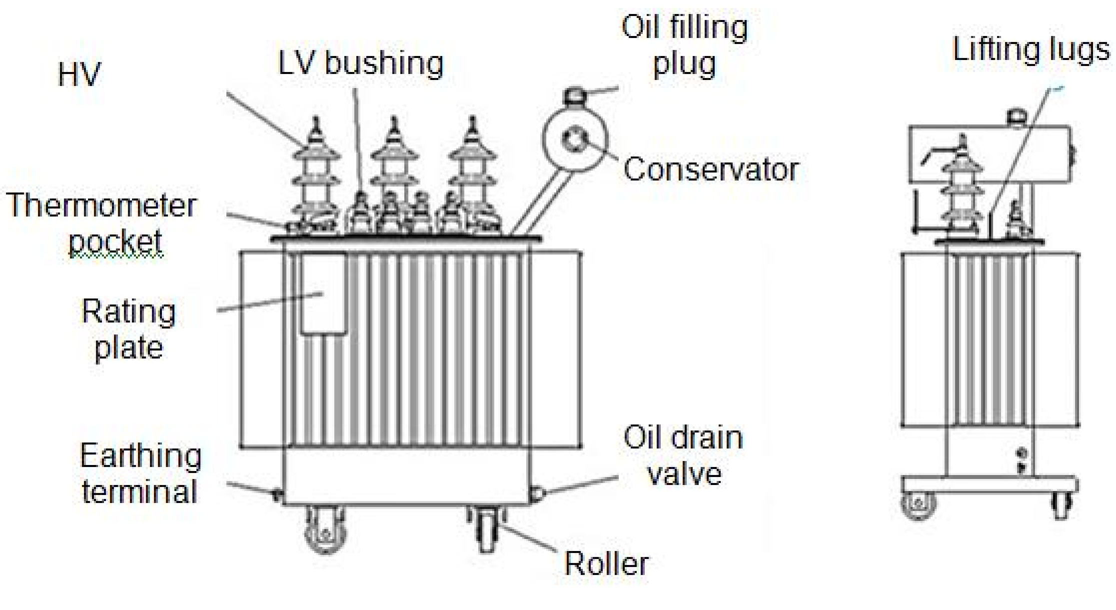


Fig. 10.9 Outer construction of a transformer

5. **Cooling arrangement:** Heat is produced in a transformer by the iron losses in the core and I^2R loss in the windings. To prevent undue temperature rise, this heat is removed by cooling. Type of cooling

methods used are:

- Dry type transformer: Natural air circulation, air blast
- Liquid (oil) immersed: self-cooled, forced air cooled, forced water cooled, forced oil cooled

a) In small transformers (below 50 kVA), natural air cooling is employed i.e. the heat produced is carried away by the surrounding air.

b) Medium size power or distribution transformers are generally cooled by housing them in tanks filled with oil. The oil serves a double purpose, carrying the heat from the windings to the surface of the tank and insulating the primary from the secondary. Self oil cooled transformer have cooling tubes on the outer body. Due to heat dissipation from the winding convective circulation of oil occurs in the cooling tubes.

c) For large transformers, external radiators are added to increase the cooling surface of the oil filled tank. The oil circulates around the transformer and moves through the radiators where the heat is released to surrounding air. Sometimes cooling fans blow air over the radiators to accelerate the cooling process (Fig. 10.10).

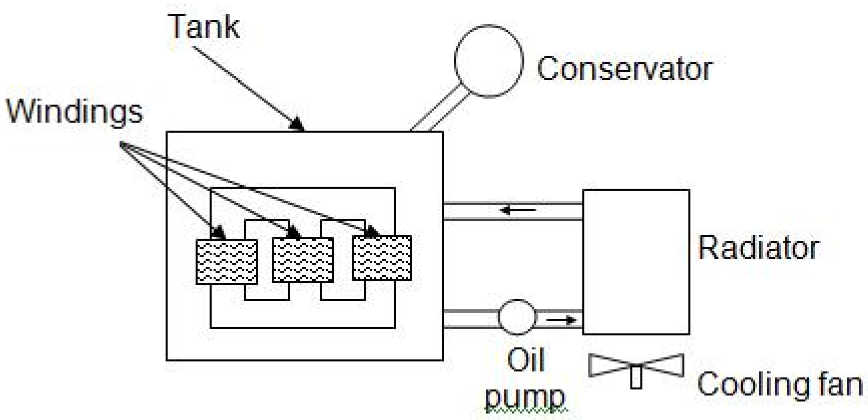


Fig. 10.10 Oil cooled transformer

Numericals

1. Calculate transformation ratio if the voltage in the primary and secondary coil are 11000 and 440 volts respectively.

transformation ratio $k = \frac{E_2}{E_1}$

$$= \frac{11000}{440} = 25$$

2. Calculate the number of turns in the secondary coils of a transformer if transformation ratio is 10 and number of turns in primary side is 2500.

Given

$K = 10$

$N_1 = 2500$

$K = N_1 / N_2$

$N_2 = 10 * 2500$

$= 25000$ turns.

3. If the number of turns in the primary and secondary windings of the transformer is 500 and 1000 respectively. Find the voltage in the secondary side of transformer. The primary side voltage is 220 V.

transformation ratio $K = N_1 / N_2 = 500/1000 = 0.5$

$$k = \frac{E_2}{E_1}$$

$$\frac{E_2}{220} = 0.5$$

$E_2 = 110$ V

Lesson 11

TRANSFORMER THEORY-II

11.1 Three-Phase Transformer

In commercial power network and distribution system three-phase transformers are required to transform the three-phase voltage. Step up and step down of voltage is known as transformation. In a three-phase system, the voltage is lowered or raised either by a bank of three single-phase transformers or by one 3-phase transformer. The windings of either core-type or shell-type three-phase transformers may be connected in either wye or delta. Four possible combinations of connections for the three-phase, two-winding transformers are Y-Y, Δ-Δ, Y-Δ or Δ-Y. A three-phase transformer, compared to a bank of three single-phase transformers, for a given rating will weigh less, cost less, require less floor space, and have somewhat higher efficiency.

11.2 Classification of Transformer

Transformers can be classified according to:

11.2.1 Core construction: core type, shell type.

11.2.2 Winding arrangement: Helical, disc, cross-over, sandwich.

11.2.3 Cooling system: Dry type, oil cooled.

11.2.4 Power capacity: from a fraction of a volt-ampere (VA) to over a thousand MVA

11.2.5 Duty of a transformer: continuous, short-time, intermittent, periodic, varying

11.2.6 Voltage class: from a few volts to hundreds of kilovolts

11.2.7 Number of phases: Single phase/polyphase

11.2.8 Step up/step down

11.2.9 Application: such as power supply, impedance matching, output voltage and current stabilizer or circuit isolation

11.2.10 According to method of mounting: Pole, platform, subway

11.2.11 According to purpose: Constant-voltage, variable-voltage, current, constant-current

11.2.12 According to service

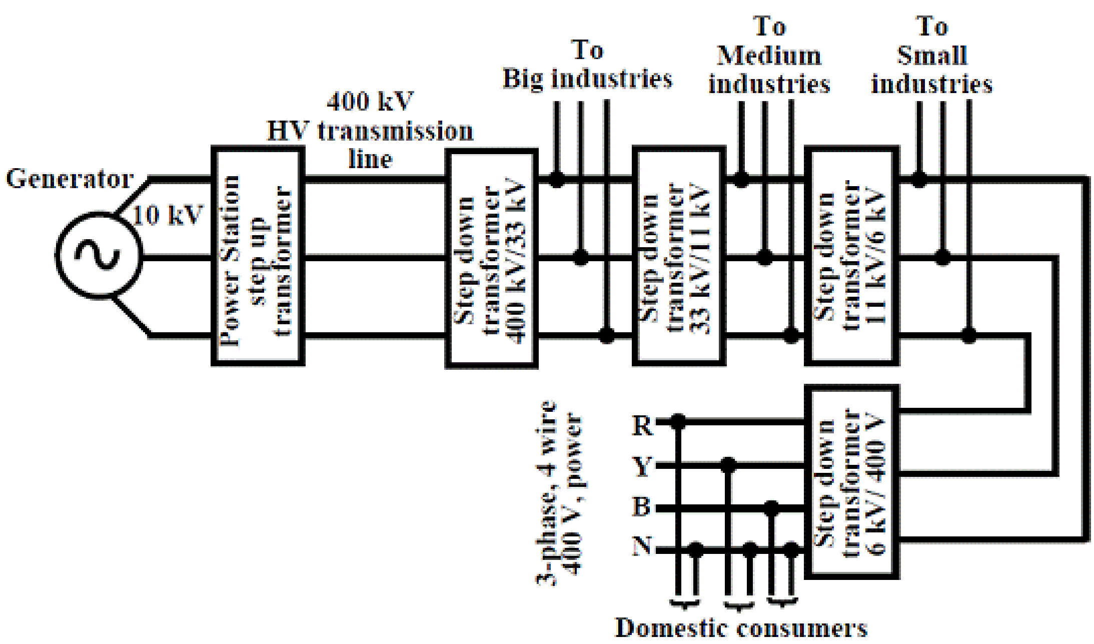


Fig. 11.1 Power distribution system

a. Power transformer: Used for power generation and transmission at power stations. These are of step up type.

b. Distribution transformers: These are step down type transformer (16 to 2500 kVA) used to distribute power to domestic or industrial units. A distribution transformer is a transformer that provides the final voltage transformation in the electric power distribution system, stepping down the voltage used in the distribution lines to the level used by the customer. If mounted on a utility pole, they are called pole-mount transformers (or colloquially a pole pig). If the distribution lines are located at ground level or underground, distribution transformers are mounted on concrete pads and locked in steel cases, thus known as pad-mount transformers. Because of weight restrictions transformers for pole mounting are only built for primary voltages under 30 kV. Distribution transformers are classified into different categories based on certain factors such as:

Type of insulation: Liquid-immersed distribution transformers or dry-type distribution transformers

Number of Phases: Single-phase distribution transformers or three-phase distribution transformers

Voltage class (for dry-type): Low voltage distribution transformers or medium voltage distribution transformers

Basic impulse insulation level (BIL): for medium-voltage, dry-type.

11.3 Efficiency of Transformer

The efficiency of a transformer is expressed as:

Efficiency = (output/Input) x 100%

= (input - 1osses)/input x 100%

= [1 - (losses/input)] x 100%

Where, input, output and losses are all expressed in units of power.

11.4 Equivalent Circuit of Transformer

A transformer can be depicted in terms of equivalent circuit (Fig. 11.2). But it is not very convenient for use due to the presence of the ideal transformer of turns ratio T1 : T2. If the turns ratio could be made unity by some transformation the circuit becomes very simple to use. This is done here by replacing the secondary by a `hypothetical' secondary having T1 turns which is `equivalent ' to the physical secondary. The equivalence implies that the ampere turns, active and reactive power associated with both the circuits must be the same. As the ideal transformer in this case has a turns ratio of unity the potentials on either side are the same and hence they may be conductively connected dispensing away with the ideal transformer. This particular equivalent circuit is as seen from the primary side (Fig. 11.3). It is also possible to refer all the primary parameters to secondary by making the hypothetical equivalent primary winding on the input side having the number of turns to be T2 (Fig. 11.4).

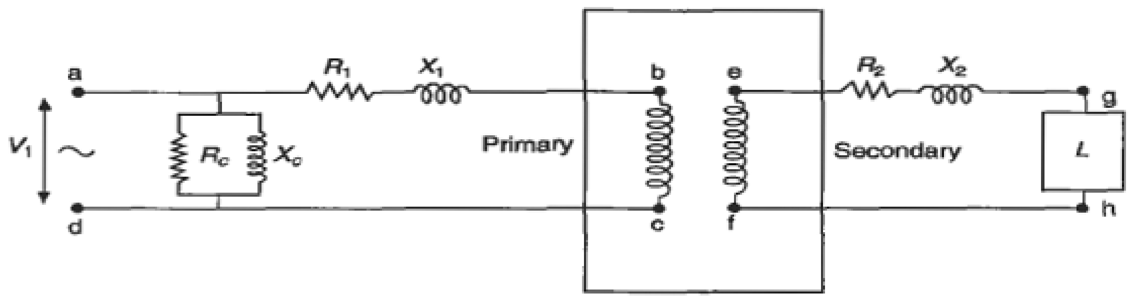


Fig. 11.2 Equivalent circuit of transformer

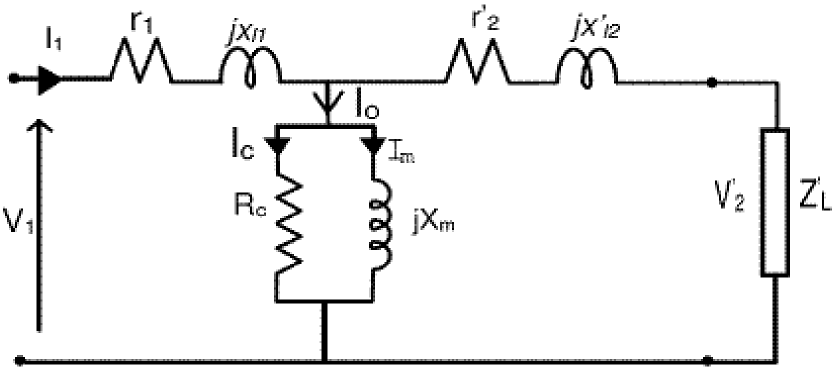


Fig. 11.3 Equivalent circuit of transformer referred to primary side

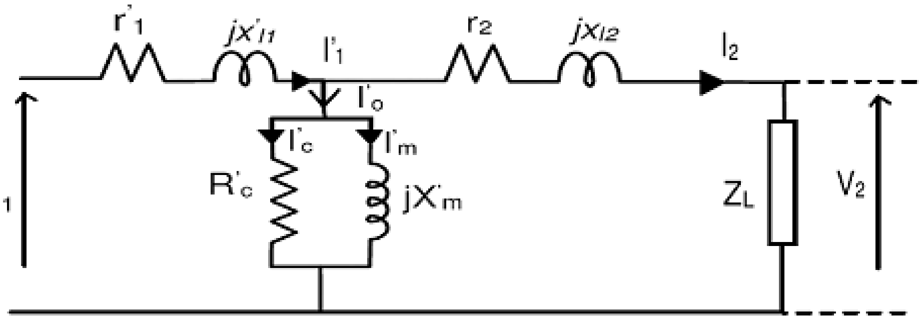


Fig. 11.4 Equivalent circuit of transformer referred to secondary side

11.5 Auto transformer

An autotransformer (sometimes called "auto step down transformer") is an electrical transformer with only one winding. The 'auto' prefix refers to the single coil acting on itself rather than any automatic mechanism. In an autotransformer portions of the same winding act as both the primary and secondary. The winding has at least three taps where electrical connections are made. An autotransformer can be smaller, lighter and cheaper than a standard dual-winding transformer however the autotransformer does not provide electrical isolation. The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, having one terminal in common with the primary voltage (Fig. 11.5). The primary and secondary circuits therefore have a number of windings/turns in common. Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer, part of the current flows directly from the input to the output, and only part is transferred inductively, allowing a smaller, lighter, cheaper core to be used.

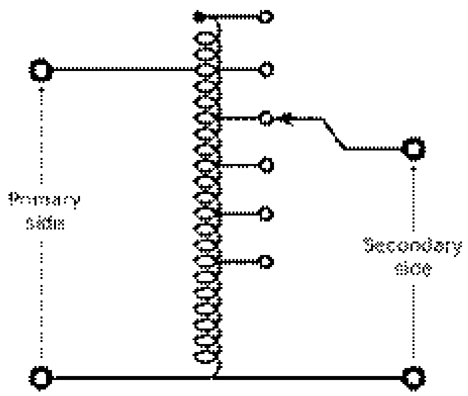


Fig. 11.5 Single-phase tapped autotransformer with output voltage range of 40%–115% of input

11.5.1 Operation

An autotransformer has a single winding with two end terminals, and one or more terminals at intermediate tap points. One end of the winding is usually connected in common to both the voltage source and the electrical load. The other end of the source and load are connected to taps along the winding. Different taps on the winding correspond to different voltages, measured from the common end. In a step-down transformer the source is usually connected across the entire winding while the load is connected by a tap across only a portion of the winding. In a step-up transformer, conversely, the load is attached across the full winding while the source is connected to a tap across a portion of the winding.

As in a two-winding transformer, the ratio of secondary to primary voltages is equal to the ratio of the number of turns of the winding they connect to. For example, connecting the load between the middle and bottom of the autotransformer will reduce the voltage by 50%.

11.5.2 Limitations

An autotransformer does not provide electrical isolation between its windings as in an ordinary transformer. A failure of the insulation of the windings of an autotransformer can result in full input voltage applied to the output. These are important safety considerations when deciding to use an autotransformer in a given application.

Because it requires fewer windings and a smaller core, an autotransformer for power applications is typically lighter an less costly than a two-winding transformer, up to a voltage ratio of about 3:1; beyond that range, a two-winding transforme is usually more economical. In three phase power transmission applications, autotransformers have the limitations of no suppressing harmonic currents. In practice, losses in standard transformers and autotransformers are not perfectl reversible; one designed for stepping down a voltage will deliver slightly less voltage than required if used to step up. Th difference is usually slight enough to allow reversal where the actual voltage level is not critical.

11.5.3 Variable Transformer

A variable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio. By exposing part of the winding coils and making the secondary connection through a sliding brush, an almost continuously variable turns ratio can be obtained, allowing for very smooth control of voltage. Applicable only for relatively low voltage designs, this device is known as a variable AC transformer, or commonly by the trade name of VARIAC.

As with two-winding transformers, autotransformers may be equipped with many taps and automatic switchgear to allow them to act as automatic voltage regulators, to maintain a steady voltage during a wide range of load conditions. They can also be used to simulate low line conditions for testing.

Lesson 12

VECTOR DIAGRAM AND LOSSES

12.1 Vector Diagram without Load

Let us consider a transformer without load (Fig. 12.1). Primary winding of the transformer is supplied with sinusoidal alternating voltage V_1 and current I_m flows through it. This current I_m lags behind the applied voltage V_1 by 90^0 as primary coils exhibit pure inductance. Magnetic flux $\emptyset$ produced in the core is in phase with I_m. Emfs E_1 and E_2 are induced in the primary and secondary winding of the transformer respectively. Phasor diagram of E_1 and E_2 are shown in Fig. 12.2 and 12.3. When transformer is on no load, a small current I_0 (2-10% of I_m) known as exciting current is taken up by the primary winding. This current I_0 lags behind the voltage vector V_1 by an angle $\emptyset_0$.

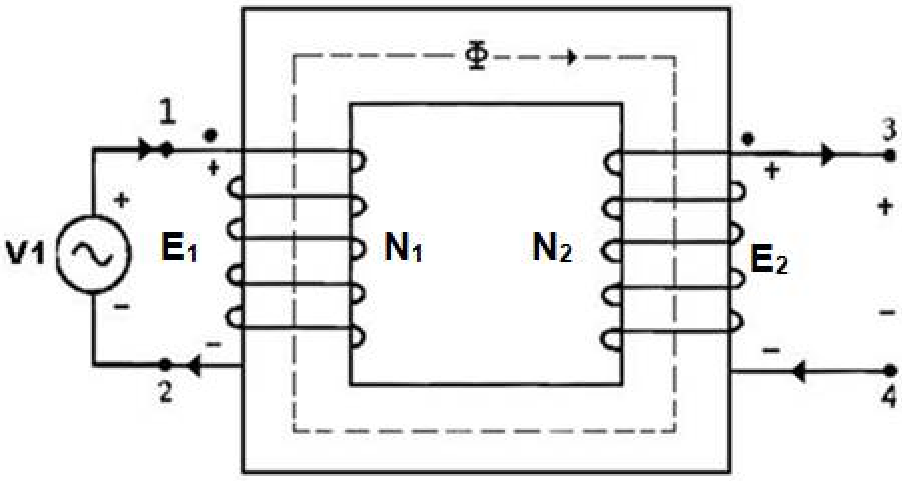


Fig. 12.1 Transformer under no load condition

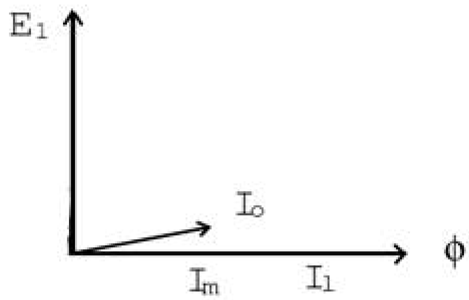
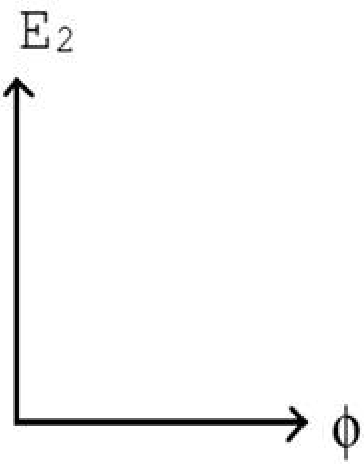


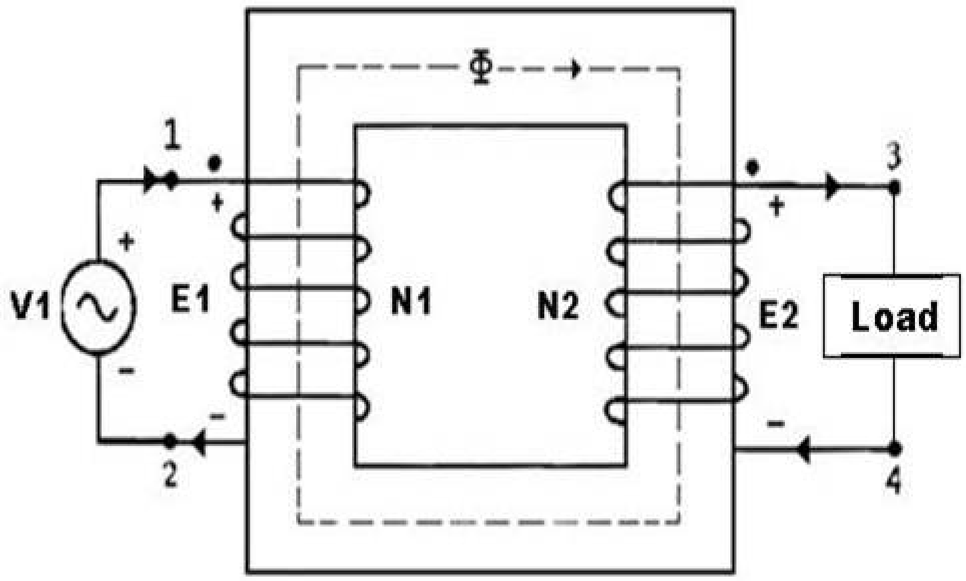
Fig. 12.2 Phasor diagram for the primary side of transformer



12.3 Phasor diagram for the secondary side of transformer

12.2 Vector Diagram with Load

Consider a transformer with load (Fig. 12.4). I_2 current flows through the secondary winding and magnitude of I_2 depends on the terminal V_2 voltage and impedance of the load. The phase angle of secondary current I_2 depends upon the nature of load i.e. whether the load is resistive, inductive or capacitive. I_0 is the no load current. The secondary current I_2 is in phase, lags behind and leads the secondary terminal voltage for resistive, inductive and capacitive load respectively.



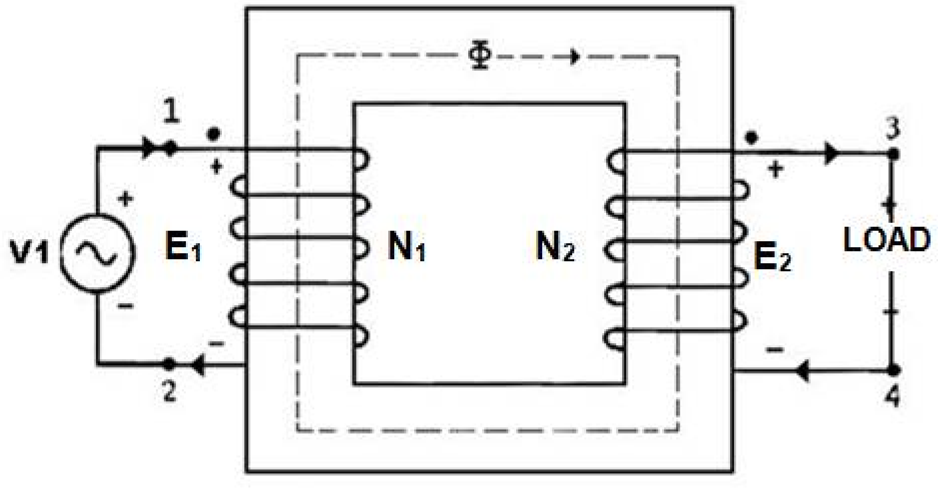
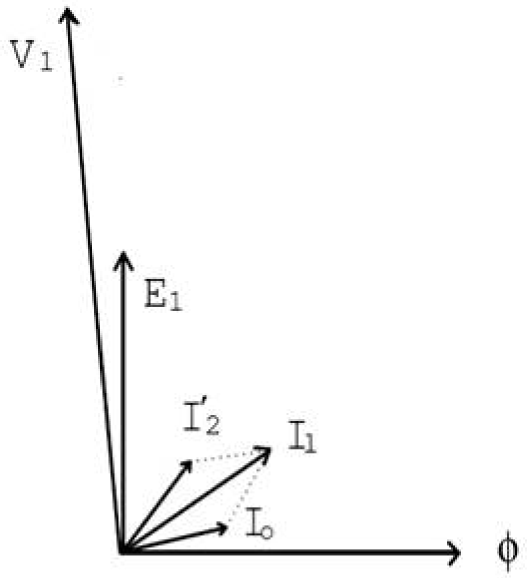
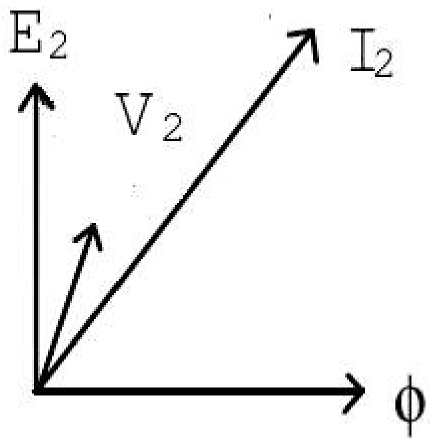


Fig. 12.4 Transformer with load



12.5. Phasor diagram for the primary side of transformer



12.6 Phasor diagram for the secondary side of transformer

12.3 Losses in Transformer

There are certain losses in a transformer which are as follows:

12.3.1 Iron losses

Iron core of the transformer is subjected to alternating flux which causes eddy current and hysteresis loss in it. The sum of these two losses is known as iron or core loss. The iron losses depend upon the construction material of core, frequency of a.c. supply, maximum flux density in the core, volume of the core etc. The value of iron looses is very small compared to copper loss.

a Eddy current loss

Due to the alternating magnetic flux current is induced in the core of the transformer which is known as eddy current. If transformer core was made of solid material (Fig. 12.7) the magnitude of eddy current and thus losses would be very high. Therefore core of the transformer is made of laminated sheets (Fig.12.8).

Eddy current loss $P_e = AB_{max}^2 f^2$

Where A is constant

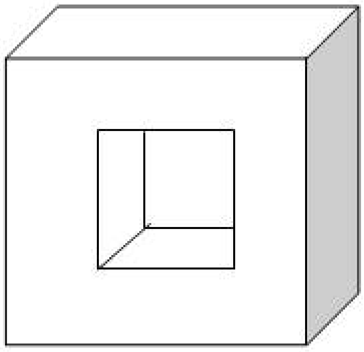


Fig. 12.7 Solid transformer core (high eddy current loss)

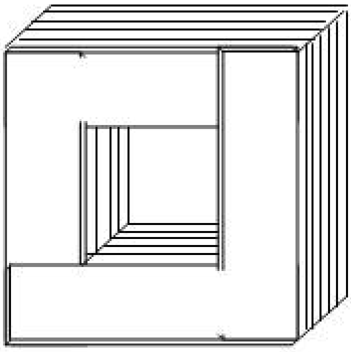


Fig. 12.8 Laminated transformer core (low eddy current loss)

b. Hysteresis losses

When the steel core of the transformer is magnetized and demagnetized by the alternating flux heat is generated. This causes hysteresis losses.

Hysteresis loss $P_h = BB_{max}^{1.6}f$

Total loss $= P_e + P_h = AB_{max}^{2}f^2 + BB_{max}^{1.6}f$

Where A and B are constants

12.3.2 Copper loss due to winding resistances

The primary and secondary windings are made of copper wires which has certain resistance. If resistance of primary and secondary windings are R_1 and R_2 respectively, Copper loss will be given as:

Total copper loss = $I_1^2R_1 + I_2^2R_2$

Where,

I_1 and I_2 are current flowing through primary and secondary winding respectively.

12.3.3 Leakage flux losses

Magnetic flux is produced in both the windings of the transformer (primary and secondary). The flux Ø which links both the winding is the useful flux and is called mutual flux. The fluxes which do not link with the other winding are known as leakage flux.

12.3.4 Stray losses

Losses caused due to eddy current in channels, bolts etc.

12.4 Transformer Test

The performance of a transformer can be determined by:

1. Open-circuit or no-load test.
2. Short-circuit or impedance test.

12.4.1 Open-circuit or no-load test

Open-circuit or no-load test is done to determine:

i. No-load loss or core loss.
ii. No-load current I_0 by which equivalent resistance R_0 and leakage resistance X_0 can be calculated

For no load test, one of the transformer winding is kept open and the other is connected to voltage source at rated frequency (Fig. 12.9). No-load current (I_0) is measured using ammeter. No-load power (P_0) is measured by wattmeter.

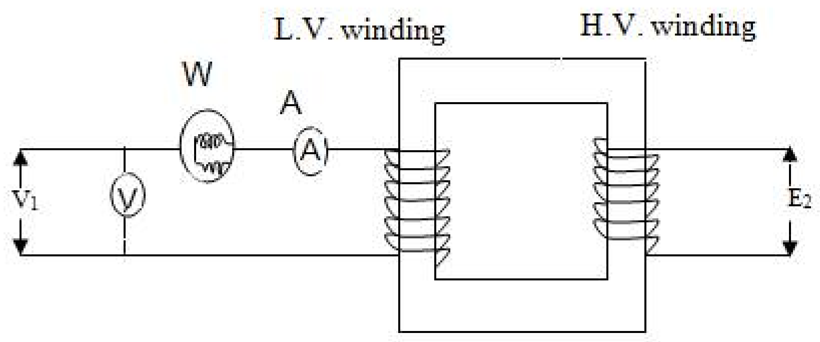


Fig. 12.9 Diagram for open-circuit test

Primary no-load current I_0 in Low Voltage (LV) winding is very small 2 to 10% of rated load current due to which the copper loss ($I_o^2R_1$) is negligibly. As the secondary side is open, no current flows in secondary so copper loss or winding loss is zero. Thus the power measured by wattmeter is due to core loss.

No load input power = $P_0 = V_1 I_0 \cos\phi_0$

Where,

P_0 = No load input power = Core loss or iron loss

$\cos\phi_0$ =no-load power factor = $\frac{I_w}{I_0}$ = P_0/V_1I_0

I_0 = no-load current

V_1 = primary voltage

No-load current I_0 has two components and is given as:

$$I_0 = \sqrt{I_w^2 + I_m^2}$$

a. No-load current wattful component (iron loss component),

$$I_w = I_0 \cos\phi_0 = \frac{P_0}{V_1}$$

b. No-load current magnetizing component (produces magnetic flux in core),

$$I_m = I_0 \sin\phi_0 = \sqrt{I_0^2 - I_w^2}$$

No-load resistance is given by

$$R_0 = \frac{V_1}{I_w} = \frac{V_1^2}{P_0}$$

No-load reactance is given by,

$$X_0 = \frac{V_1}{I_m} = \frac{V_1}{\sqrt{I_0^2 - I_w^2}}$$

No-load current I_0 drawn by the transformer is the exciting current. Admittance Y_0 of the transformer is given by:

$$Y_0 = \frac{V_1}{I_0}$$

The exciting core loss conductance G_0,

$$G_0 = \frac{P_0}{V_1^2}$$

The exciting or magnetising susceptance B_0,

$$B_0 = \sqrt{Y_0^2 - G_0^2}$$

12.4.2 Short-circuit or impedance test

This test is done to measure:

(i) Full-load loss or copper loss (in the winding)

(ii) Equivalent resistance and reactance referred to measuring side.

In this test, the secondary (low-voltage winding) is short-circuited by a thick wire (Fig. 12.10) and low voltage i.e. 5 to 10% of rated primary voltage is applied to the primary winding.

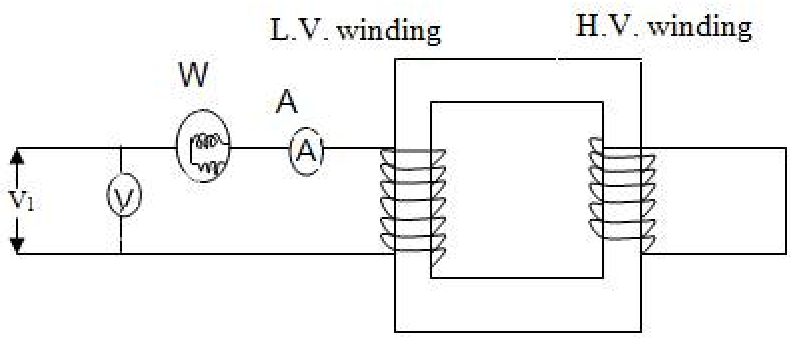


Fig. 12.10 Diagram of short-circuit test

The low input voltage is gradually raised till at voltage V_{SC}, full-load current I_1 flows in the primary. As the input voltage is small the magnetic flux linking the primary and secondary side is very small. Thus iron losses can be neglected. The wattmeter only measures the copper loss. Fig. 12.11 shows the equivalent circuit of a transformer on short circuit as referred to primary side. As no-load current I_0 is small it is neglected in the equivalent circuit.

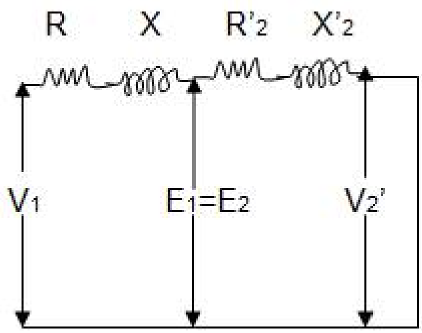


Fig. 12.11a Equivalent circuit of transformer under short circuit condition.

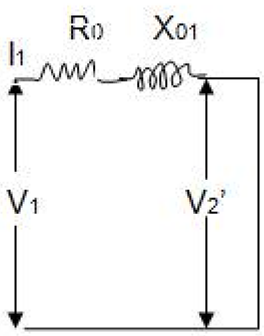


Fig. 12.11b Equivalent circuit of transformer under short circuit condition.

Full load copper loss = W (wattmeter reading) $P = I_1^2 R_{01}$

V_{SC}= Applied voltage applied so that full-load current I_1 flows in the primary winding

I_1 = reading of the ammeter on the primary side

Total impedance as referred to primary side $Z_{01} = \frac{V_{SC}}{I_1}$

Total resistance as referred to primary side $R_{01} = \frac{P}{I_1^2}$

Total reactance as referred to primary side $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

Lesson 13

VOLTAGE REGULATION AND EFFICIENCY OF TRANSFORMER

13.1 Voltage Regulation

The electrical equipments are designed to be operated at a certain voltage. A tolerance limit is provided so that equipment may operate between this range. Transformers connect equipments and machines to the supply. If the terminal voltage drops too low below the rated value due to the load currents, it may affect the performance of the equipments. This is not desirable. It is therefore important to specify and quantify that there is a voltage drop when certain load current is taken up from the transformer. Voltage regulation is quantified using two terms:

a. Regulation down
b. Regulation up

13.2 Regulation Down

Regulation down is the change in terminal voltage when a load current at any power factor is applied, expressed as a fraction of the no-load terminal voltage.

$$Regulation\ down\ = \frac{|V_{nl}| - |V_l|}{|V_{nl}|}$$

Where,

V_{nl} = no-load terminal voltage

V_l = load terminal voltage

13.3 Regulation Up

Regulation up is the ratio of the change in the terminal voltage when a load at a given power factor is removed, and the load voltage.

$$Regulation\ up\ = \frac{|V_{nl}| - |V_l|}{|V_l|}$$

Where,

V_{nl} = no-load terminal voltage.

V_l = load voltage.

13.4 Efficiency of Transformer

A practical transformer has following losses:

13.4.1 Iron losses

Since the iron core is subjected to alternating flux, the eddy current and hysteresis loss occurs in it. These two losses together are known as iron losses or core losses. The iron losses depend upon the supply frequency, maximum flux density in the core, volume of the core etc. It may be noted that magnitude of iron losses is quite small in a practical transformer.

13.4.2 Winding resistances

Since the windings consists of copper conductors, it immediately follows that both primary and secondary will have winding resistances. The primary resistance R_1 and secondary resistance R_2 act in series with the respective windings

13.4.3 Leakage reactances

Both primary and secondary currents produce flux. The flux $\emptyset$ which links both the winding is the useful flux and is called mutual flux. However, primary current would produce some flux $\emptyset_1$ which would not link the secondary winding. Similarly, secondary current would produce some flux $\emptyset_2$ that would not link the primary winding. The flux such as $\emptyset_1$ or $\emptyset_2$ which links only one winding is called leakage flux. The leakage flux paths are mainly through the air.

The dielectric losses take place in the insulation of the transformer due to the large electric stress. In the case of low voltage transformers this can be neglected. For constant voltage operation this can be assumed to be a constant.

The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link the metallic structural parts, tank etc. and produce eddy current losses in them. Thus they take place 'all round' the transformer instead of a definite place, hence the name 'stray'. Also the leakage flux is directly proportional to the load current unlike the mutual flux which is proportional to the applied voltage. Hence this loss is called 'stray load' loss. This can also be estimated experimentally. It can be modeled by another resistance in the series branch in the equivalent circuit. The stray load losses are very low in air-cored transformers due to the absence of the metallic tank.

Iron and copper losses are wasted as heat and temperature of the transformer rises. Therefore output power of the transformer will be always less than the input power drawn by the primary from the source and efficiency is defined as

$$Efficiency\ \eta = \frac{Output\ power}{Input\ power}$$

$$\eta = \frac{Output\ power\ in\ kW}{Output\ power\ in\ kW + losses}$$

$$\eta = \frac{Output\ power\ in\ kW}{Output\ power\ in\ kW + iron\ loss + copper\ loss}$$

$$\eta = \frac{Output\ power\ in\ kW}{Output\ power\ in\ kW + P_i + I_1^2R_1 + I_2^2R_2}$$

Input power = $V_1 I_1 \, Cos\ \phi$

Output power = $V_2 I_2 \, Cos\ \phi$

$$\eta = \frac{V_2 I_2 \, Cos\ \phi}{V_2 I_2 \, Cos\ \phi + P_i + I_1^2R_1 + I_2^2R_2}$$

13.4.4 Condition for maximum efficiency

Copper loss $P_c = I_1^2R_{01} = I_2^2R_{02}$

Iron losses $P_i = P_e + P_h$

Where,

P_e = Eddy current loss

P_h = Hysteresis loss

$$Efficiency\ \eta = \frac{Output\ power}{Input\ power}$$

Or,

$$Efficiency\ \eta = \frac{Input\ \ power - \ Losses}{Input\ power}$$

$$= \frac{V_1 I_1\ Cos\ \phi_1 - \ Losses}{V_1 I_1\ Cos\ \phi_1}$$

$$= \frac{V_1 I_1\ Cos\ \phi_1 - I_1^2 R_{01} - P_i}{V_1 I_1\ Cos\ \phi_1}$$

$$= 1 - \frac{I_1\ \ R_{01}}{V_1 Cos\ \phi_1} - \frac{P_i}{V_1 I_1\ Cos\ \phi_1}$$

Differentiating the above equation by I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 Cos\ \phi_1} + \frac{P_i}{V_1 I_1^{\ 2}\ Cos\ \phi_1}$$

For maximum efficiency $\frac{d\eta}{dI_1} = 0$

$$-\frac{R_{01}}{V_1 Cos\ \phi_1} + \frac{P_i}{V_1 I_1^{\ 2}\ Cos\ \phi_1} = 0$$

$$\frac{R_{01}}{V_1 Cos\ \phi_1} = \frac{P_i}{V_1 I_1^{\ 2}\ Cos\ \phi_1}$$

Or,

$P_i = I_1^{\ 2} R_{01}$

Condition for maximum efficiency of transformer lies when iron loss is equal to copper loss. i.e.

$P_i = P_c$

13.5 All Day Efficiency

Heavy duty transformers are classified into power transformers and distribution transformers. Power transformers are used at the power generation stations and are operated as per need. In a power station there may be number of generators and transformers. Power transformers will be operated depending on the power generated. Thus, in a particular instant all the power transformers may not be put in use. Distribution transformers on the other hand are used in electrical network systems for power distribution. These have to be operated round the day (24 hours). There will be power loss due to operation of such transformers. The energy efficiency of these transformers is measured considering a 24 hour operation and is known as "All day efficiency"

$$\eta\ (all\ day) = \frac{Output\ of\ transformer\ in\ 24\ hour\ (kWh)}{Input\ to\ transformer\ in\ 24\ hour\ (kWh)}$$

Numericals

1. Calculate regulation down value if the no load terminal voltage is 230 V and load voltage is 220 V

$$\%\ Regulation\ down\ = \frac{|V_{nl}| - |V_l|}{|V_{nl}|}$$

$$= \frac{230-220}{230} \times 100 = 4.3\ \%$$

1. Calculate regulation up value if the no load terminal voltage is 240 V and load voltage is 210 V

$$\%\ Regulation\ up\ = \frac{|V_{nl}| - |V_l|}{|V_l|}$$

$$= \frac{240-210}{210} \times 100 = 14.2\ \%$$

Lesson 14

CONSTRUCTION AND TYPES OF ALTERNATORS

14.1 Introduction

Electrical machines (generators and motors) operated by alternating current are known as synchronous machines. An alternator is an electromechanical device that converts mechanical energy to electrical energy in the form of alternating current. A.C. generators are also called as alternators. A.C. generators are used in to generate electricity in hydroelectric (Fig. 14.1) and thermal plants. Alternators are also used in automobiles to generate electricity (Fig. 14.2).

Fig. 14.1 Alternator/A.C. generator in a hydroelectric station

Fig. 14.2 Alternator mounted on an automobile engine

14.2 Construction

A.C. generator has mainly two parts

a. Stator

b. Rotor

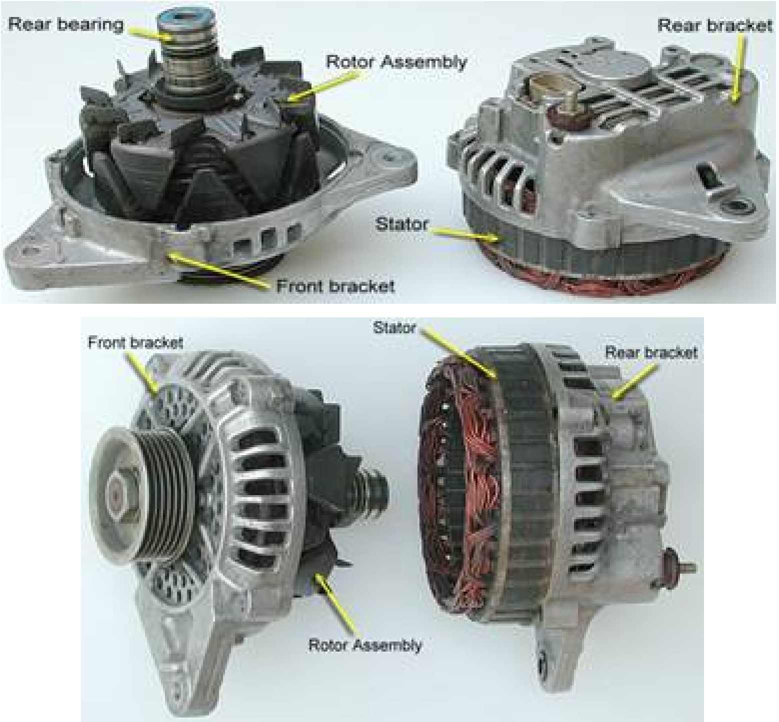


Fig. 14.3 Parts of an alternator

14.2.1 Stator

The Stationary part of the alternator is known as stator. It provides housing and support for the rotor. Slots are provided in the inner side of the stator to fix poles or windings (Fig. 14.4).

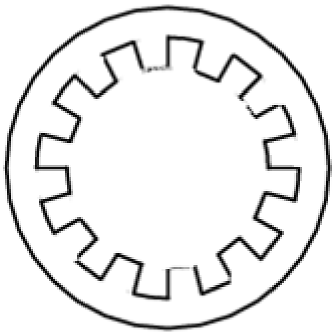


Fig. 14.4 Slots in stator

14.2.2 Rotor

It is the rotating part of an alternator.

14.3 Terms used in Alternator

1. **Armature**– The part of the alternator where emf is induced.
2. **Winding**- Insulated copper wires are wound over steel structure to induce magnetic field when current is supplied.
3. **Slip rings**- Two rings are provided to supply current to the rotor winding.
4. **Brushes**-The brushes rest on the slip ring to provide contact for supplying current.
5. **Pole**-Made of cast iron or steel of good magnetic quality. Act as north or South Pole alternately.
6. **Prime mover**- The mechanical system to provide rotation to the alternator is known as prime mover

14.4 Arrangement of Synchronous Generator

Two possible arrangement of armature in an alternator are:

1. Stationary armature winding and rotating poles.
2. Stationary poles and rotating armature winding.

14.4.1 Stationary armature winding and rotating poles

The stator is provided with slots where the armature winding along with the insulation is placed. The rotor has magnetic poles arranged alternately as North (N) and South (S). The numbers of poles vary according to the speed of the prime mover.

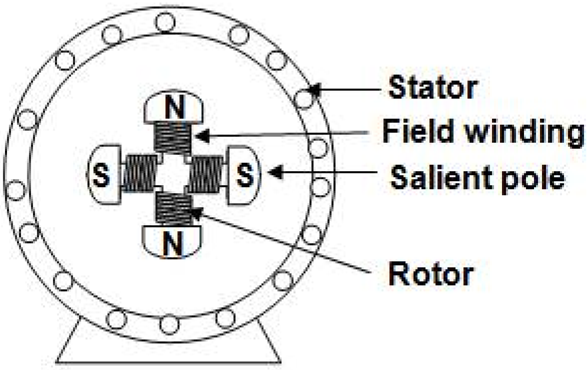


Fig. 14.5 Salient pole type alternator

14.4.2 Stationary poles and rotating armature winding

In this type of arrangement the poles are fixed in the stator and the armature winding is provided on the rotor.

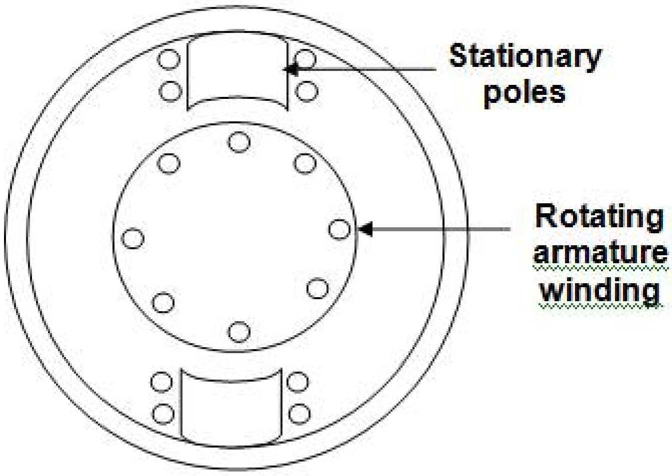


Fig. 14.6 Stationary poles and rotating armature winding

First type of arrangement i.e. stationary armature winding and rotating poles are preferred over the second arrangement (stationary poles and rotating armature winding) because of the following reasons:

1. More space is available for armature windings, therefore more coils and insulator can be provided. This allows achieving voltages as high as 33kV.
2. Less number of slip rings is required.
3. Simple in design and construction.
4. Less rotor weight and reduced mechanical power required to move rotor.
5. Reduced chances of burning of windings.

When an alternator is operated heat is generated in the windings. Slots and fan are provided for air circulation. This helps in ventilation and removal of heat from the windings and thus protects the armature winding.

14.5 Rotor Construction

Rotors are of two types:

1. Salient (or projected) pole type.
2. Smooth cylindrical or non-salient type.

14.5.1 Salient (or projected) pole type.

As the name suggests, the poles are made with projections. This type of rotor is used for low to medium speed/rpm alternators, were more number of poles are required may be 20 or 30 poles. Such alternator can be identified by large diameter and short length. The pole is made of steel or cast iron and the pole winding is excited by a D.C. generator driven by the shaft of alternator.

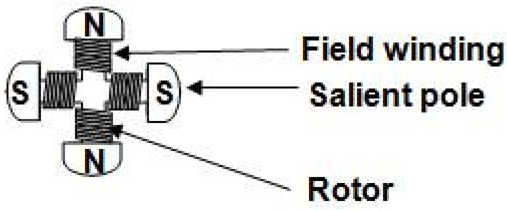


Fig. 14.7 Salient pole type rotor

14.5.2 Smooth cylindrical or non-salient type rotor

Such rotors are used for high speed alternators. The rotor is made of steel cylinder with number of slots cut on the periphery of the cylinder. The field windings are placed in the slots. The chart area acts as the pole. These axial alternators have more length and smaller diameter.

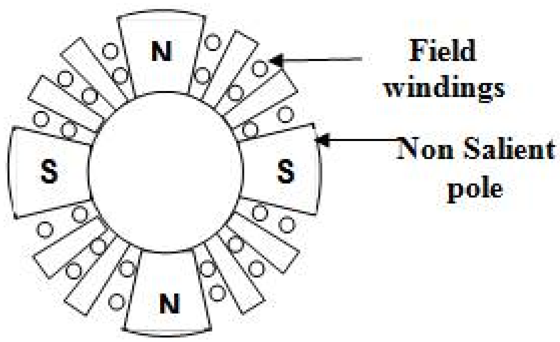


Fig. 14.8 Smooth cylindrical or non salient type rotor

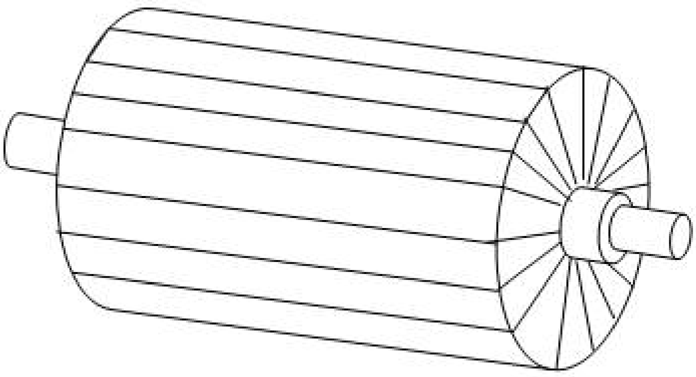


Fig. 14.9 3D view of smooth cylindrical or non-salient type rotor

Lesson 15

PRINCIPLES OF ALTERNATORS

15.1 Principle of Operation

In alternators, a rotating magnet, called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF (electromotive force), as the mechanical input causes the rotor to turn.

The rotating magnetic field induces an A.C. voltage in the stator windings. Often there are three sets of stator windings, physically offset so that the rotating magnetic field produces a three phase current, displaced by one-third of a period with respect to each other.

The rotor's magnetic field may be produced by induction (as in a "brushless" alternator), by permanent magnets (as in very small machines), or by a rotor winding energized with direct current through slip rings and brushes. The rotor's magnetic field may even be provided by stationary field winding, with moving poles in the rotor. Permanent magnet machines avoid the loss due to magnetizing current in the rotor, but are restricted in size, due to the cost of the magnet material. Since the permanent magnet field is constant, the terminal voltage varies directly with the speed of the generator.

An automatic voltage control device controls the field current to keep output voltage constant. If the output voltage from the stationary armature coils drops due to an increase in demand, more current is fed into the rotating field coils through the voltage regulator (VR). This increases the magnetic field around the field coils which induces a greater voltage in the armature coils. Thus, the output voltage is brought back up to its original value.

According to Faraday's laws of electromagnetic, induced emf is generated when a coil is rotated in any magnetic field. The magnitude of the induced emf in the coil rotating in a magnetic field in given as:

$$\text{emf } (e) = B\,l\,v\,N \sin\theta$$

Where,

e = induced emf in volt.

B = Magnetic field flux density, Wb/m^2

l = length of the wire in the coil.

v = Velocity of rotation

N = Number of turns in the coils.

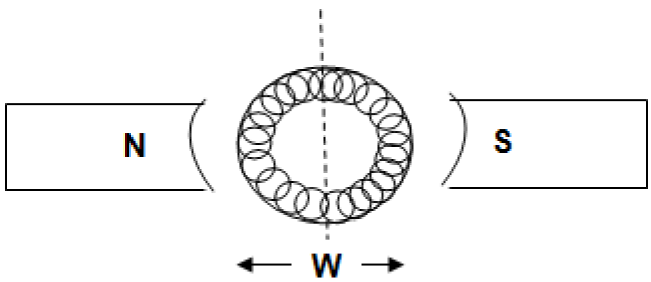


Fig. 15.1 Two sides of coil in an alternator

Since the coil has two sides (Fig. 15.1):

$$\text{Total emf generated } e = 2\,B\,l\,v\,N \sin\theta$$

Since the angular velocity of the spinning coil is ω = v/r and in this case r = W/2, then v = ωW/2 . ω is in radians/sec, so if θ = 0 at t = 0, then θ = ωt , and our expression for e becomes,

$$e = 2BLv \sin\theta$$
$$= 2BL(\omega W/2) \sin\omega t$$
$$= (LW)B\omega \sin\omega t$$

Where,

W = width of the coil
L = length of the coil
N = Number of turns or loops
For a coil of N loops and identifying A = LW (valid for any planar shape),

$$e = NAB\omega \sin\omega t$$

$$= e_o \sin\omega t$$

Where,
e_o = maximum emf = NABω

An A.C. generator converts mechanical energy into electrical energy. The mechanical system to provide rotation to the alternator is known as the prime mover (Fig. 15.2). Thus an alternator can be operated using a steam turbine, hydraulic turbine or a diesel/kerosene engine.

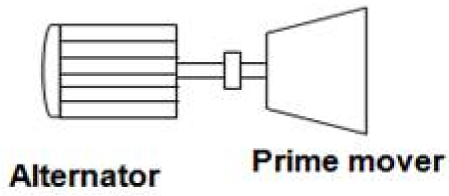


Fig. 15.2 Prime mover for an alternator

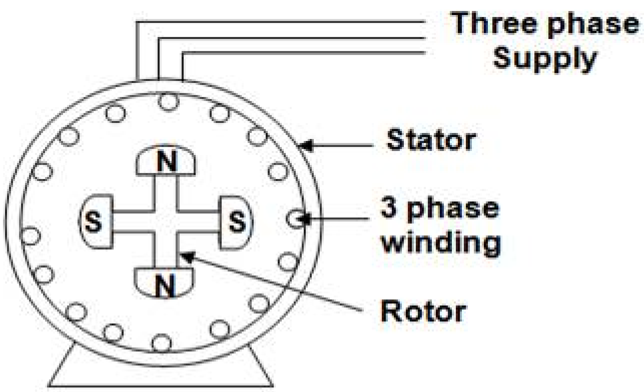


Fig. 15.3 3Ø alternator

Fig 15.3 shows a 3Ø alternator. When the rotor rotates, the stator winding are cut by the magnetic flux of the poles. Since the poles are arranged alternately North (N) and South (S) on the rotor the emf induced is of alternating type.

15.2 Relationship between Speed, Frequency and Number of Poles.

Following equation gives the relation between speed, frequency and number of poles

$$frequency\ (f) = \frac{P\ N}{120}$$

Where

P = no. of poles

N = r.p.m.

The output frequency of an alternator depends on the number of poles and the rotational speed. The speed corresponding to a particular frequency is called the synchronous speed for that frequency (Table 15.1).

Table 15.1 Rotational speed and poles required for producing A.C. at different frequencies

Poles	r.p.m for 50 Hz	r.p.m for 60 Hz	r.p.m for 400 Hz
2	3,000	3,600	24,000
4	1,500	1,800	12,000
6	1,000	1,200	8,000
8	750	900	6000
10	600	720	4800
12	500	600	4000
14	429	515	3429
16	375	450	3000
18	333	400	2667
20	300	360	2400
40	150	180	1200

In India the frequency of alternating current is 50 Hz. This value is the standard frequency for generation and distribution of electricity. Electrical appliances are designed accordingly to work at 50 Hz.

Suppose a steam turbine rotates at 1000 rpm. Number of poles required in an alternator to generate 50 Hz alternator current is:

$$P = \frac{(f \times 120)}{N}$$

$$= \frac{50 \times 120}{1000}$$

$$= 6\ Poles$$

Similarly table 15.2 denotes the rotational speed required for alternator with different number of poles for producing a.c. at 50 Hz:

Table 15.2 Rotational speed and poles required for producing a.c. at 50 Hz frequency

No. of poles in alternator	2	4	6	8	10	12	16	20
Speed (rpm)	3000	1500	1000	750	600	500	375	300

Numericals

1. Calculate the frequency of the alternating current if speed = 300 rpm and numer of poles = 8.

$$frequency\ (f) = \frac{P\ N}{120}$$

Where

P = no. of poles

N = r.p.m.

$$frequency\ (f) = \frac{8 \times 300}{120} = 20 \text{ Hz}$$

2. A generator with a circular coil of 75 turns of area 3.0 x 10-2 m^2 is placed in a 0.20 T magnetic field and rotated with a frequency of 60 Hz. Find the maximum emf which is produced during a cycle.

Solution:

N = 75, A = 3.0 x 10-2 m2, B = 0.20 T and f = 60 Hz .

Since ω = 2πf = 2π(60) = 377 radians/s

e_o = (75)(3.0 x 10-2)(0.20)(377) = 170 V

Lesson 16

E.M.F. IN ALTERNATORS, CIRCUIT BREAKERS

16.1 E.M.F in Alternators

In an alternator, let,
No. of poles=P
Rotor speed in rpm=N
Frequency of the induced e.m.f=f
Number of turns in the coils=T

Flux per poles=Ø Wb

In one rotation of the rotor the flux cut by the conductor=Ø p Webers………… (1)

Number of rotation in a min=N

$$\text{Number of rotation per second} = \frac{N}{60}$$

$$\text{Time required for one rotation} = \frac{60}{N}\ \textit{Seconds}\ \ldots(2)$$

$$\text{Magnetic flux cut per second} = \frac{\textit{total flux cut in one rotation}}{\textit{Time required for one rotation}} = \frac{eqn\ 1}{eqn\ 2}$$

$$= \frac{\text{Ø}P}{60/N} = \frac{\text{Ø}PN}{60}$$

$$\text{Average e.m.f per conductor} = \frac{\text{Ø}PN}{60}\ Volt\ \ldots.\ (3)$$

Total number of conductor or coil sides per phase=2T
Then average e.m.f

$$e_{av} = \frac{\text{Ø}PN2T}{60}\ Volt\ldots\ldots.(4)$$

$$Since\ f = \frac{PN}{120}$$

$$N = \frac{120\,f}{P}\ \ldots\ldots\ldots.(5)$$

From equation 4 and 5

$$e_{av} = \frac{2}{P}f\text{Ø}P2T$$

$$= 2f\text{Ø}2T$$

$$e_{av} = 2f\text{Ø}2T\ \ldots\ldots(6)$$

$$\text{And since } e_{rms} = 1.11\ e_{av}\ldots..(7)$$

From equation 6 and 7

$e_{rms} = 4.44\, f \O T\ volt$

16.2 Circuit Breakers

Before moving into the topic of circuit breakers we need to first know the hazards available with electric current. Electricity has become a necessity for life. But with all the usefulness, electric power has certain dangers. An electric shock can cause hazards to man. The effect of an electric shock depends on the magnitude of current passing through the human body and duration of contact. Electric shock can sometimes be dangerous to life. The consequences of electric shock are listed below (Table 16.1):

Table 16.1 Consequences of electric shock

	Electric current intensity (A)	Consequence to human body
1.	0.001-0.0075	Slight sensation
2.	0.0075-0.01	Mild sensation
3.	0.01-0.075	Painful sensation
4.	0.075-1	-Difficulty in breathing -Ventricular fibrillation -Paralyzing respiratory system -Severe burns

The effect of electric shocks on human body depends, mainly on faulty current and the time of its action. Maximum permissible contact voltages with respect to time of disconnection are as follows:

Table 16.2 Maximum permissible contact voltages with respect to time of disconnection

Maximum Permissible Contact Voltage in V	Disconnection time in (S)
240	0.04
220	0.05
110	0.2
75	1
50	5
<50	α

A circuit breaker is an automatic electric switch which protects an electrical circuit from damage caused by overload or short circuit. It stops the flow of current as soon as it detects a fault condition. In a fuse the wire is to be placed in the fuse clamp. But in a circuit breaker there is no fuse. It can be reset manually or automatically to resume normal conditions.

16.3 Ground Fault Circuit Interrupter (GFCI)

GFCI is a special safety circuit used primarily with outdoor circuits and in places where the risk of death by electric shock is greatest. A GFCI provides protection from potentially lethal ground loops by sensing both the hot wire (B) and the neutral (N) currents. If the difference between hot wire current I_B and the neutral current I_N is more than a few milli amperes then the GFCI disconnects the circuit nearly instantaneously.

Any significant difference between the hot and neutral (return path) currents means that a second path to ground has been created and a potentially dangerous condition has arisen. GFCI are typically reset table circuit breakers so that one does not need to replace a fuse every time.

16.4 Miniature Circuit Breaker (MCB)

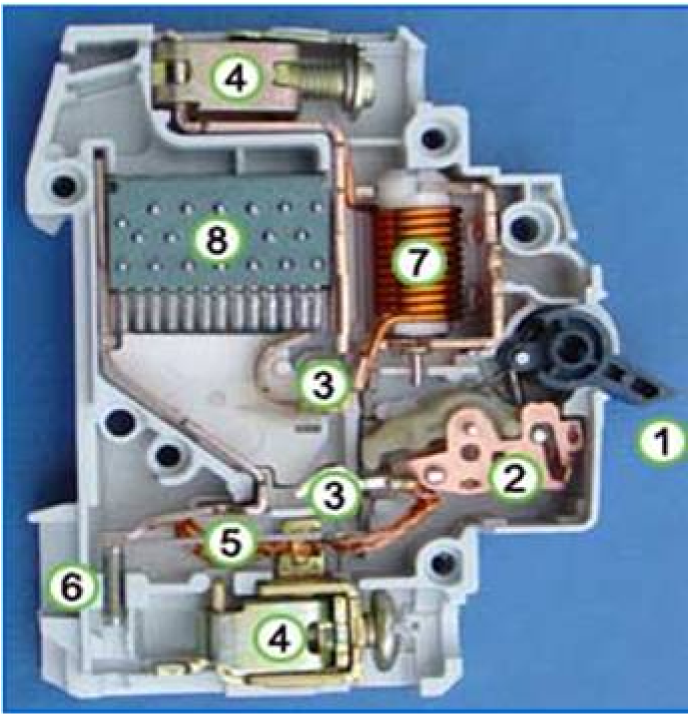
Once a fault is detected, contacts within the circuit breaker must open to interrupt the circuit; some mechanically-stored energy (using something such as springs or compressed air) contained within the breaker is used to separate the contacts, although some of the energy required may be obtained from the fault current itself. Small circuit breakers may be manually operated; larger units have solenoids to trip the mechanism, and electric motors to restore energy to the springs.

The circuit breaker contacts must carry the load current without excessive heating, and must also withstand the heat of the arc produced when interrupting the circuit. Contacts are made of copper or copper alloys, silver alloys, and other materials. Service life of the contacts is limited by the erosion due to interrupting the arc. Miniature and molded case circuit breakers are usually discarded when the contacts are worn, but power circuit breakers and high-voltage circuit breakers have replaceable contacts.

16.4.1 Construction

The 10 ampere DIN rail-mounted thermal-magnetic miniature circuit breaker is the most common style in modern domestic consumer units and commercial electrical distribution boards throughout Europe. The design includes the following components:

1. Actuator lever - used to manually trip and reset the circuit breaker. Also indicates the status of the circuit breaker (On or Off/tripped). Most breakers are designed so they can still trip even if the lever is held or locked in the "on" position. This is sometimes referred to as "free trip" or "positive trip" operation.
2. Actuator mechanism - forces the contacts together or apart.
3. Contacts - Allow current when touching and break the current when moved apart.
4. Terminals
5. Bimetallic strip.
6. Calibration screw - allows the manufacturer to precisely adjust the trip current of the device after assembly.
7. Solenoid
8. Arc divider/extinguisher



Source: Wikipedia.com

Fig. 16.1 Circuit breaker

16.4.2 Application

16.4.2.1 MCB (Miniature Circuit Breaker)

Rated current not more than 100 A. Trip characteristics normally not adjustable. Thermal or thermal-magnetic operation.

16.4.2.2 MCCB (Molded Case Circuit Breaker)

Rated current up to 2500 A. Thermal or thermal-magnetic operation. Trip current may be adjustable in larger ratings.

Numerical

1. Calculate average emf generated by an alternator if flux per pole is 0.025 Wb, frequency of the current is 40 Hz, number of turns in the coil is 100.

$$e_{av} = 2f\emptyset 2T$$

$$e_{av} = 2 \times 40 \times 0.025 \times 2 \times 100 = 400 \text{ V}$$

2. Calculate the rms value if voltage generated in the above numerical

$$e_{rms} = 4.44\ f\emptyset T\ volt$$

$$e_{rms} = 4.44 \times\ 40 \times 0.025 \times 100 = 444\ V$$

Lesson 17

CONSTRUCTION OF INDUCTION MOTORS

17.1 Introduction

Induction motors work on the principle of electromagnetic induction. Electrical energy from the stator winding is transferred to the rotor winding by electromagnetic induction. Therefore these are called as induction motors.

17.2 Types of Induction Motors

17.2.1 Single phase induction motors

It is used for domestic electrical appliances like washing machines, juicer/mixers, refrigerators etc. These machines are built in small sizes upto 3 hp.

17.2.2 3-Phase induction motor

About 90% of mechanical power in the industry is provided by 3-phase induction motors. e.g. conveyors, elevators, large capacity pumps etc.

17.2 Constructional Features of a Three Phase Induction Motor

A 3-phase induction motor (Fig. 17.1) consists of two main parts namely stator and rotor (Fig. 17.2).

Fig.17.1 Three phase induction motor

Fig. 17.2 Stator and rotor of three phase induction motor

17.3.1 Stator

It is the outer body of the motor and consists of outer frame, stator core and windings.

17.3.1.1 Outer frame

The outer frame acts as housing for the motor and supports the stator core. It also protects the inner parts of the motor. Fins are provided on the outer surface of the frame for heat dissipation and cooling of the motor. Frame is provided with legs/base plate to bolt it on the foundation. Motor housing is the outer cover or frame of the motor which contains stator, rotor and other parts. Fins are provided on the outer frame to increase heat dissipation. Housing can be square (Fig. 17.3) or round (Fig. 17.4).

Fig. 17.3 Square motor housing

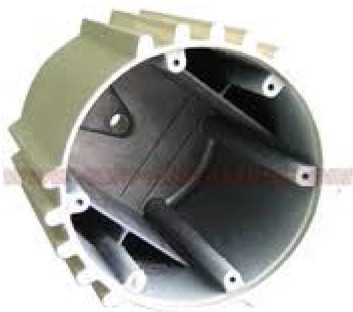


Fig. 17.4 Round motor housing

Depending on the application it can made of any one of the following material:

a. Aluminum/ Aluminum alloy (Fig. 17.5)
b. Mild Steel (Fig. 17.6)
c. Stainless Steel (Fig. 17.7)

Fig. 17.5 Aluminum motor housing

Fig. 17.6 Mild steel motor housing

Fig. 17.7 Stainless steel motor housing

17.3.1.2 Stator core

It is made of high grade silicon steel stampings of thickness 0.3 to 0.6 mm which are insulated from each other by a varnish layer. To minimize the hysteresis and eddy current losses core is constructed of steel stampings of high magnetic permeability. The stampings are assembled one over the other under hydraulic pressure and are fixed into the frame. The function of stator core is to carry the alternating magnetic field. Slots are cut on the inner side of the stamping, as shown in fig. 17.9, to accommodate stator winding.

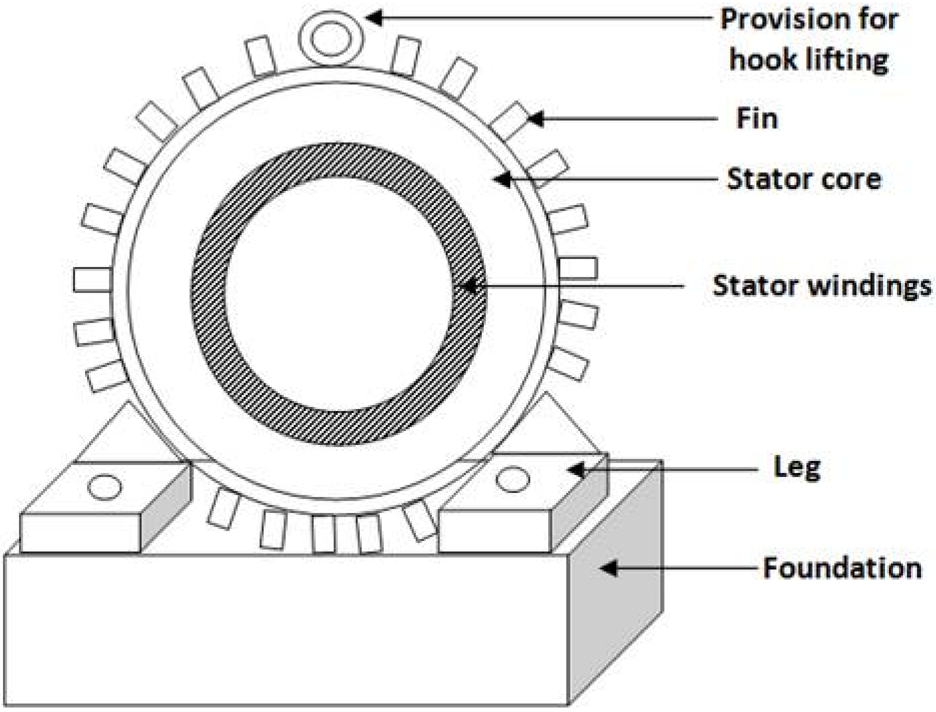


Fig. 17.8 Outer frame

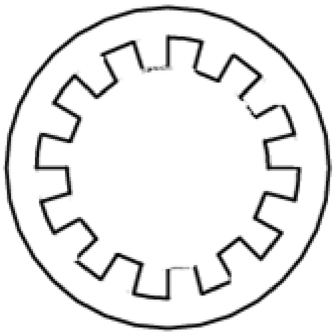


Fig. 17.9 Stator Stamping

17.3.1.3 Stator winding

Coils of insulated wires are inserted into the slots of the stator. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The three phase stator windings are connected directly to the three phase power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created. There are six terminals of the stator winding; two for each phase are connected in the terminal box of the motor. Number of poles depends on the speed requirement. For lower speed more number of poles are required as,

$$N_s \propto \frac{1}{P}$$

$$N_s = \frac{120f}{P}$$

17.3.1.4 Rotor

It is the rotating part of the motor. There are two types of rotor, which are employed in 3-phase induction motors.

(i) Squirrel cage rotor

(ii) Phase wound rotor or slip ring rotor *a) Squirrel cage rotor*

The term squirrel cage comes from the shape of the rotor which resembles the shape of the cage of squirrel animal (Fig. 17.10). Almost 90% of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings (Fig. 17.11). As the rotor bar ends are permanently short circuited, it is not possible to add any external resistance in the rotor circuit.

The slots and bars of the rotor are generally not constructed parallel to the shaft (Fig. 17.11) but are skewed (Fig. 17.12). Here skewed means that the bars and slots are constructed at an angle (Fig. 17.13). Circuit diagram of squirrel cage induction motor is shown in fig. 17.14.

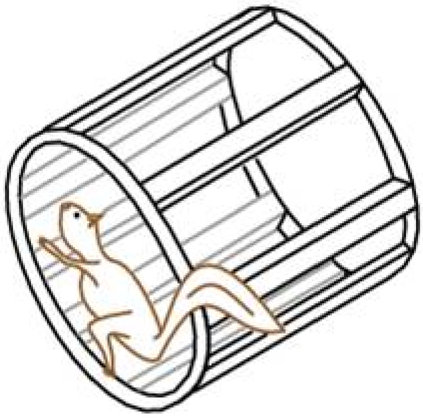


Fig. 17.10 Rotor resembles the cage of squirrel animal

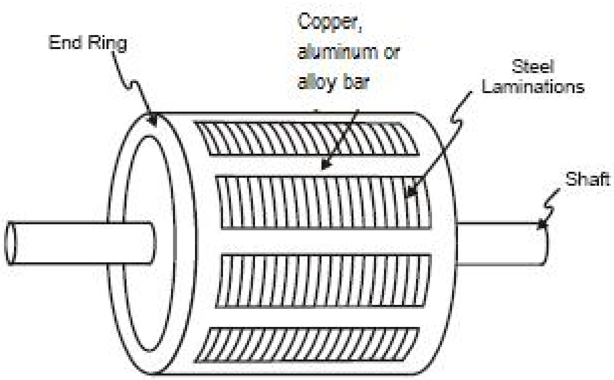


Fig. 17.11 Rotor assembly with parallel bars

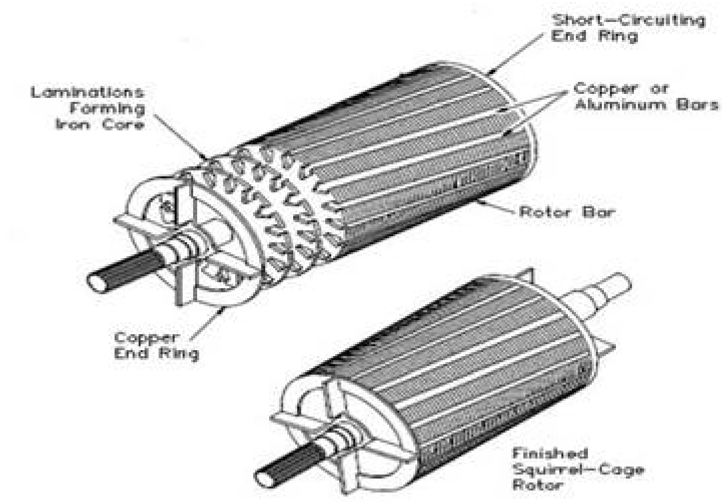


Fig. 17.12 Rotor assembly with skewed bars

Fig. 17.13 Bars and slots of rotor assembly (Skewed)

Skewing of rotor has the following advantages:

(a) It results in a smoother torque curves for different positions of the rotor,

(b) Quiet running of a motor by reducing magnetic humming.

(c) Helps to reduce magnetic locking of the stator and rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth is equal to the number of rotor teeth.

(d) It increases the rotor resistance due to increased length of the rotor bar conductors.

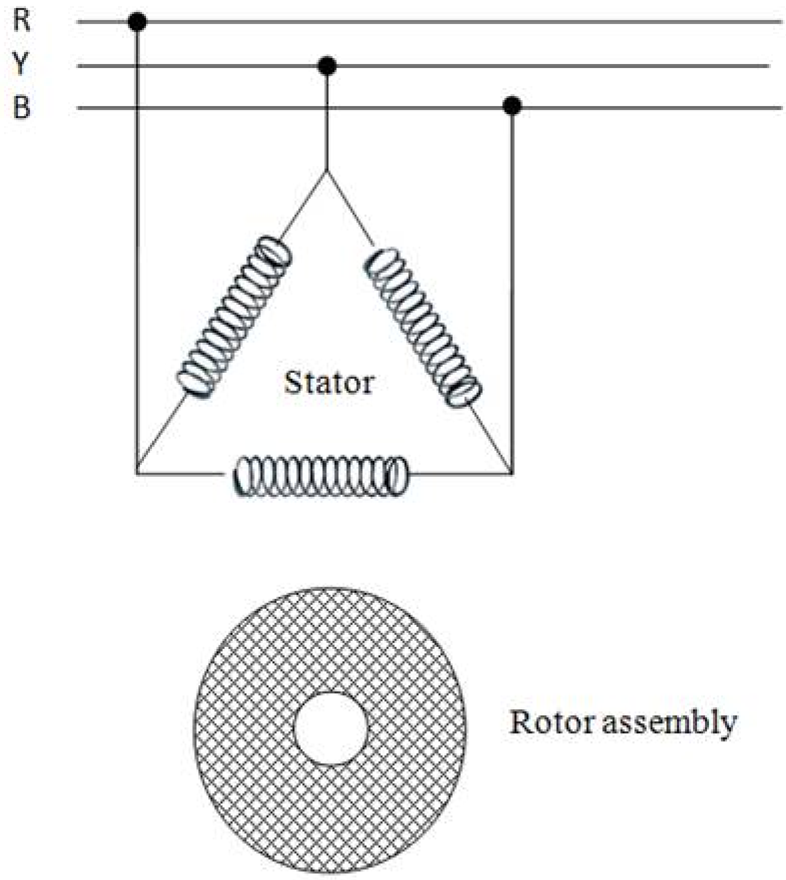


Fig. 17.14 Electrical circuit diagram of squirrel cage induction motor

b) Phase wound rotor or slip ring rotor

An alternate design, called the wound rotor, is used when variable speed is required. The rotor consists of a laminated cylindrical core having slots at the outer periphery and carries a 3-phase insulated winding. In this case, the rotor has the same number of poles as the stator and the windings are made of wire, connected to slip rings on the shaft (Fig. 17.15). Carbon brushes connect the slip rings to an external controller such as a variable resistor that allows changing the motor's slip rate. Depending upon the requirement any external resistance can be added in the rotor circuit. The motors using this type of rotor are known as phase wound or slip ring induction motors. Electrical circuit diagram of slip ring induction motor is shown in Fig. 17.16.

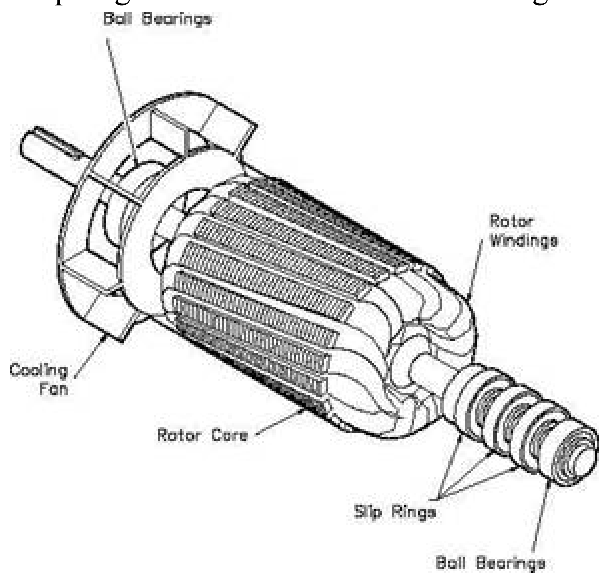


Fig 17.15 Phase wound or slip ring rotor

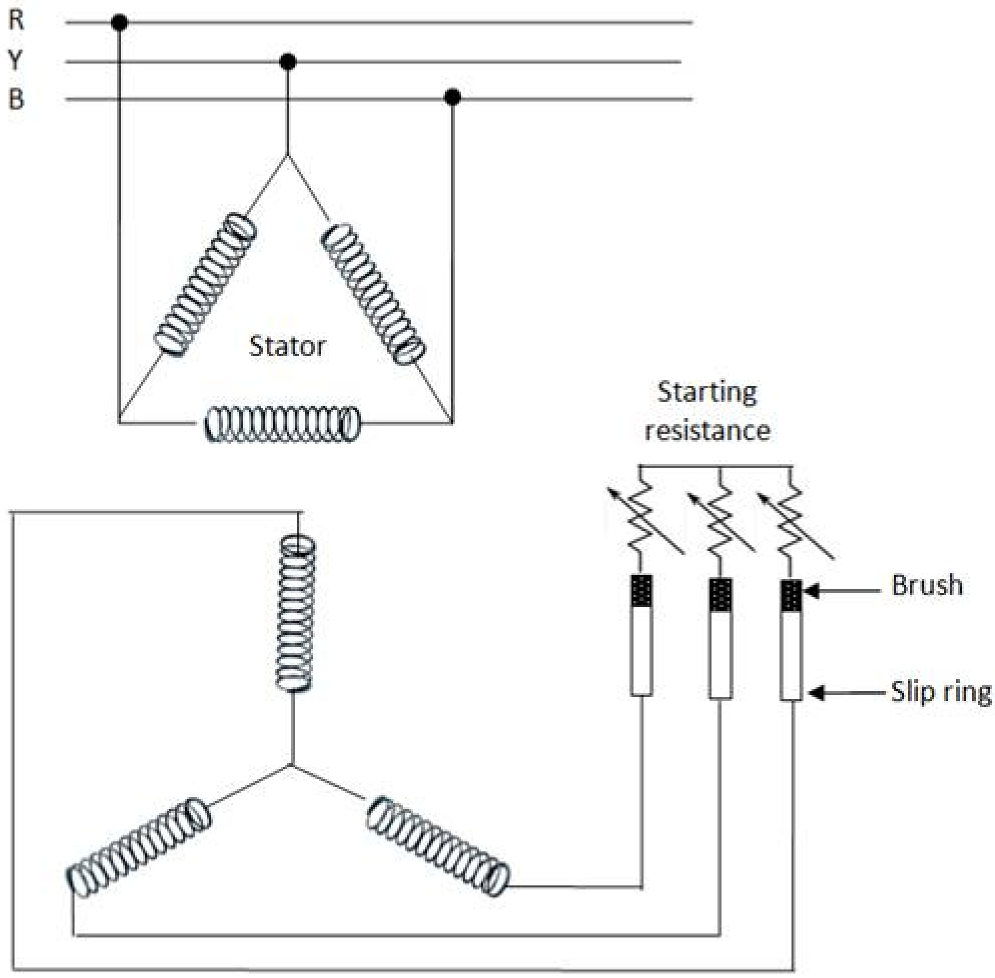


Fig 17.16 Electrical circuit diagram of slip ring induction motor

Numerical

1. Calculate synchronous speed of the motor if frequency is 50 Hz and number of poles is 8.

Solution

$$N_s = \frac{120f}{P}$$

$$= \frac{120 \times 50}{8} = 750\ rpm$$

2. At 50 Hz the motor rotates at 500 rpm. Calculate the frequency of the supply current to obtain motor speed of 1000 rpm.

Solution

$$P = \frac{120f_1}{N_{s1}}$$

$$P = \frac{120f_2}{N_{s2}}$$

Equating two equations

$$\frac{120f_1}{N_{s1}} = \frac{120f_2}{N_{s2}}$$

$$\frac{f_1}{N_{s1}} = \frac{f_2}{N_{s2}}$$

$$\frac{50}{500} = \frac{f_2}{1000}$$

$$f_2 = 100\ Hz$$

Lesson 18

PRINCIPLE OF INDUCTION MOTOR

18.1 Induction Motors

Induction motors work on the principle of electromagnetic induction. Electrical energy from the stator winding is transferred to the rotor winding by electromagnetic induction. Therefore these are called as induction motors.

Induction motors are widely used for industrial purpose because these motors are probably the simplest, low cost, high efficiency, low maintenance and most rugged of all electric motors. Two basic parts of induction motors are the wound stator and the rotor assembly. The rotor consists of laminated, cylindrical iron cores with slots to accommodate the conductors/windings. Fig 18.1 shows a induction motor. Types and detailed construction of induction motor will be taken up in the next lesson.

Fig. 18.1 Construction of the rotor

18.2 Production of Rotating Field

Consider a 3-phase induction motor having three windings placed 120^0 electrically apart. When 3-phase supply is given to the 3-phase winding, a rotating magnetic field of constant magnitude is set up by the stator. The speed of rotating field is that of the magnetic flux developed in the stator winding. The stationary rotor is effected by this magnetic field and emf is induced in the rotor windings. The conductors/windings of the rotor are short circuited at its end and therefore current is set up in the windings. Flow of current in the windings will set up a magnetic field in the rotor. Rotor windings will experience a thrust force according to Flemming right hand rule and rotor assembly starts rotating in the same direction in which the stator field is rotating. To reverse the direction of rotation of rotating field the connections of any two supply terminals are inter-changed.

The three-phase induction motor operates on the principle of a rotating magnetic field. The following discussion shows how the stator windings can be connected to a three-phase ac input and have a resultant magnetic field that rotates. Fig. 18.2 a-c shows individual windings for each phase . Figure 18.2 d shows how the three phases are tied together in a Y-connected stator. The dot in each diagram indicates the common point of the Y-connection. You can see that the individual phase windings are equally spaced around the stator. This places the windings 120º apart.

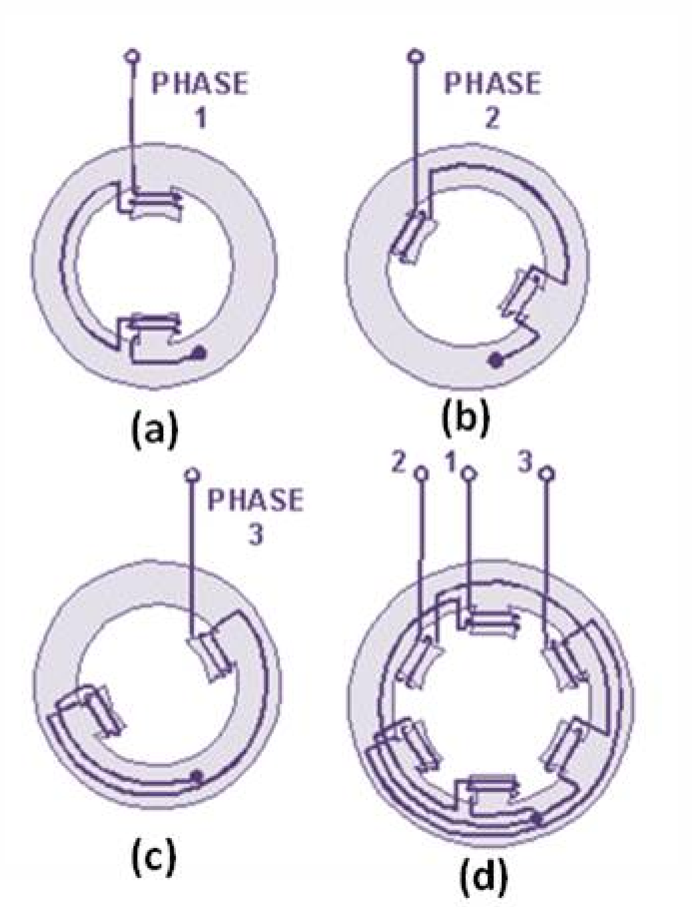


Fig. 18.2 Three phase stator

The three-phase input voltage to the stator of figure 18.2 is shown in the graph of figure 18.3. Use the left-hand rule for determining the electromagnetic polarity of the poles at any given instant. In applying the rule to the coils in figure 18.2, consider that current flows toward the terminal numbers for positive voltages, and away from the terminal numbers for negative voltages.

The results of this analysis are shown for voltage points 1 through 7 in figure 18.3. At point 1, the magnetic field in coils 1-1A is maximum with polarities as shown. At the same time, negative voltages are being felt in the 2-2A and 3-3A windings. These create weaker magnetic fields, which tend to aid the 1-1A field. At point 2, maximum negative voltage is being felt in the 3-3A windings. This creates a strong magnetic field which, in turn, is aided by the weaker fields in 1-1A and 2-2A. As each point on the voltage graph is analyzed, it can be seen that the resultant magnetic field is rotating in a clockwise direction. When the three-phase voltage completes one full cycle (point 7), the magnetic field has rotated through 360º .

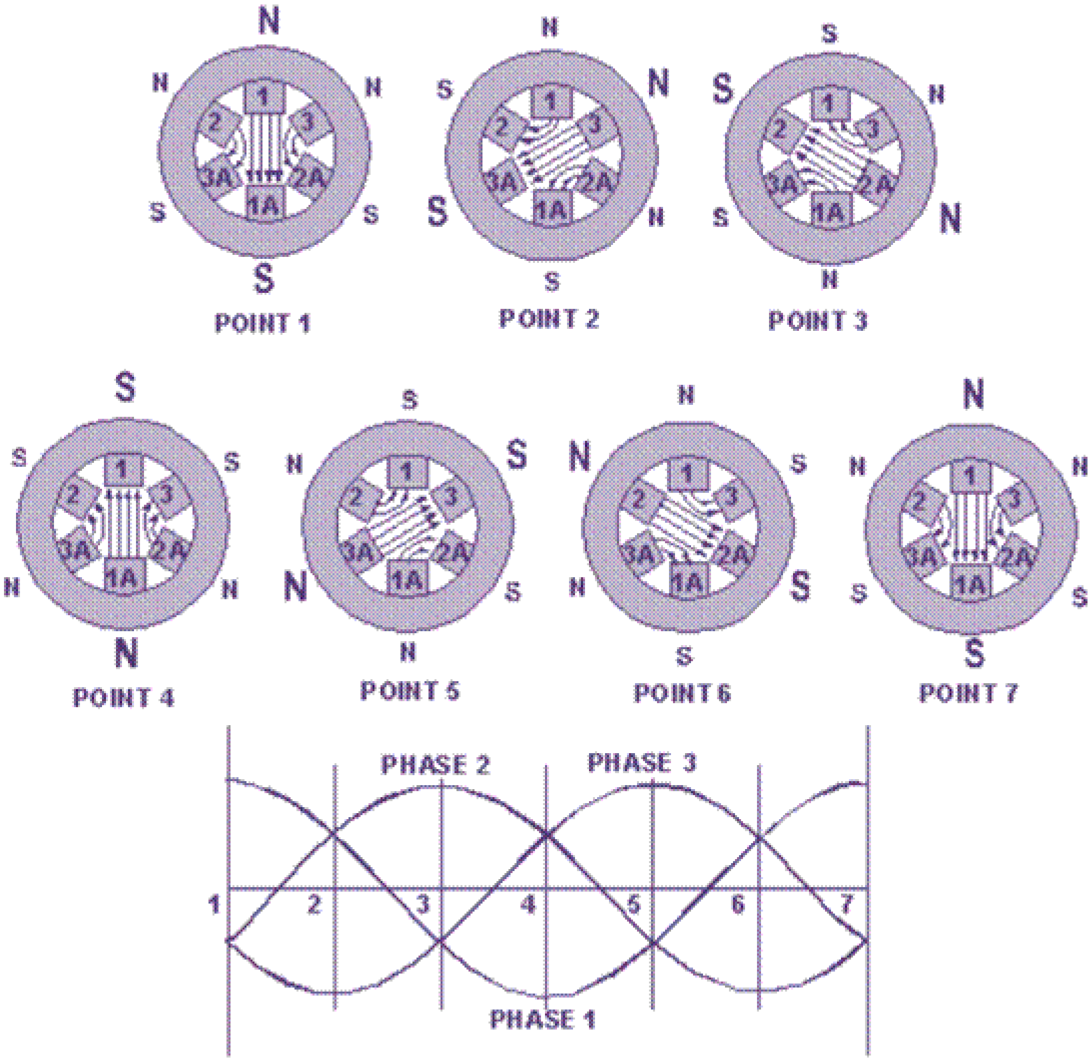


Fig. 18.3 Three phase rotating field

18.3 Slip

The speed at which the magnetic field rotates is the synchronous speed of the motor and is determined by the number of poles in the stator and the frequency of the power supply.

$$N_s = \frac{120f}{P}$$

Where:

N_S = synchronous speed

f = frequency

P = number of poles

Synchronous speed is the absolute upper limit of motor speed. At synchronous speed, there is no difference between rotor speeds and rotating field speed, so no voltage is induced in the rotor bars, hence no torque is developed. Therefore, when running, the rotor must rotate slower than the magnetic field. The rotor speed is just slow enough to cause the proper amount of rotor current to flow, so that the resulting torque is sufficient to overcome winding and friction losses, and drive the load. This difference between the rotor speeds (N) and rotating magnetic field speed (N_S), called slip, is normally referred to as a percentage of synchronous speed:

$$\%S = \frac{(N_s - N)}{N_s}\ 100$$

$$S = \frac{(N_s - N)}{N_s}$$

Where,

$\%S$= Percent slip

S= Fractional slip

N_s = synchronous speed

N = actual rotor speed

Rotor speed, $N = N_s (1-S)$

The difference between synchronous speed and rotor speed is called slip speed:

Slip speed = $N_s - N$

The difference between the rotor speed and synchronous speed of flux determine the rate at which the flux is cut by the rotor conductors and hence the magnitude of induced e.m.f. $e_2 \propto N_s - N$

Since,

Rotor current, $i_2 \propto e_2$

and torque, $T \propto i_2$

$T \propto (N_s - N)$

or $T = K (N_s - N)$

or $T = KN_s \left(\frac{N_s - N}{N_s}\right)$

or $T = K' S$

or $T \propto S$

Thus, greater the slip greater will be the induced e.m.f. and thus motor will develop higher torque. At no-load conditions, induction motor requires small torque to meet with the mechanical, iron and other losses, therefore, slip is small. When the motor is loaded, greater torque is required to drive the load, therefore, the slip increases and rotor speed decreases slightly. Slip in an induction motor adjusts itself to such a value so as to meet the required moving torque under normal operation. The value of slip varies from about 6% for small motors and 2% for large motors.

18.4 Frequency of Rotor Current

The frequency of rotor currents depends upon the relative speed between rotor and stator field. When the rotor is stationary, the frequency of rotor currents is the same as that of the supply frequency but when the rotor starts rotating, the frequency of rotor current will depend on the slip speed ($N_s - N$).

If (N_s-N) is slip, P no. of poles then the frequency of rotor current f_r is given as

$$f_r = \frac{(N_s - N)P}{120}$$

$$= \frac{(N_s - N)}{N_s} \frac{N_s P}{120}$$

$$f_r = S \times f$$

Lesson 19

SINGLE PHASE INDUCTION MOTOR

19.1 Single Phase Induction Motor

There are probably more single-phase AC induction motors in use today than the total of all the other types put together. It is logical that the least expensive, lowest maintenance type motor should be used most often. The single-phase AC induction motor best fits this description. As the name suggests, this type of motor has only one stator winding (main winding) and operates with a single-phase power supply. In all single-phase induction motors, the rotor is the squirrel cage type.

The single-phase induction motor is not self-starting (Fig. 19.1). When the motor is connected to a single-phase power supply, the main winding carries an alternating current. This current produces a pulsating magnetic field. Due to induction, the rotor is energized. As the main magnetic field is pulsating, the torque necessary for the motor rotation is not generated. This will cause the rotor to vibrate, but not to rotate. Hence, the single phase induction motor is required to have a starting mechanism that can provide the starting kick for the motor to rotate.

The starting mechanism of the single-phase induction motor is mainly an additional stator winding (start/ auxiliary winding) as shown in Figure 19.2. The start winding can have a series capacitor and/or a centrifugal switch. When the supply voltage is applied, current in the main winding lags the supply voltage due to the main winding impedance. At the same time, current in the start winding leads/lags the supply voltage depending on the starting mechanism impedance. Interaction between magnetic fields generated by the main winding and the starting mechanism generates a resultant magnetic field rotating in one direction. The motor starts rotating in the direction of the resultant magnetic field.

Once the motor reaches about 75% of its rated speed, a centrifugal switch disconnects the start winding. From this point onward, the single-phase motor can maintain sufficient torque to operate on its own. Except for special capacitor start/capacitor run types, all single-phase motors are generally used for applications up to 3/4 hp only. Depending on the various starting techniques, single-phase AC induction motors are further classified as described in the following sections.

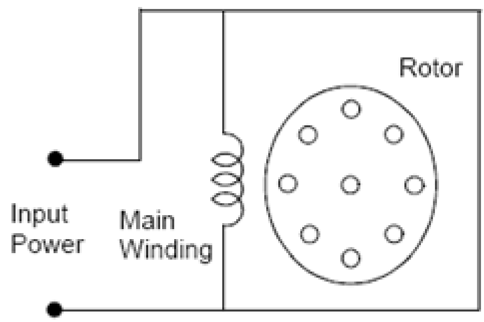


Fig. 19.1 Single phase induction motor (without start mechanism)

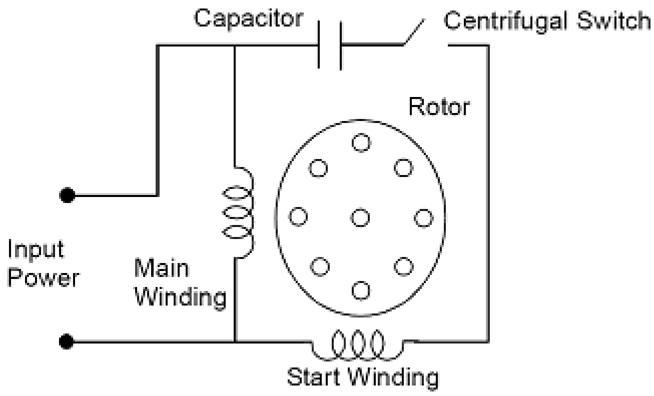


Fig. 19.2 Single phase induction motor (with start mechanism)

19.2 Types of Single Phase Induction Motor

19.2.1 Split-phase induction motor

The split-phase motor is also known as an induction start/induction run motor. It has two windings: a start and a main winding. The start winding is made with smaller gauge wire and fewer turns, relative to the main winding to create more resistance, thus putting the start winding's field at a different angle than that of the main winding which causes the motor to start rotating. The main winding, which is of a heavier wire, keeps the motor running the rest of the time.

The starting torque is low, typically 100% to 175% of the rated torque. The motor draws high starting current, approximately 700% to 1,000% of the rated current. The maximum generated torque ranges from 250% to 350% of the rated torque (see Figure 19.8 for torque-speed curve).

Good applications for split-phase motors include small grinders, small fans and blowers and other low starting torque applications with power needs from 1/20 to 1/3 hp. Avoid using this type of motor in any applications requiring high on/off cycle rates or high torque.

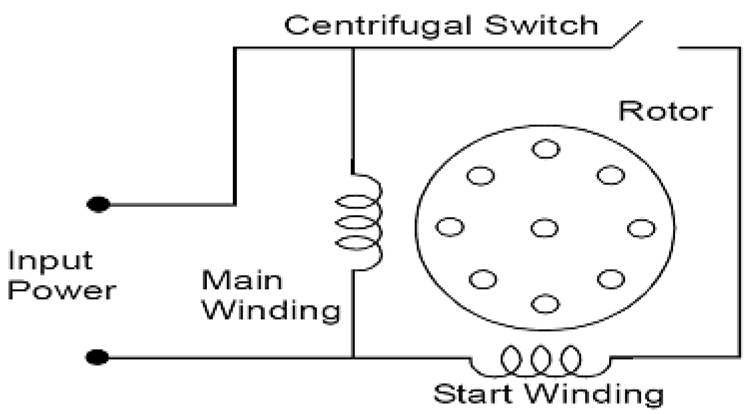


Fig. 19.3 Split-phase induction motor

19.2.2 Capacitor start induction motor

This is a modified split-phase motor with a capacitor in series with the start winding to provide a start "boost." Like the split-phase motor, the capacitor start motor also has a centrifugal switch which disconnects the start winding and the capacitor when the motor reaches about 75% of the rated speed.

Since the capacitor is in series with the start circuit, it creates more starting torque, typically 200% to 400% of the rated torque. And the starting current, usually 450% to 575% of the rated current, is much lower than the split-phase due to the larger wire in the start circuit. Refer to Figure 19.8 for torque-speed curve.

A modified version of the capacitor start motor is the resistance start motor. In this motor type, the starting capacitor is replaced by a resistor. The resistance start motor is used in applications where the starting torque requirement is less than that provided by the capacitor start motor. Apart from the cost, this motor does not offer any major advantage over the capacitor start motor. They are used in a wide range of belt-drive applications like small conveyors, large blowers and pumps, as well as many direct-drive or geared applications.

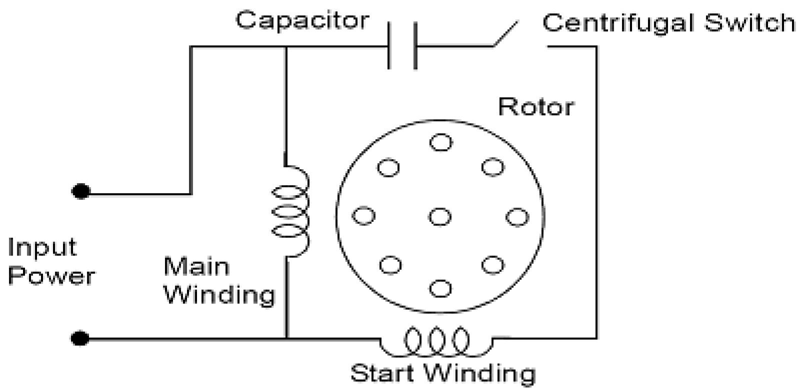


Fig. 19.4 Capacitor start induction motor

19.2.3 Permanent split capacitor (capacitor run) induction motor

A permanent split capacitor (PSC) motor has a run type capacitor permanently connected in series with the start winding. This makes the start winding an auxiliary winding once the motor reaches the running speed. Since the run capacitor must be designed for continuous use, it cannot provide the starting boost of a starting capacitor. The typical starting torque of the PSC motor is low, from 30% to 150% of the rated torque. PSC motors have low starting current, usually less than 200% of the rated current, making them excellent for applications with high on/off cycle rates. Refer to Figure 19.8 for torque-speed curve.

The PSC motors have several advantages. The motor design can easily be altered for use with speed controllers. They can also be designed for optimum efficiency and High-Power Factor (PF) at the rated load. They're considered to be the most reliable of the single-phase motors, mainly because no centrifugal starting switch is required.

Permanent split-capacitor motors have a wide variety of applications depending on the design. These include fans, blowers with low starting torque needs and intermittent cycling uses, such as adjusting mechanisms, gate operators and garage door openers.

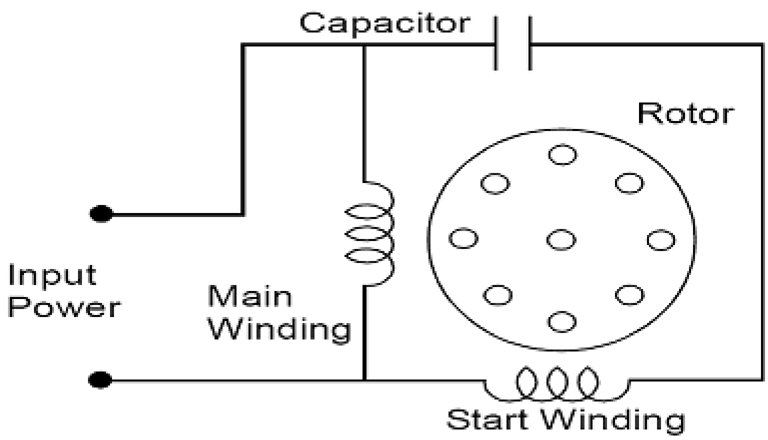


Fig. 19.5 Permanent split capacitor (capacitor run) induction motor

19.2.4 Capacitor start/capacitor run induction motor

This motor has a start type capacitor in series with the auxiliary winding like the capacitor start motor for high starting torque. Like a PSC motor, it also has a run type capacitor that is in series with the auxiliary winding after the start capacitor is switched out of the circuit. This allows high overload torque.

This type of motor can be designed for lower full-load currents and higher efficiency (see Figure 19.8 for torque-speed curve). This motor is costly due to start and run capacitors and centrifugal switch. Application of these motors include air compressors, high-pressure water pumps, vacuum pumps and other high torque applications requiring 1 to 10 hp.

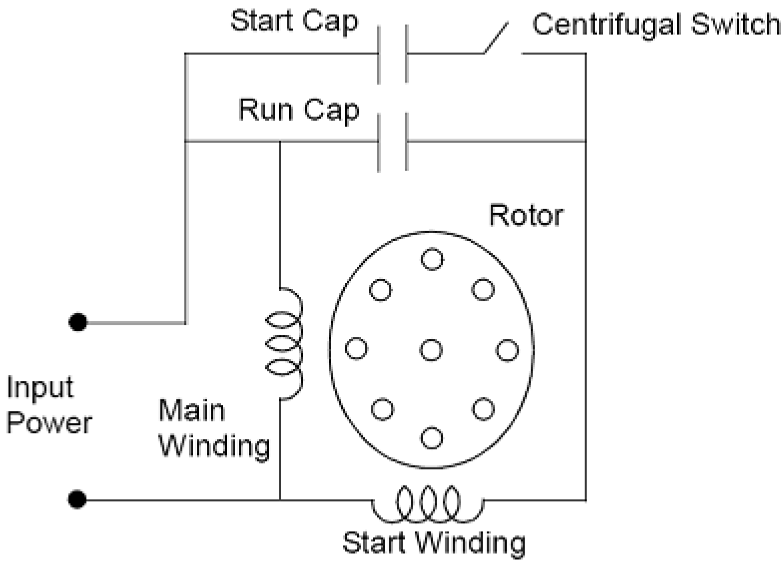


Fig. 19.6 Capacitor start/capacitor run induction motor

19.2.5 Shaded-pole induction motor

Shaded-pole motors have only one main winding and no start winding. Starting is by means of a design that rings a continuous copper loop around a small portion of each of the motor poles. This “shades” that portion of the pole, causing the magnetic field in the shaded area to lag behind the field in the unshaded area. The reaction of the two fields gets the shaft rotating.

Because the shaded-pole motor lacks a start winding, starting switch or capacitor, it is electrically simple and inexpensive. Also, the speed can be controlled merely by varying voltage, or through a multi-tap winding. Mechanically, the shaded-pole motor construction allows high-volume production. In fact, these are usually considered as “disposable” motors, meaning they are much cheaper to replace than to repair.

The shaded-pole motor has many positive features but it also has several disadvantages. Its low starting torque is typically 25% to 75% of the rated torque. It is a high slip motor with a running speed 7% to 10% below the synchronous speed. Generally, efficiency of this motor type is very low (below 20%).

The low initial cost suits the shaded-pole motors to low horsepower or light duty applications. Perhaps their largest use is in multi-speed fans for household use. But the low torque, low efficiency and less sturdy mechanical features make shaded-pole motors impractical for most industrial or commercial use, where higher cycle rates or continuous duty are the norm. Figure 19.8 shows the torque-speed curves of various kinds of single-phase AC induction motors.

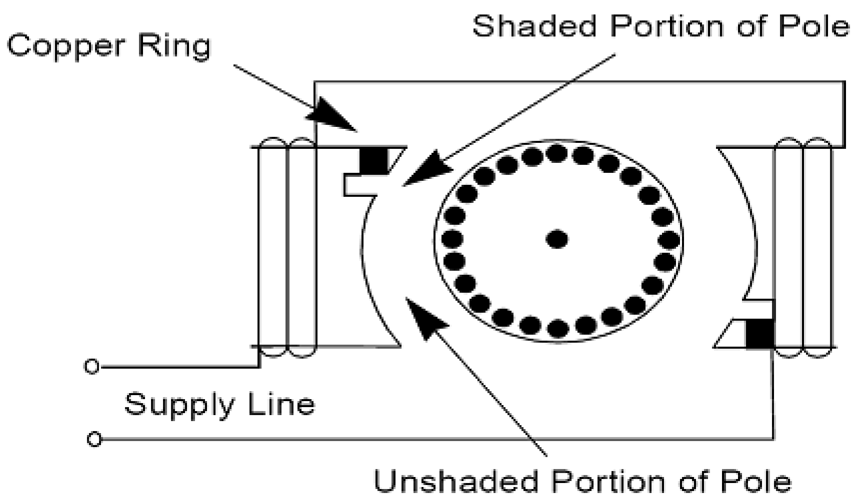


Fig. 19.7 Shaded-pole induction motor

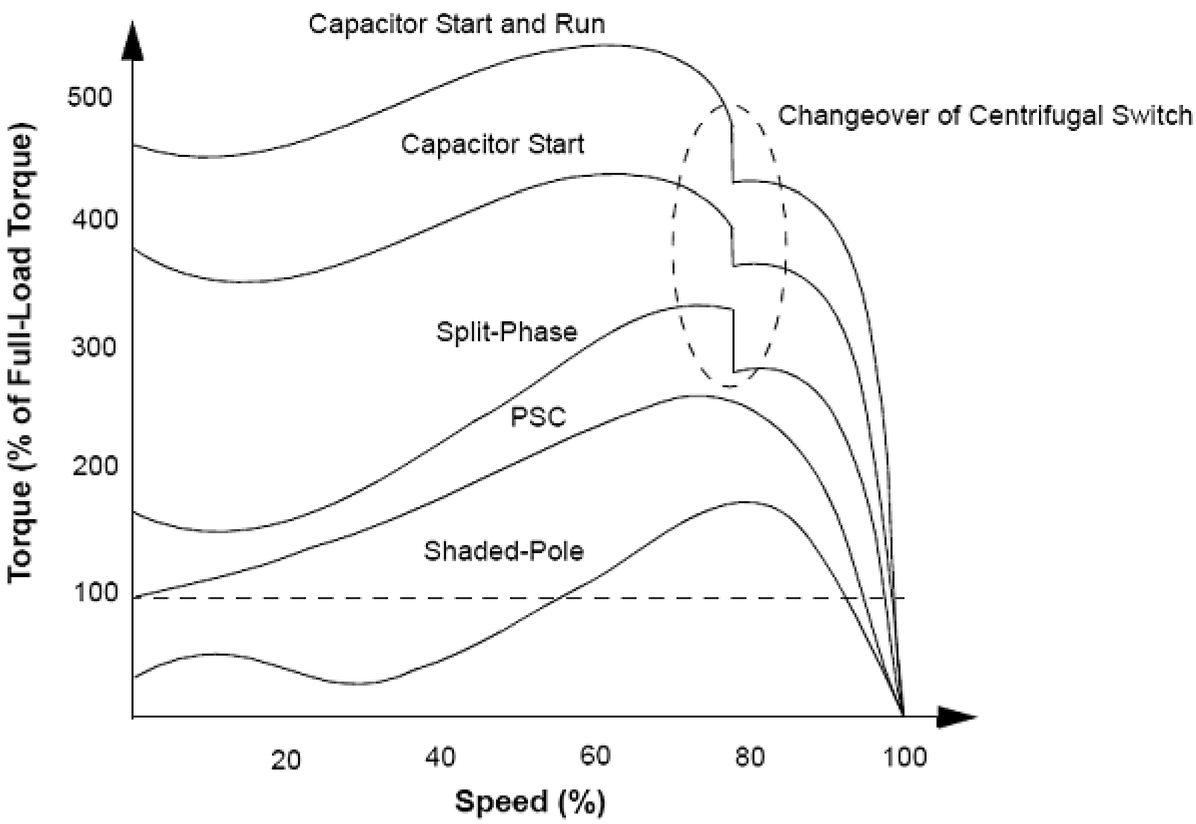


Fig. 19.8 Torque-speed curves of different types of single-phase induction motors

Lesson 20

PERFORMANCE CHARACTERISTICS OF INDUCTION MOTORS

20.1 Important Terms and Definitions

20.1.1 Torque

Torque is the turning force through a radius and the units is in Nm.

20.1.2 Slip

The difference between synchronous speed and rotor speed is called slip speed or simply slip:

Slip speed (S) = $N_s - N$

And $T \propto S$

From above equation greater the slip greater will be the induced e.m.f. and thus motor will develop higher torque.

20.2 Expression for Torque

Torque developed by an induction motor is given by the following equation:

$$T = \frac{m.\,S{E_{2s}}^2 R_2}{\omega_s[(R_2)^2 + (SX_{2s})^2]}$$

Where,

m = number of phases

S = Slip

E_{2s} = Induced emf in rotor when rotor is stationary

R_2 = Resistance of rotor

ω_s(angular synchronous speed$\frac{rad}{s}$) $= \frac{2\pi N_s}{60}$

X_{2s} = Leakage reactance of rotor when rotor is stationary

20.3 Condition for Maximum Torque

Condition for maximum torque is given by,

$$R_2 = S\,X_{2s} \qquad \text{………….....…..equ. 1}$$

Where,

R_2 = Resistance of rotor

S = Slip

X_{2s} = Leakage reactance of rotor when rotor is stationary

Or, Slip $S = R_2/X_{2s}$ ……………..equ. 2

Substituting value of equ. 2 into expression for torque in section 20.2,

$$\text{Maximum Torque } T_m = \frac{m.\,{E_{2s}}^2}{2\omega_s}$$

From the above equation it is evident that to achieve higher torque, the value of leakage reactance of the rotor should be minimum. Therefore rotor conductors are placed close to the outer periphery of the rotor and the air gap between rotor and stator is kept as small as possible.

20.4 Starting Torque

At start of motor rotor is stationary and the value of slip (N_s–N) is one i.e. S=1. Thus,

$$\text{Starting Torque } T_s = \frac{m.\,SE_{2s}{}^2 R_2}{\omega_s[(R_2)^2 + (X_{2s})^2]}$$

Where,

m = number of phases

E_{2s} = Induced emf in rotor when rotor is stationary

R_2 = Resistance of rotor

$$\omega_s(\text{angular synchronous speed}\frac{\text{rad}}{\text{s}}) = \frac{2\pi N_s}{60}$$

X_{2s} = Leakage reactance of rotor when rotor is stationary

We know Condition of maximum torque, R_2 = S X_{2s} and for heavy loaded induction motors, sometimes maximum torque is required at start. For maximum torque during starting placing S= 1

$$R_2 = X_{2s}$$

To obtain maximum torque at start, the value of rotor resistance must be equal to rotor leakage reactance at standstill. External resistance is added in the rotor circuit at the start of motor to get higher torque. Addition of variable resistance is only possible in case of slip ring induction motors. Therefore slip ring induction motors used for heavy loads applications like in cranes, conveyors, mechanical jacks, elevators etc.

20.5 Torque-Slip Characteristics

Torque-slip curve can be plotted (fig. 20.1) by considering different cases for the following torque expression discussed in section 20.2:

$$T = \frac{m.\,SE_{2s}{}^2 R_2}{\omega_s[(R_2)^2 + (SX_{2s})^2]}$$

Case 1: When rotor speed N = Synchronous speed N_s

Slip S = 0 and Torque T = 0

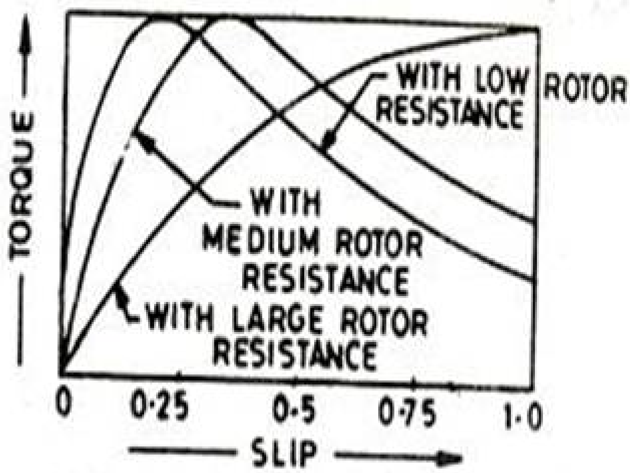


Fig. 20.1 Torque slip characteristics

Case 2: When rotor speed N close to Synchronous speed N_s i.e. very low slip

When S is very small $SX_{2s} << R_2$ then SX_{2s} can be neglected.

From torque equation:

$$T = \frac{m.SE_{2s}{}^2R_2}{\omega_s[(R_2)^2 + 0]}$$

$$= \frac{m.SE_{2s}{}^2R_2}{\omega_s(R_2)^2}$$

$$= \frac{m.SE_{2s}{}^2}{\omega_s R_2}$$

$$T = KS$$

Where K = constant

$$K = \frac{m.E_{2s}{}^2}{\omega_s R_2}$$

Or, $T \propto S$

Thus at very small value of slip S, torque (T) is directly proportional to S and straight line can be observed.

Case 3: Maximum value of torque

When Slip S = R_2/X_{2s}

Case 4: At high slip

When value of slip increases further beyond the maximum torque value of slip, $SX_{2s} >> R_2$

Or, $SX_{2s}{}^2 >> R_2{}^2$

$$T = \frac{m.SE_{2s}{}^2R_2}{\omega_s[0 + (SX_{2s})^2]}$$

$$T = K'\frac{1}{S}$$

$$T \propto \frac{1}{S}$$

At higher value of slip, torque is inversely proportional to slip.

20.6 Torque Speed Characteristics

It's important to understand some details of motor performance as shown by a typical Torque-Speed curve in the Figure 20.2. The plot shows what happens in terms of output torque and motor speed when a motor is started with full voltage applied. The motor is initially at zero speed and develops locked-rotor torque (Point A). As the motor accelerates, some motor designs produce a slight dip in torque. If they do, the lowest point on this curve is called the pull-in or pull-up torque (Point B). As the speed increases further, the torque generally increases to the highest point on the curve (Point C), which is called the pullout or breakdown torque. Finally, when the motor is loaded to its full-load torque, the motor speed stabilizes (Point D). If the motor isn't driving anything, its speed goes up to its no-load speed or synchronous speed (Point E). For example, on a four-pole motor operating at 60 Hz, the no-load speed might be 1,799 RPM and synchronous speed would be 1,800 RPM. Each of these points (A, B, C, and D) has absolute values (usually expressed in pound-feet). However, they're frequently given in terms of a percentage of the full-load torque. Torque speed curve varies when external resistance is added to the rotor winding (Fig. 20.3).

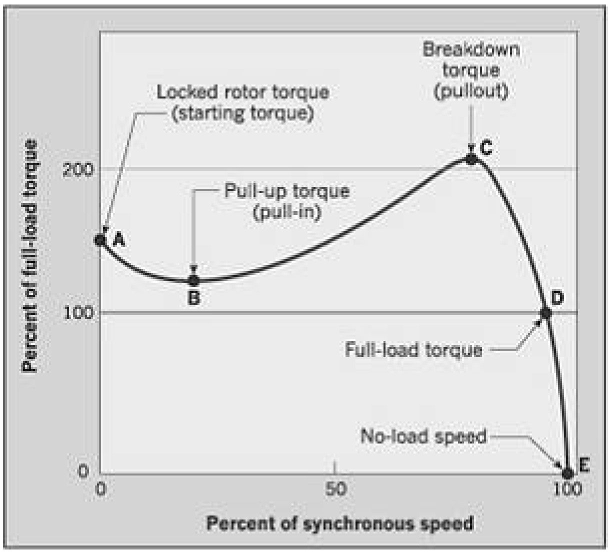


Fig. 20.2 Torque speed curve for induction motor

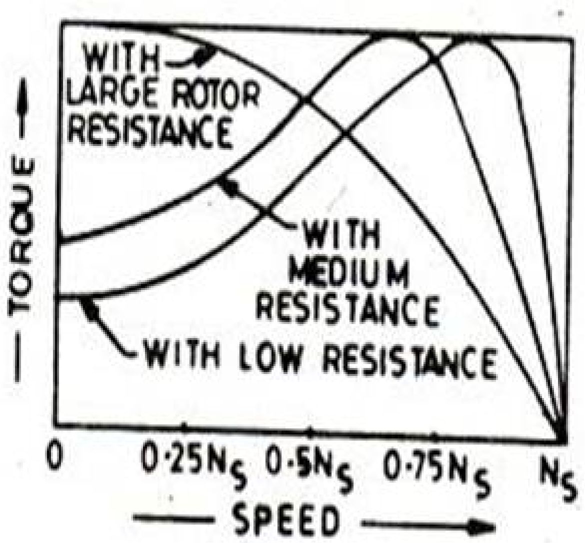


Fig.20.3 Torque speed curve for induction motor

20.7 Losses in an Induction motor

The major losses in an induction motor can be classified as stator and rotor losses (Fig. 20.4 and Table 20.1):

20.7.1 Stator losses

Losses occurring in the stator of an induction motor are called stator losses.

i. **Stator copper losses** – $I^2_1 R_1$ per phase

ii. **Stator iron losses** – Hysteresis and eddy current losses.

20.7.2 Rotor losses

Losses occurring in the rotor of an induction motor are called rotor losses.

i. **Rotor copper losses** – $I^2_2 R_2$ per phase

ii. **Rotor iron losses** –These losses small and can be neglected.

20.7.3 Mechanical losses

The sums of winding and friction losses are called mechanical losses.

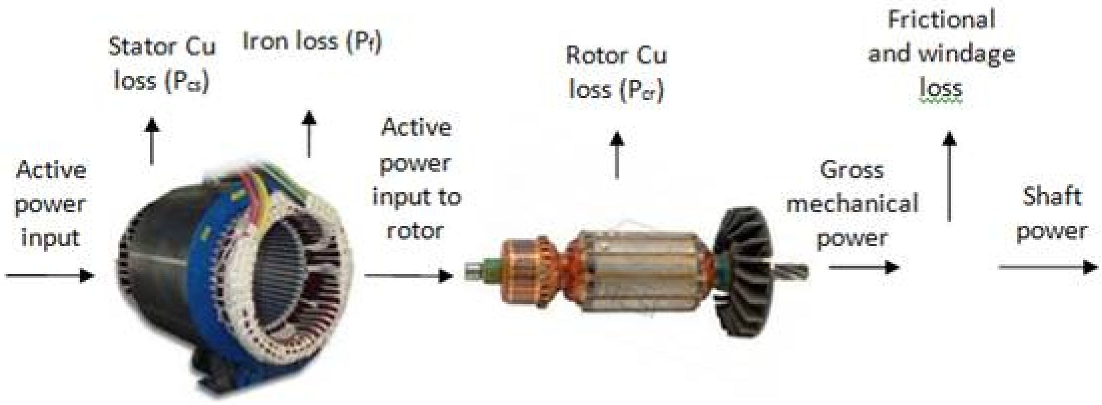


Fig. 20.4 Losses in an Induction motor

Table 20.1 Percentage of losses in an induction motor

Name	Percent of total loss Losses	Description	Fixed or Variable	How to reduce
Core Losses	15-15%	Energy required to magnetize core.	Fixed	Improved permeability steel, lengthening core, using thinner laminations in the core.
Windage and Friction	5-15%	Losses due to bearing friction and air resistance, which is primarily caused by the cooling fan.	Fixed	Lower friction bearings, improve fan design and air flow.
Stator Losses	25-40%	Heating due to current flow through the resistance of the stator winding.	Variable	Increasing the volume of copper wire in the stator, through improved stator slot designs, and by using thinner insulation.
Rotor Losses	15-25%	Heating due to I2R losses in the rotor conductive bars.	Variable	Increasing the size of rotor conductive bars and end rings to reduce resistance.
Additional Load Losses	10-20%	Leakage fluxes induced by load currents and	Variable	Various design and manufacturing details.

		various other minor losses.		

Lesson 21

STARTING AND SPEED CONTROL OF INDUCTION MOTOR

21.1 Need of a Starter

The main problem in starting induction motors having large or medium size lies mainly in the requirement of high starting current when directly started from the main supply. As a consequence there will be a large voltage drop in the distribution line and will affect operation of other electrical machines, which is undesirable. Purpose of the starter is to limit the initial peak current drawn by the induction motor.

21.2 Starters for Squirrel Cage Induction Motors

Starters for squirrel cage induction motors can be classified as follows:

1. Direct On Line (D.O.L) Starter;
2. Star/Delta Starter;
3. Auto-transformer Starter.

21.2.1 Direct on line (D.O.L) starter

In this method stator is directly connected to the main power supply. The current drawn by motor, depending on its design class, will be from 5 to 7 times the nominal current rating. Since this amount of current flows only for a short period of time, it would not damage the squirrel cage motor, but it may cause undesirable drop in supply voltage, power factor and subsequently affects the performance of other equipment connected to the same supply. For this reason, the supply authorities limit the size of motor upto 5 H.P. which can be started by this starter.

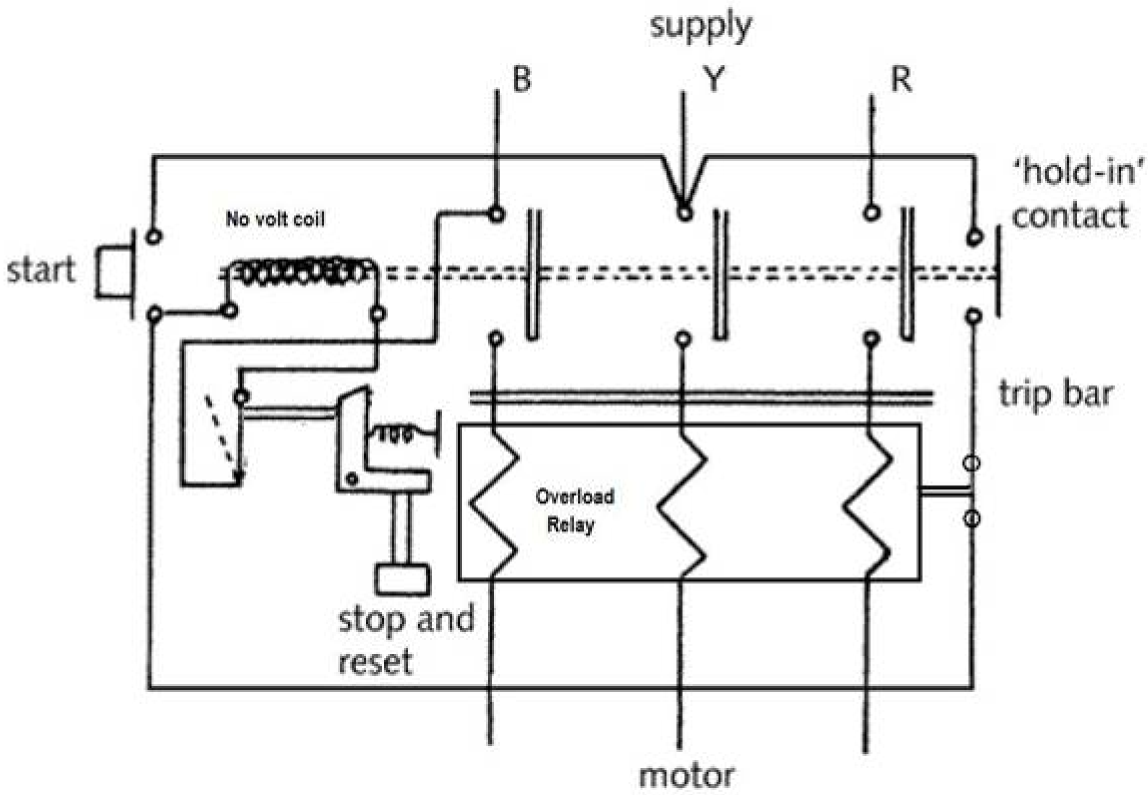


Fig. 21.1 Direct online starter

A direct on line Starter essentially consists of a contactor having four normally open (N.O.) contacts and a energizing coil also known as no-volt coil. The function of this coil is to keep together the N.O. contacts when starter is switched on. In case power supply fails, no-volt coil de-energizes and the circuit is open. The motor will not start automatically if the power supply is resumed and starter has to be switched ON once gain. Two push buttons ON and OFF are provided on the starter to start and stop the motor. To protect motor against overload, thermal or magnetic over-load coils are connected in each phase.

21.2.1.1 Start condition

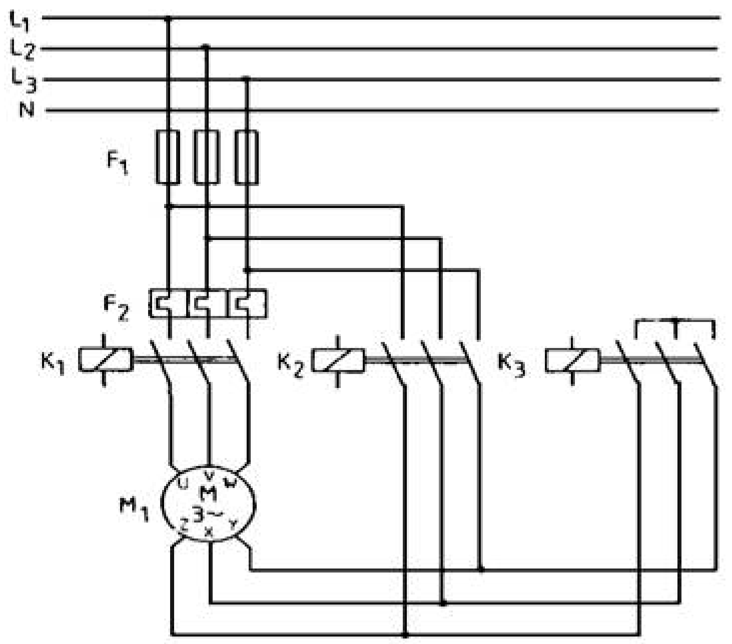
ON button of starter completes the circuit of the no volt coil and it is energized. The four N.O. contacts are brought together by the bar connected to no volt coil and the motor starts.

21.2.1.2 Stop condition

To stop the motor, OFF push button is pressed which de-energies the no volt coil opening the main contacts.

21.2.2 Star-delta starter

This method is used for motors that are designed to operate with Δ (delta) connection. The components normally consist of three contactors, an overload relay and a timer for setting the time in the star-position at starting position (Fig. 21.2). The phases of stator are initially (star) connected using a relay switch (K3). Once up to a particular running speed a double throw switch (K2) changes the winding arrangements from Y to Δ whereupon full running torque is achieved (Fig. 21.3). In this method the starting voltage across each phase is $V_L/\sqrt{3}$ and thus the starting current is lower which leads to a smaller starting torque. Such an arrangement means that the ends of all stator windings must be brought to terminations outside the casing of the motor. The starter is provided with overload and under voltage protection devices.



L: Line conductor

N: Neutral conductor

F_1: Fuses

F_2: Thermal overload cut-out

K_1: Main contactor

K_2: Delta contactor

K_3: Star contactor

M_1: Three-phase motor

Fig. 21.2 Star-delta starter

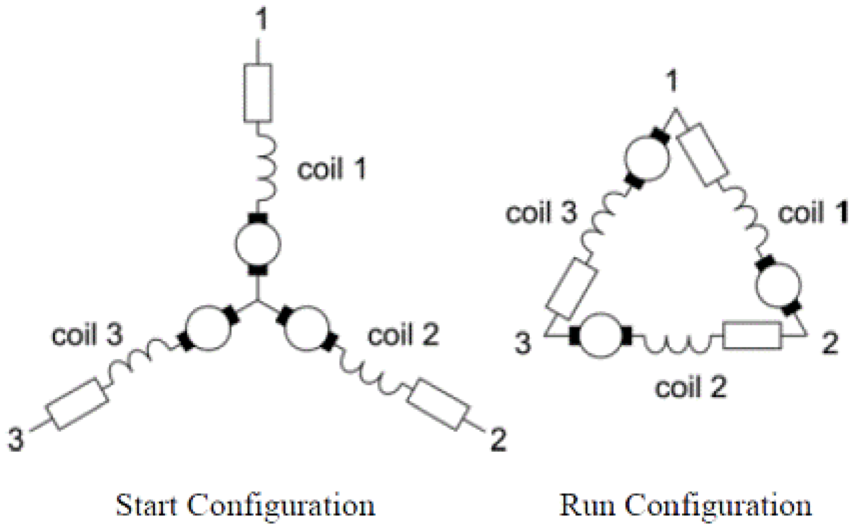


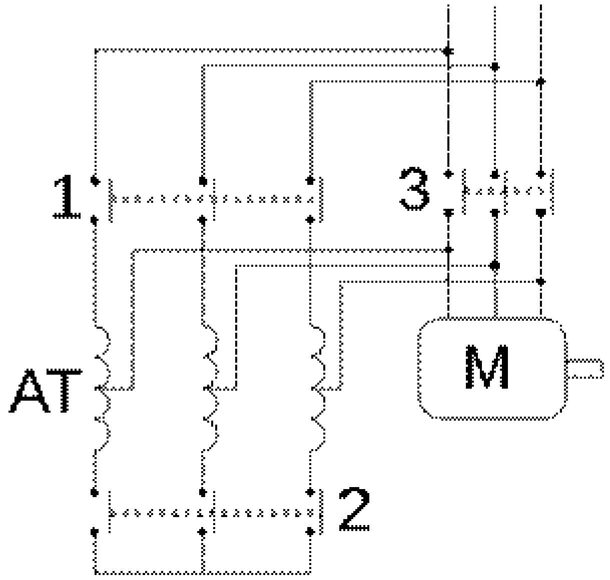
Fig. 21.3 Start and running configuration of rotor winding

The received starting current is about 30 % of the starting current during direct on line start and the starting torque is reduced to about 25 % of the torque available at a D.O.L start. This starting method only works when the application is light loaded during the start. If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position. When starting up, the load torque is low at the beginning of the start and increases with the square of the speed. When reaching approximately 80-85% of the motor rated speed the load torque is equal to the motor torque and the acceleration ceases. To reach the rated speed, a switch over to delta position is necessary, and this will very often result in high transmission and current peaks. In some cases the current peak can reach a value that is even bigger than for a D.O.L start. Applications with a load torque higher than 50% of the motor rated torque will not be able to start using the star-delta starter.

21.3.3 Auto transformer starter

This is another starting method that reduces the starting current and starting torque but contrary to Star-Delta starting where this starting method needs three wires and three terminals on the motor. Autotransformers are generally equipped with taps at each phase in order to adapt the starting parameters to the application starting requirement. During starting, the motor is connected to the autotransformer taps. With the star and autotransformer contactors closed, the motor is under reduced voltage. Consequently the torque is reduced as the square of the applied voltage. When the motor reaches the 80 to 95% of the nominal speed, the star contactor opens. Then the line contactor closes and the autotransformer contactor opens. The motor is never disconnected from the power supply during starting (closed transition) and reduces transient phenomena. Taps on the autotransformer allow for selection of the motor with 50%, 65%, or 80% of the current inrush seen during a full voltage start. The resulting starting torque will be 25%, 42%, or 64% of full voltage values, as will be the current draw on the line. Thus, the autotransformer provides the maximum torque with minimum line current.

In this method, quite less current is drawn from supply as compared to previous method, but the extra equipment is still required. On the other hand, the starting torque is small as a result of low amount of voltage at starting instant, so this method is not useful for high inertia loads.



AT: Auto transformer1, 2, 3: Switches

Fig. 21.4 Auto transformer starter

21.4 Starting Method of Slip Ring Induction Motor

If it is necessary to start a three phase induction motor on load then a wound rotor machine also known as slip ring motor will normally be selected. Such a machine allows an external resistance to be connected to the rotor of the machine through slip rings and brushes. A 3-phase rheostat is connected in series with the rotor circuit through brushes (Fig.21.5). At start-up the rotor resistance is set at maximum but is reduced as speed increases until eventually it is reduced to zero and the machine runs as if it is a cage rotor machine. By inserting external resistance in the rotor circuit, not only the starting current is reduced but at the same time starting torque is increased due to improvement of power factor.

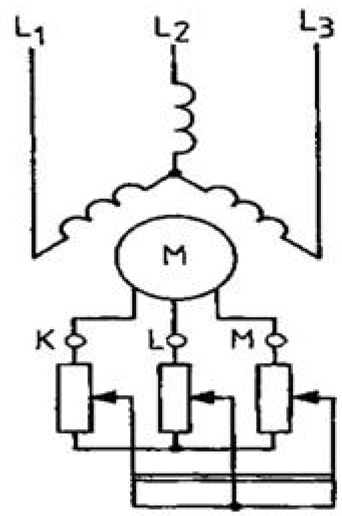
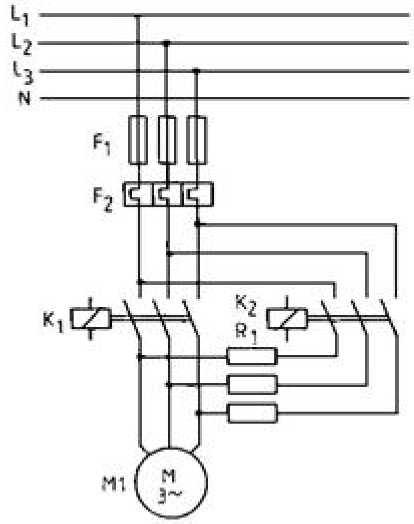


Fig. 21.5 Starting of slip ring induction motor using variable resistance



L: Line conductor

N: Neutral conductor

F_1: Fuses

F_2: Thermal overload cut-out

K_1: Main contactor

K_2: Resistance circuit contactor

R_1: Starting resistance

M_1: Three-phase motor

Fig. 21.6 Starting of slip ring induction motor using fixed starting resistance

21.5 Soft Starter

When starting, an AC Induction motor develops more torque than is required at full speed. This stress is transferred to the mechanical transmission system resulting in excessive wear and premature failure of chains, belts, gears, mechanical seals, etc. Additionally, rapid acceleration also has a massive impact on electricity supply charges with high inrush currents drawing +600% of the normal run current (Fig. 21.7). The use of Star Delta only provides a partial solution to the problem. If the motor slow down during the transition period, the high peaks are repeated and can even exceed direct on line current.

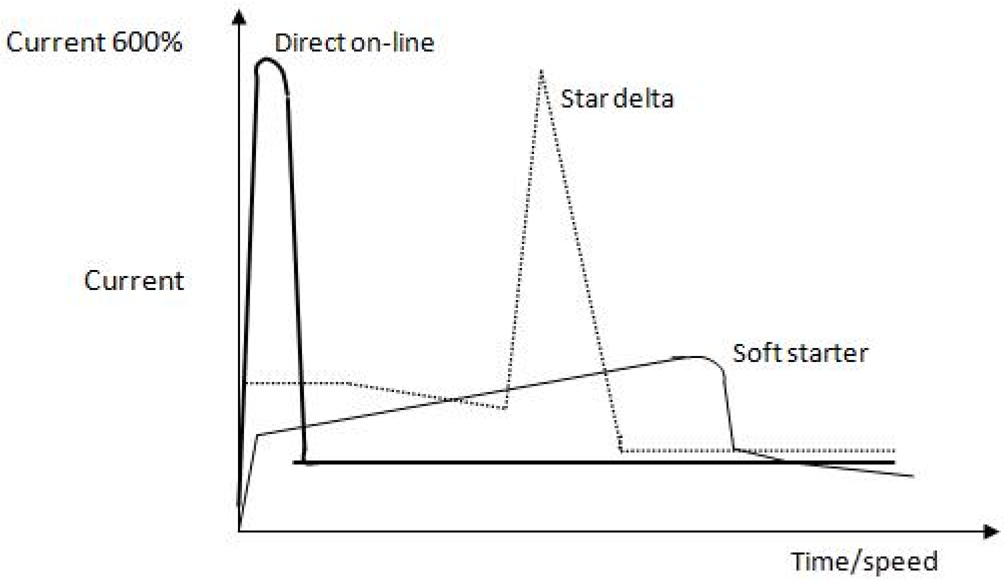


Fig. 21.7 Comparison of current drawn by DOL, Star delta and soft start methods

A soft starter shown in fig. 21.8 is a solid state motor starter that is used to start or stop a motor by notching the voltage waveform, thereby, reducing the voltage to each phase of a motor and gradually increasing the voltage until the motor gets up to full voltage/speed all at a fixed frequency. The profile of the increase of voltage depends on the application. The voltage is reduced and controlled by 3 pairs of back-to-back silicon-controlled rectifiers (SCRs), which are a type of high speed thyristor. A soft starter takes the place of a contactor and can also take the place of an overload relay in a standard motor starting application.

Fig. 21.8 Soft starter

In general, there are two reasons to use a soft starter: the power distribution network may not be able to handle the inrush current of the motor and/or the load cannot handle the high starting torque. As a rule of thumb, a motor utilizes around 600-800% of its full load current (FLA) to start. This current is referred to as inrush current or locked-rotor current. If a large motor is on a smaller power distribution network or on a generator system, this inrush current can cause the system voltage to dip, or to “brown out”. Brown outs can cause problems with whatever else is connected to the system, such as computers, lights, motors, and other loads. Another problem is that the system may not even be able to start the motor because it cannot source or supply enough current. Most industrial businesses run during the day can be fined or charged extra (Maximum Demand Charges) during this peak usage time for large transients caused by large horsepower (hp)/Kilowatt (kW) motor start ups. These Maximum Demand Charges can add up very quickly, especially if the motor needs to be started multiple times during any given day. The inrush current can be controlled one of two ways with a soft starter: either with a current limit (discussed later) or reduced linearly with the reduced voltage

21.6 Comparison of Different Starting Methods

21.6.1 Direct on-line starting

- Three-phase motor with low to medium power rating
- 3 conductors to the motor
- High starting torque
- High current peak
- Voltage dip
- One simple switching device

21.6.2 Star-delta start-up

- Three-phase motor with low to high power rating
- Six conductors to the motor

- Reduced starting torque, 1/3 of the nominal torque
- High mains load due to current peak during switchover from Y to Δ
- High mechanical stress due to torque surge during switchover from Y to Δ
- Two or three switching devices, more maintenance

21.6.3 Autotransformer starter

- lower relative cost (costs about 66% of a similar sized solid-state starter)
- Includes solid-state motor protection relays and vacuum contactors.
- Disadvantages include its non-continuous acceleration and inflexibility

21.6.4 Starting method using external resistance (Slip ring induction motor)

- Additional resistance is used only for starting,
- Resistance is rated for intermittent duty,
- Resistance is to be decreased in steps, as the motor speed increases.
- Finally, the external resistance is to be completely cut out.
- Additional cost of the external resistance is to be incurred,
- Decrease of starting current, along with increase of starting torque both being advantageous
- Only used in case higher starting torque is needed to start induction motor with high load torque.

21.6.5 Soft start-up

- Three-phase motor with low to high power rating
- 3 conductors to the motor
- Variable starting torque
- No current peak
- No torque peaks
- Negligible voltage dip
- One simple switching device
- Optional: Guided soft stop, protective functions, etc.
- Zero maintenance

Lesson 22

CONSTRUCTION AND PRINCIPLE OF D.C. GENERATOR

22.1 DC Generator

A D.C. Generator converts mechanical energy into electrical energy (d.c. current). A d.c. generator provides direct current. Difference between a.c. and d.c. is as follows:

A.C. = alternating current

D.C. = direct current

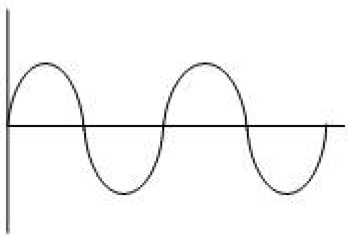


Fig. 22.1 A.C. wave

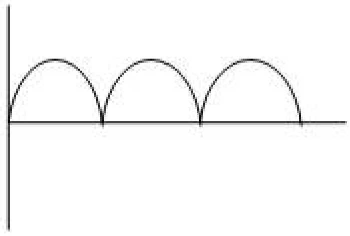


Fig.22.2 D.C. wave form

To understand the working of a d.c. generator, first we need to know the mechanism of current in a coil rotated in a magnetic field. From faraday laws of electromagnetic induction we know emf induced in the coil is directly proportional to the rate of change of flux linkage, i.e.

$$e.m.f.\ e = -\frac{N\,d\emptyset}{dt}$$

Where

N = number of turns in the coil

$\frac{d\emptyset}{dt}$ = rate of change of flux linkage.

We can see from fig. 22.3 that for 180° rotation of the coil generates +ve emf and for another 180° rotation it is –ve. Such type of current having +ve and –ve loop is known as alternating current. Please note that the current is drawn from the coil using slip ring.

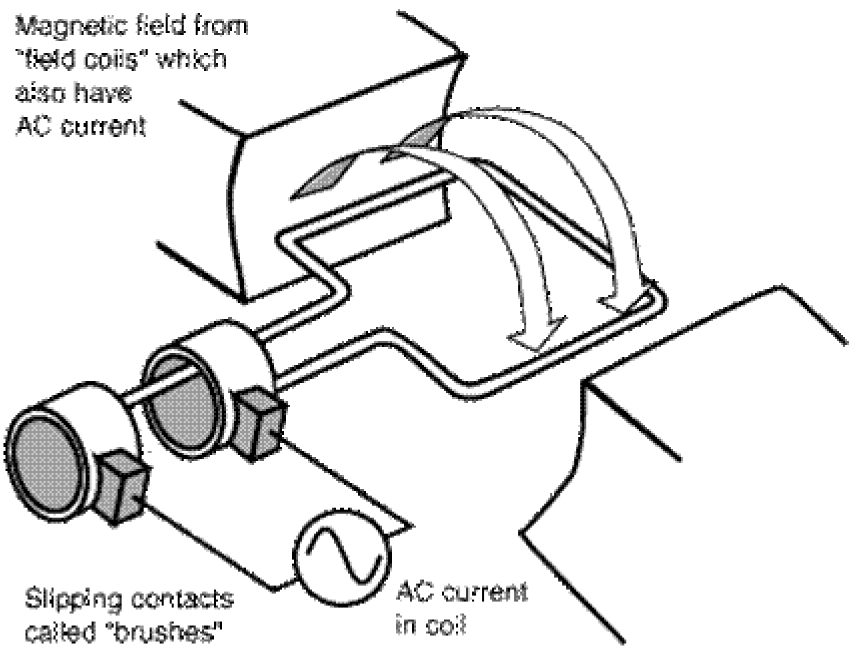


Fig. 22.3 A.C. generator

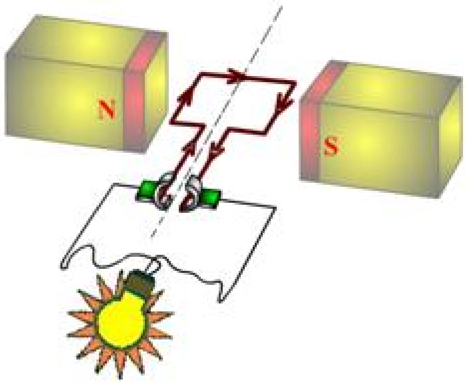


Fig. 22.4 D.C. generator

Consider the same setup of magnetic field and coils fitted with split rings. The function of the split ring is to make the current unidirectional. The split ring is cylindrical having two segments separated by an insulator. The carbon brushes touch the segments as shown in figure 22.4. When the coil will rotate in the magnetic field it will produce unidirectional current (Fig 22.5). Difference between A.C. and D.C. generator is the contact type by which current is drawn (Fig. 22.6)

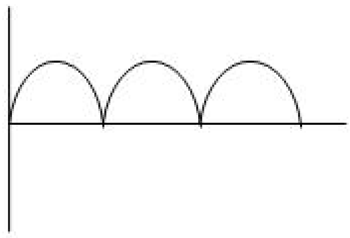


Fig. 22.5 D.C. wave form

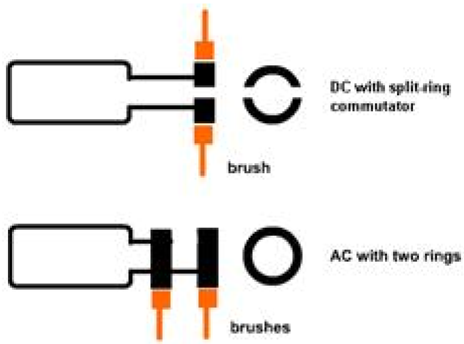


Fig. 22.6 Difference between D.C. and A.C. generator

22.2 Construction of D.C. Generator

Parts of the D.C. generator are as follows (Fig. 22.7):

1. Frame
2. Field poles
3. Field coils
4. Armature (core + winding)
5. Commutator
6. Brush assembly

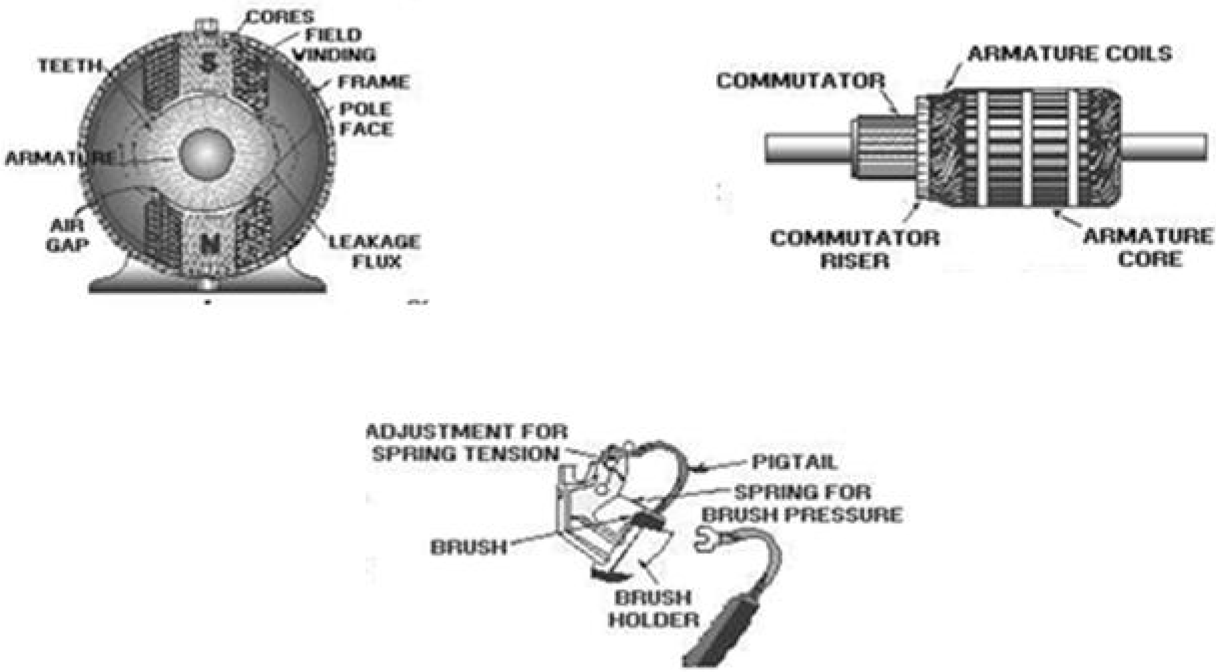


Fig. 22.7 Parts of the D.C. generator

22.2.1 Frame

The frame is also known as yoke and acts as housing for poles, armature etc. It gives mechanical support and covers the parts of the machine. The yoke also transmit the magnetic flux provided by the poles. Therefore it is made of steel having higher capacity to carry magnetic flux 1.6 Wb/m^2.

22.2.2 Field poles

a. **Main poles.** It consists of a pole and pole shoes. It is made of laminated sheets to reduce the effect of eddy current in the poles.
b. **Inter poles.** Also known as a commutation poles and is situated between two main poles.

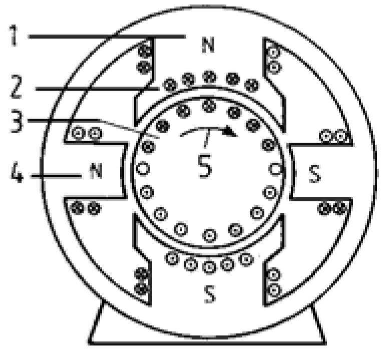


Fig. 22.8 Main pole and interpole

1. Main pole with exciter winding
2. Compensation winding
3. Rotor with rotor winding
4. Interpole with interpole winding
5. Rotational direction during generator operation

22.2.3 Field coils

Field coils are pre wound to give proper shape and are placed around the main poles. As the current passes through the field coils it magnetizes the main pole.

22.2.4 Armature

a. **Armature core:** Slots are cut in the thin laminated steel disc. A number of disc are arranged in a shape of cylinder to from the armature core.

b. **Armature winding:** The winding of the armature are first wound in form of loop. These windings are of insulated wires. The winding loops are then placed into the slots of armature core. The windings are also called conductors as they carry electric current. Armature winding are of the following types.

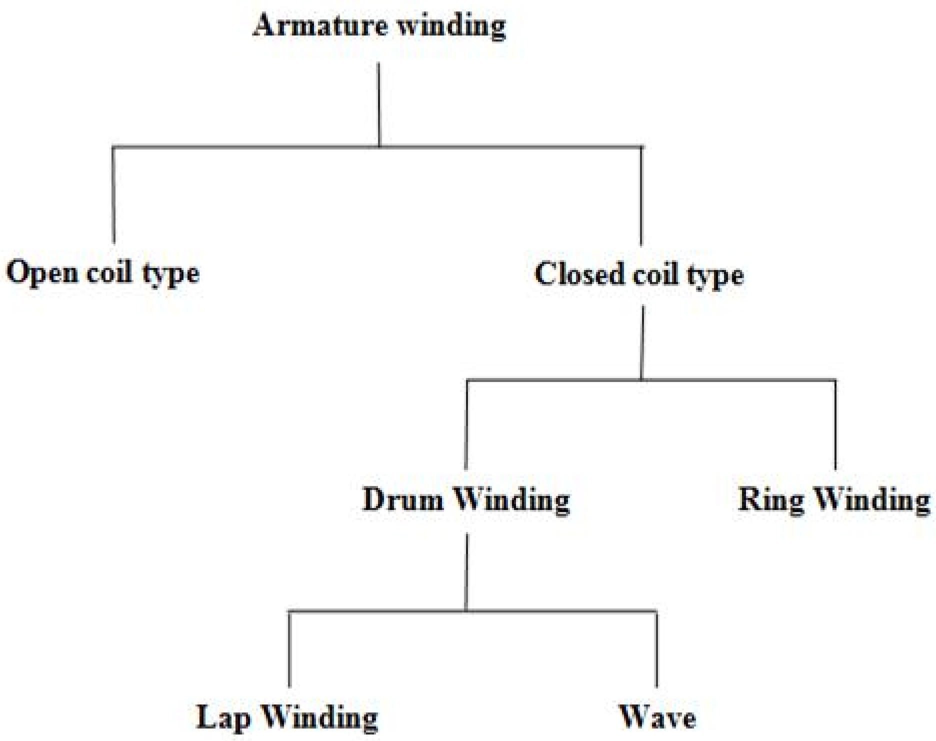


Fig 22.9 Classification of armature winding

22.2.5 Commutator

Commutator is mounted next to armature core and winding on the shaft. It is a cylindrical structure and is made up of segments separated from each other by thin strip of mica. The segments of the commutator are connected to the armature winding. The current is then drawn from the Commutator.

22.2.6 Brush assembly

The brush assembly consists of brush, brush holder, studs rocker and bushes. The brushes are made of carbon graphit or graphite. The function of the brush is to collect current from the commutator.

Lesson 23

TYPES AND CHARACTERISTIC OF D.C. GENERATORS

23.1 Types of D.C. Generators

D.C. generators can be classified as:

1. Permanent magnet type
2. Electromagnet type

23.2 Permanent Magnet Type

In this type of generator the poles are made of permanent magnet. The poles do not require any windings. Such type of D.C. generators are of small size. These are employed mainly in dynamo in cycles and bikes. It is not used for industrial purpose because:

a. It would require large magnet which is economically not feasible.
b. Magnetic strength decreases with time so magnetic flux will not remain constant.

23.3 Electromagnet Type

The poles of D.C. generator is magnetized using windings. Electromagnetic type generators can further classifies as:

(i) Externally exited D.C. generator,
(ii) Self-exited D.C. generator.

23.3.1 External or separately excited D.C. generators

A D.C. generator whose field magnet winding is supplied from an independent external D.C. source (e.g., a battery etc.) is called a separately excited generator. Fig. (23.1) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current (Eg =PΦ ZN/60 A). The greater the speed and field current, greater is the generated e.m.f. It may be noted that separately excited D.C. generators are rarely used in practice. The D.C. generators are normally of self-excited type

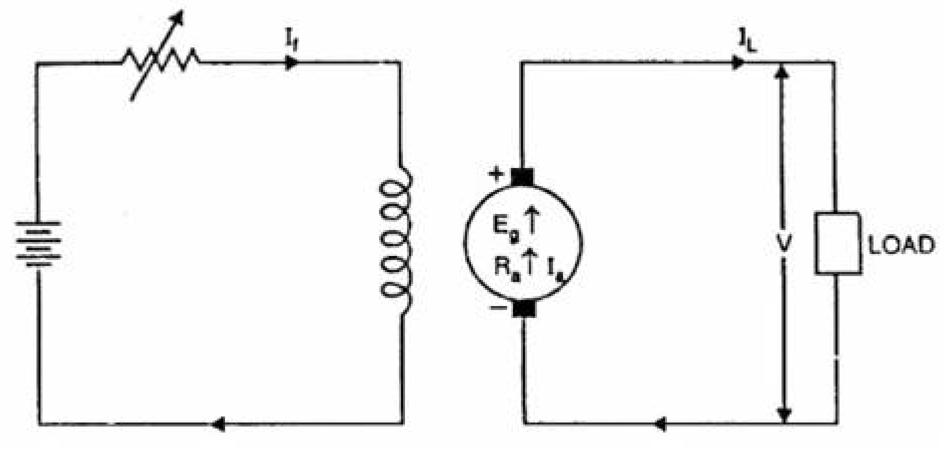


Fig. 23.1 External or separately excited D.C. generators

Armature current, $I_a = I_L$
Terminal voltage, $V = E_g - I_aR_a$
Electric power developed $= E_gI_a$
Power delivered to load $= E_gI_a - I_a^2R_a = I_a(E_g - I_aR_a) = VI_a$

23.3.2 Self-excited D.C. generators

A D.C. generator whose field magnet winding is supplied with current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

(i) Series generator
(ii) Shunt generator
(iii) Compound generator

23.3.2.1 Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. (Fig. 23.2) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., boosters.

Armature current, $I_a = I_{se} = I_L = I(\text{say})$
Terminal voltage, $V = E_g - I(R_a + R_{se})$
Power developed in armature $= E_gI_a$
Power delivered to load
$$= E_gI_a - I_a^2(R_a + R_{se}) = I_a[E_g - I_a(R_a + R_{se})] = VI_a \text{ or } VI_L$$

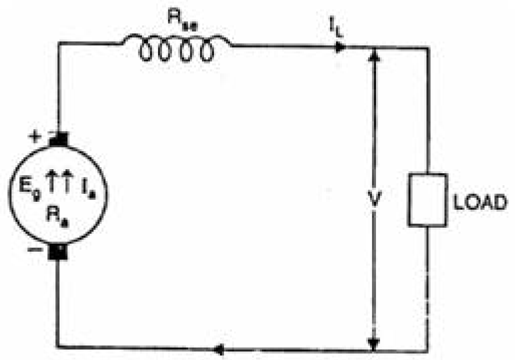


Fig. 23.2 Series generator

23.3.2.2 Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. (Fig. 23.3) shows the connections of a shunt-wound generator.

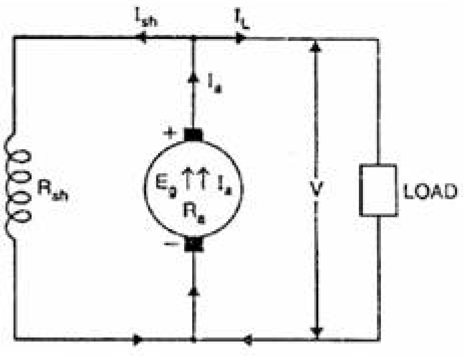


Fig. 23.3 Shunt generator

Shunt field current, $I_{sh} = V/R_{sh}$
Armature current, $I_a = I_L + I_{sh}$
Terminal voltage, $V = E_g - I_aR_a$
Power developed in armature = E_gI_a
Power delivered to load = VI_L

23.3.2.3 Compound generator

In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding (Fig. 23.4).

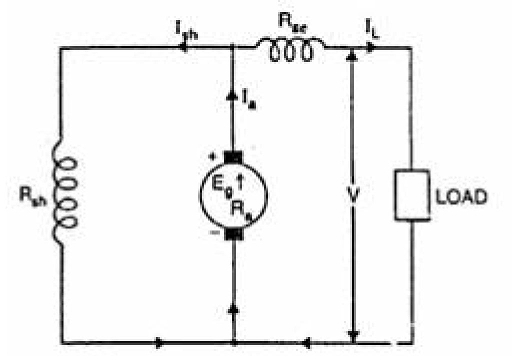


Fig. 23.4 Short shunt generator

(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding (Fig. 23.5).

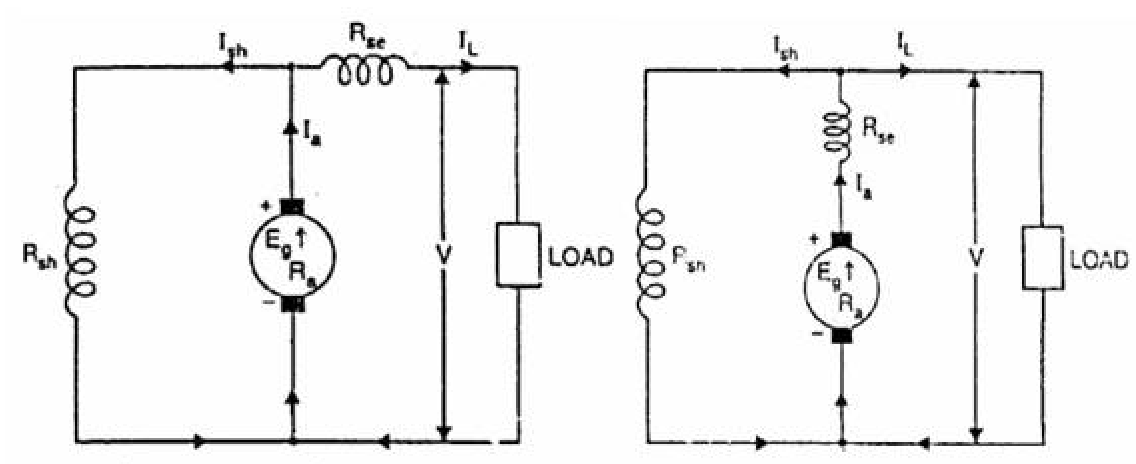


Fig. 23.5 Long shunt generator

Short shunt

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \frac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

Terminal voltage, $V = E_g - I_a(R_a + R_{se})$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

23.4 Efficiency of d.c. generators

Various power stages in the case of a d.c generator are shown in Fig. 23.6.

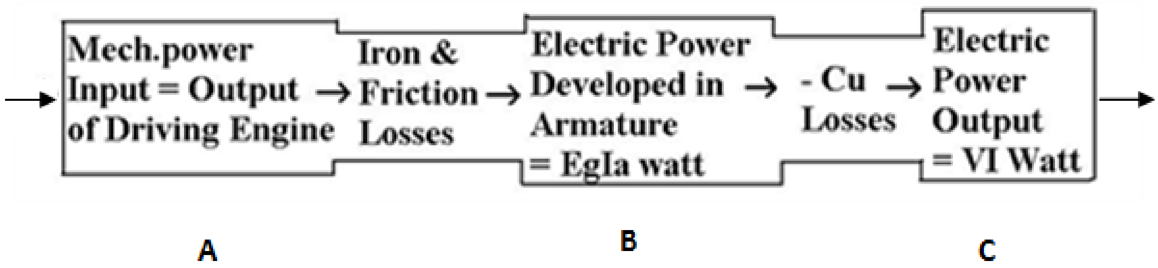


Fig. 23.5 Various losses

Mechanical Efficiency

Mechanical losses = Iron + Friction losses

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_gI_a}{\text{Output of driving engine}}$$

Electrical Efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_gI_a}$$

Overall Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

In general generator efficiency = Output / (Output + losses)

The condtion for maximum efficiency of generator is given by

$$I^2R_a = W_c$$

i.e Variable loss = Constant loss.

Lesson 24

TYPES AND CHARACTERISTICS OF D.C. MOTORS-I

24.1 Introduction

D.C. motor is used to convert electrical energy into mechanical energy. The shaft of the motor rotates when current is supplied to the motor. Motor are used to operate pumps, lifts, cranes etc. The construction of D.C. motor is similar to a D.C. generator. When the armature and field winding of a D.C. generator is connected to a D.C. Source (e.g. battery) it will work like a motor. The advantages of a D.C. motor includes low initial cost, ease in speed control, high initial torque. D. C. motors require more maintenance and have less useful life.

24.2 Types of D.C. MOTOR

D.C. motors can be classified into three types according to the connection of field windings to the armature windings:

1. Shunt wound motor
2. Series wound motor
3. Compound wound motor

24.2.1 Shunt wound motor

Here the field windings are connected in parallel with the armature.

- For constant applied voltage, the field current is constant.
- The speed of the shunt wound makes it almost constant as the flux and back emf are constant. Therefore it is also considered constant speed machine.

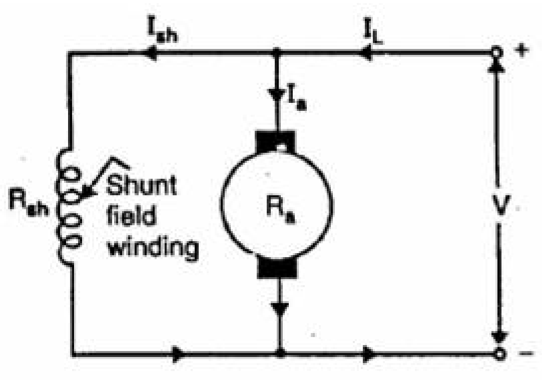


Fig. 24.1 Shunt wound motor

24.2.2 Series wound motor

Since the field winding and armature are connected in series.

$$I_{field} = I_{armature}$$

One of the characteristic and advantage of D.C. motor is that as the motor is loaded heavily, the speed of the motor automatically gets reduced.

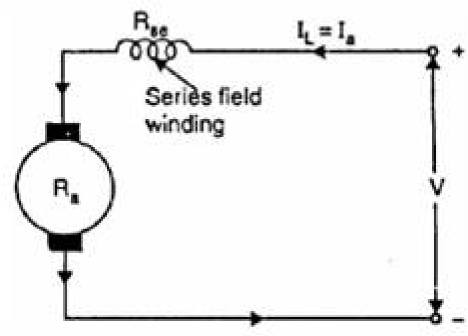


Fig. 24.2 Series wound motor

24.2.3 Compound motor

In compound wound motor the field (pole) winding comprise of two windings:

a. Shunt field winding
b. Series field windings

The field windings connected in series and shunt this produce the resultant flux to drive the motor. D.C. compound motor is a combination of the series and the shunt motor. The series field winding is connected in series with the armature and a shunt field is in parallel with the armature. The combination of series and shunt winding allow the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor.

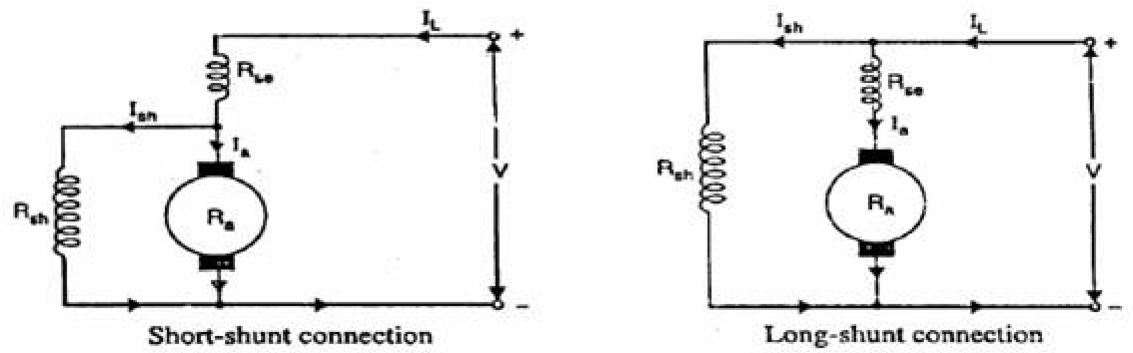


Fig. 24.3 Compound motor

24.3 Back E.M.F in D.C. Motors

When the motor is operated magnetic flux is produced by the field winding and armature winding. The flux produced at the field winding is also known as main flux. As the armature rotates the windings of the armature (also known as conductor) cuts the flux. Thus an e.m.f is induced in the armature winding whose direction is opposite to the applied voltage. The induce e.m.f is opposite in direction and opposes the applied voltage, it is also known as back e.m.f.

Thus relation between applied voltage and back e.m.f is given as follows:

$V = E_b + I_a R_a$

Where,

V = applied voltage

E_b = back e.m.f

I_a = armature current

R_a = armature resistance

24.4 Motor Torque

24.4.1 Torque

It is also known as moment of force. Torque is the tendency of a force to rotate an object about an axis or pivot. Force is defined as push or pull; similarly a torque can be thought of as a twist.

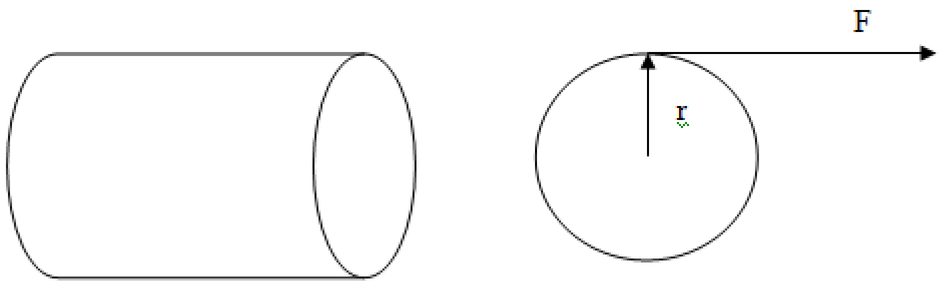


Fig. 24.4 Shaft of radius r

Consider a shaft of radius r which is rotated by its axis by force F acting on the circumference of the shaft (Fig. 24.4).

$T = r \times F$

Where

T = Torque

r = radius of shaft

(Or the distance from the axis to the application of force)

F = applied force

24.4.2 Machine torque

One of the basic specifications of an engine is Torque. The power output of an engine can be given as:

Power developed P = Torque × rotational speed

$$= T \times \omega \text{ watt}$$

$$= T \times \frac{2\pi N}{60} \quad \ldots \ldots (1)$$

Where

P = Power developed

T = Torque

ω = angular velocity in radian/second.

N = rpm (rotation per minute)

24.4.3 Torque in a motor

From equation 1, power developed is given as:

$$P = T_a \times \frac{2\pi N}{60} \ldots \ldots \ldots (2)$$

Where,

T_a = Torque developed by the armature

Electrical equivalent of mechanical power developed by the armature is given by

$$P = E_b I_a \quad Watt \ldots\ldots\ldots(3)$$

Where,

E_b = back e.m.f

I_a= armature current

Equating equation (2) and (3)

$$T_a \times \frac{2\pi N}{60} = E_b I_a \ldots\ldots\ldots(4)$$

$$back\ e.m.f\ E_b = \frac{\emptyset Z N}{60}\frac{p}{a} \ldots\ldots(5)$$

Where, $\emptyset$ = flux/pole in Weber's

Z = total number of armature conductors

= number of slots × conductors/slot

N = armature rotation r.p.m

P = number of poles

a = number of parallel paths in armature

Placing value of equation (5) into equation (4)

$$T_a \times \frac{2\pi N}{60} = \frac{\emptyset Z N}{60}\frac{p}{a} I_a$$

Arranging,

$$T_a = 0.159\emptyset Z I_a \frac{p}{a} \qquad Nm$$

Since Z, p and a are constant for any motor

$$T_a \propto \emptyset I_a$$

Case 1: For shunt motors

$\emptyset$ i.e. flux per pole is changing,

$$T_a = 0.159\emptyset Z I_a \frac{p}{a} \quad Nm \ldots\ldots\ldots(6)$$

Since Z, p and a are constant for any motor.

$$T_a \propto \emptyset I_a$$

Case 2: For series motors

Since field windings carry full armature current, $\emptyset$ is directly proportional to I_a before saturation.

$$T_a \propto {I_a}^2$$

24.4.4 Shaft torque (T_{sh})

The armature torque developed in the motor is not fully available to the shaft due to iron and friction losses. The torque available at the shaft will be always lower than the armature torque.

$$T_{armature} = T_{shaft} + Iron\ loss + Frictional\ losses$$

$$T_{shaft} = T_{armature} - Iron\ loss - Frictional\ losses$$

The horse power at the shaft is known as brake horse power (B.H.P). B.H.P is calculated using shaft torque.

$$Brake\ Horse\ Power\ (B.H.P) = \frac{T_{sh} \times 2\pi N}{735.5 \times 60}$$

$$T_{sh} = \frac{B.H.P \times 735.5 \times 60}{2\pi N}$$

Note1: The Brake Power mentioned here is metric brake horse power.

1 B. H. P (metric) = 735.5 watt

Do not confuse with Electrical horse power which is equivalent to 746 watt.

Note 2: The difference $T_{armature} - T_{shaft}$ is known as lost Torque.

Lesson 25

TYPES AND CHARACTERISTICS OF D.C. MOTORS-II

25.1 Characteristics of D.C. Motor

The performance of a d.c. motor is expressed using different graphs and curves known as characteristic curves. Operating characteristics are given by the following curve.

1. Torque - Armature current (T_a - I_a) characteristic also known as electrical characteristic.
2. Speed – Armature current (N -I_a) characteristics.
3. Speed – Torque (N - T_a) characteristics also known as the mechanical characteristic

As per syllabus we will be looking into speed torque (N - T_a) characteristics.

25.2 Speed Torque (N - T_a) Characteristics

25.2.1 Series motor

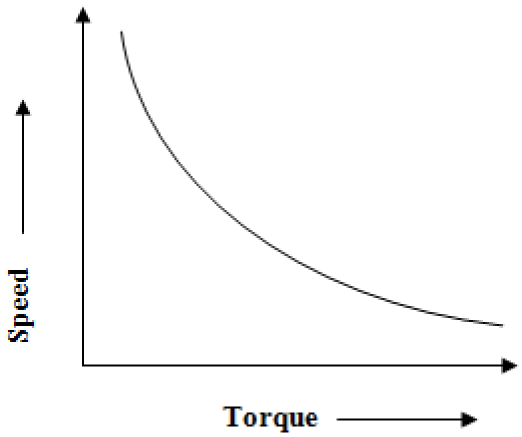


Fig. 25.1 Speed torque curve for D.C. series motor

- From the plot it is evident that the series motor exhibit high torque at low speed and vice versa.
- Series motor must never be started at no load. Under no load conditions the value of the armature is very small.

  We know,

$$\emptyset \propto I_a \qquad \text{......... (1)}$$

$$N \propto \frac{1}{\emptyset} \qquad \text{......... (2)}$$

From relation (1) if armature current (I_a) is small, flux would be small. If flux (∅) has a very small value. The motor speed (N) will become very high to cause changes to the motor part. Therefore series motors are used in place where “no load” condition doesn’t occur.

25.2.2 Shunt motors

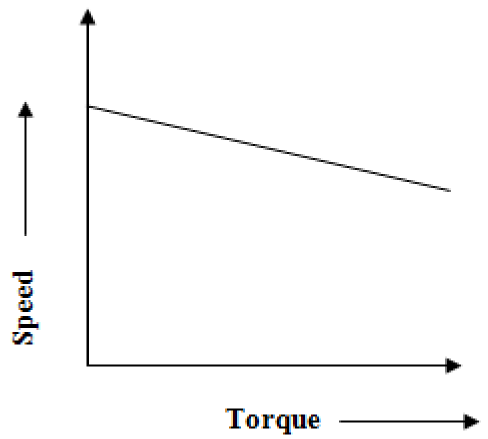


Fig. 25.2 Speed torque curve for D.C. shunt motor

From the plot we can see as the load (Torque) on the shunt motor increase there is slight fall in the motor speed. Due to insignificant redirection in the speed, shunt motor are considered to be constant speed motor. Therefore shunt motor will approximately be operated at same speed under no load and full load conditions.

26.3.3 Compound motors

25.3.3.1 Differential – compound motors

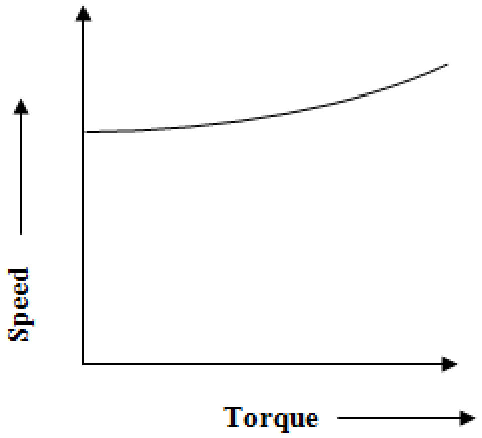


Fig. 25.3 Speed torque curve for differential compound motor

Differential compound motor are rarely used due to its poor Torque –speed characteristics. The machine can be operated at constant speed on medium load. But at very high load / torque the speed is very high to damage the motor.

25.3.3.2 Cumulative compound motor

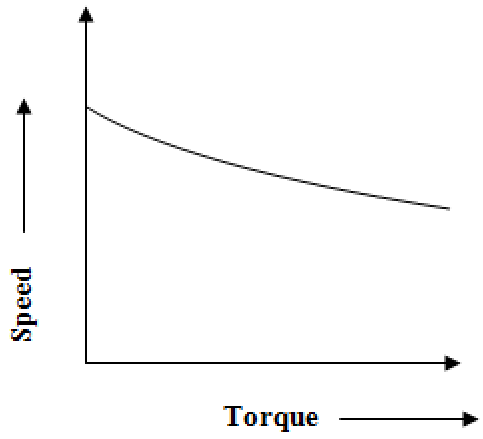


Fig. 25.4 Speed torque curve for cumulative compound motor

- In cumulative compound motor speed falls considerably at heavy load / torque.
- When the load / torque is low the motor runs at the safe speed.
- Motor shows the characteristics in between that of series and shunt motor.

To compare performance of different motors, the speed – torque characteristics is shown in same plot.

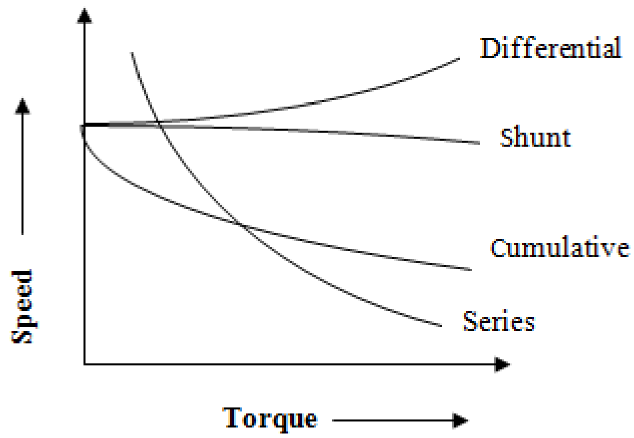


Fig. 25.5 Speed torque curve for different D.C. motors

Lesson 26

STARTING AND SPEED CONTROL OF D.C. MOTORS

26.1 Need for D.C. Motor Starter

At the time of starting of motor it is at rest and no back e.m.f. is generated. On application of full voltage, armature winding draws a heavy current due to small armature resistance. This high armature current may damage the armature windings, commutator and brushes. To prevent high armature current during the starting of motors, variable resistance is connected in series with the armature winding. The starting resistance is reduced as the motor speeds up. The resistance is cut off fully when the motor attains full speed. This arrangement is known as starter. For very small D.C. motor (e.g. 6v, 12v, motor) starter is not required and it can be started directly. A D.C. Motor starter consists of:

a) **External resistance** – External resistance is placed in the armature circuit to limit the starting current drawn by the motor. As the motor accelerates the resistance is gradually removed.

b) **No-volt release coil** – In case of power failure the starter arm is brought back to the off position.

c) **Overload release coil** – In case of overloading of motor or any fault the starter circuit is switched off by overload release coil mechanism.

26.2 Types of Starters

1. Three point starter
2. Four point starter
3. Two point starter

26.2.1 Three point starter

Three point starters have three terminals:

i) **Armature terminals A** – It is connected to one of the armature winding ends.

ii) **Field terminal Z** – is connected to one of the field winding of the motor.

iii) **Line terminal L –** is connected to any of +ve or –ve wire coming from the d.c. source.

26.2.1.1 Operation of the d.c. motor starter

The incoming power is indicated as L_1 and L_2. The components within the broken lines form the three-point starter (Fig. 26.1). As the name implies there are only three connections to the starter. The connections to the armature are indicated as A_1 and A_2. The ends of the field (excitement) coil are indicated as F_1 and F_2. In order to control the speed, a field rheostat is connected in series with the shunt field. One side of the line is connected to the arm of the starter (represented by an arrow in the diagram). The arm is spring-loaded so, it will return to the "Off" position when not held at any other position. On the first step of the arm, full line voltage is applied across the shunt field. Since the field rheostat is normally set to minimum resistance, the speed of the motor will not be excessive; additionally, the motor will develop a large starting torque.

- The starter also connects an electromagnet in series with the shunt field. It will hold the arm in position when the arm makes contact with the magnet.
- Meanwhile that voltage is applied to the shunt field, and the starting resistance limits the current to the armature.
- As the motor picks up speed counter-emf is built up; the arm is moved slowly to short.

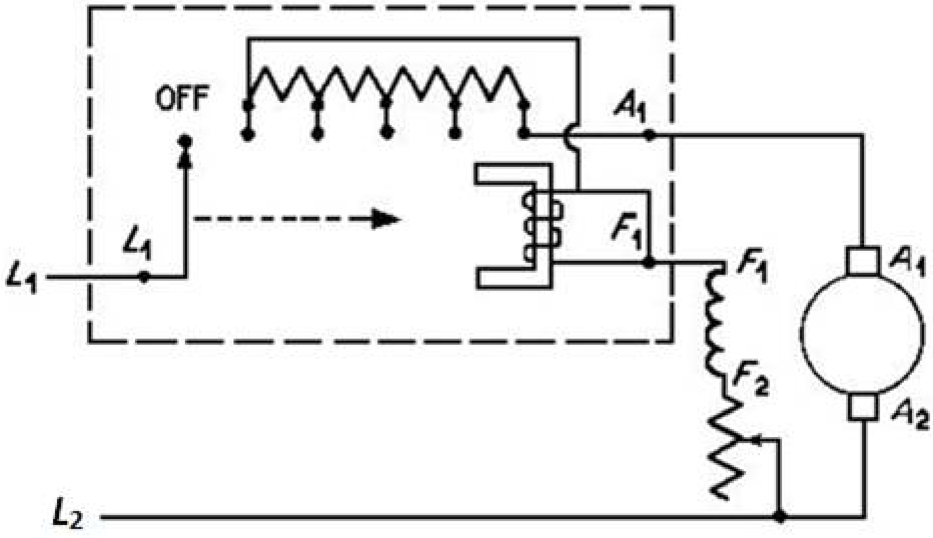


Fig. 26.1 Three point starter

26.2.1.2 Limitation

No-volt release coil is connected in series with the field circuit. While exercising speed control through field regulator, the field current may be weakened to such an extent that no-volt release coil may not be able to keep the starter lever in the ON position. This may disconnect the motor from the supply when it is not desired. This limitation is over come in four point starter.

26.2.2 Four point starter

(i) In a four-point starter, the no-volt release is connected directly across the supply line through a protective resistance R.

(ii) Now the no-volt release coil circuit is independent of the shunt field circuit. Therefore, proper speed control can be exercised without affecting the operation of non-volt release coil.

(iii) The only difference between a three-point starter and a four-point starter is that of the method in which no-volt release is connected. However, the working of the two starters is the same.

(iv) It may be noted that the three point starter also provides protection against an open field circuit. This protection is not provided by the four-point starter. But the possibility of open field circuit is quite remote.

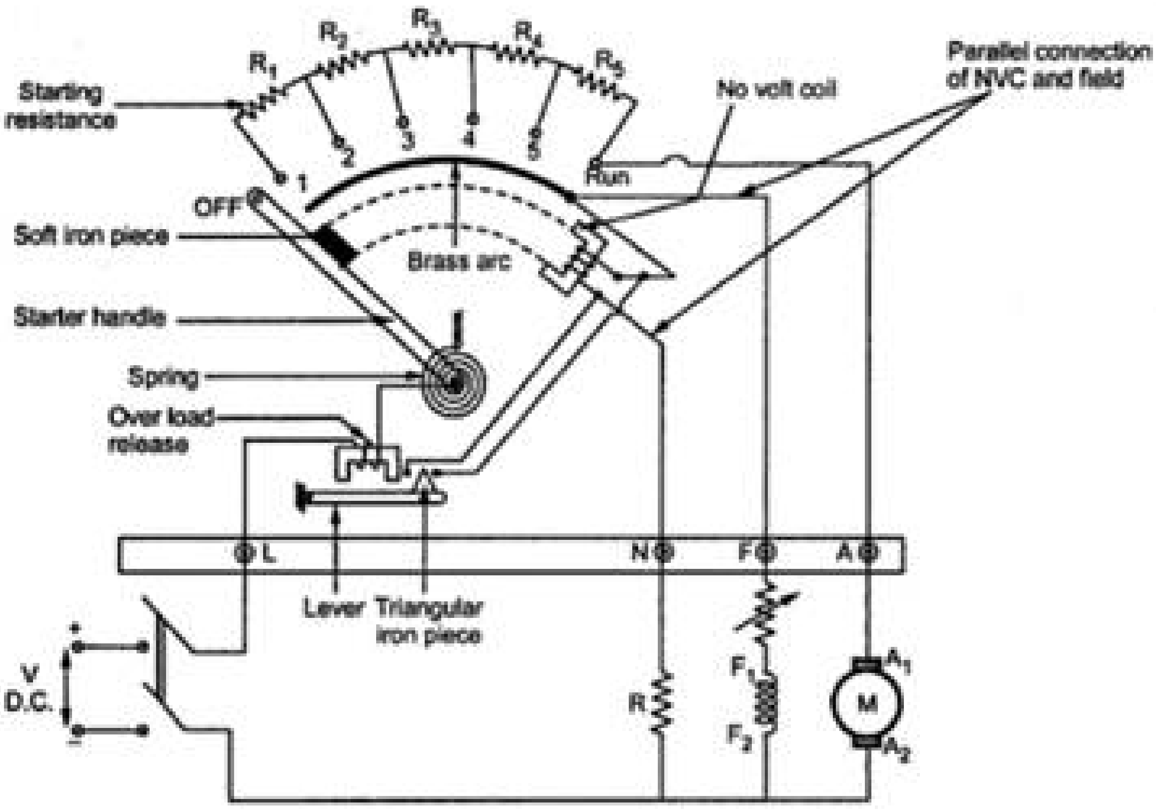


Fig. 26.2 Four point starter

26.2.3 Two point starter

1. Two point starter is used only for D. C. series motor. The basic construction of two point starter is similar to that of three point starter except the fact that it has two terminals namely line (L) and field (F).
2. The terminal F is at one end of the series combination of field and the armature winding. The action of the starter is similar to that of three point starter.
3. The main problem in case of D. C. series motor is it's over speeding action when the load is less.
4. This can be prevented using two point starters. The no-volt coil is connected in series with the motor so both currents are equal.
5. At no load situation, load current drawn by the motor decreases. At very low current no-volt coil is demagnetized and it releases the handle to OFF position.

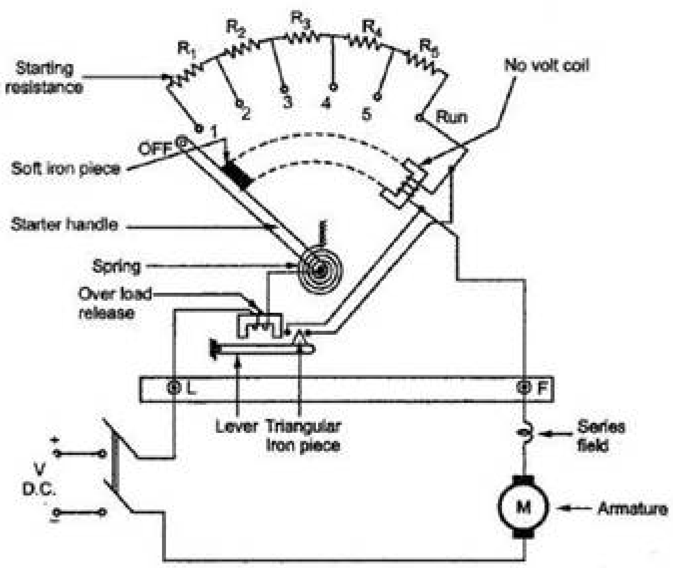


Fig. 26.3 Two point starter

Lesson 27

CHARACTERISTICS OF MEASURING INSTRUMENTS

27.1 Introduction

To understand the performance characteristics of a measurement system is very critical to the process of selection. Characteristics that show the performance of an instrument are accuracy, precision, resolution, sensitivity etc. It allows users to select the most suitable instrument for specific measuring jobs.

There are two basic performance characteristics of measuring instrument:

1. Static characteristics: value of the measured variable change slowly.
2. Dynamic characteristics: value of the measured variable change very fast.

27.2 Static Characteristics

The static characteristics and parameters of measuring instruments describe the performance of the instruments related to the steady-state input/output variables only. The various static characteristics and parameters are destined for quantitative description of the instrument's perfections and they are well presented in the manufacturer's manuals and data sheets.

27.2.1 Accuracy

The degree of exactness (closeness) of measurement compared to the true value. This term is used in the manufacturer specifications for a measurement instrument or device. Accuracy of an instrument is the quality which characterizes the ability of a measuring instrument to give indications approximating to the true value of the measured variable. The specifications of the accuracy are given actually in terms of error (in other words in terms of inaccuracy). Note, that when the accuracy of some measurement device is presented with percent error, we can estimate the error after measurement.

Example: Let us consider a voltmeter having range from 0 to 200V and accuracy X=± 1% of range. The voltmeter reading is 100V. We can obtain the limits of absolute error after measurement:

Error = 1% of (200-0) = 2V

Finally for measurement we can write the result of measurement such as:

V = VR ± V= 100V ± 2V

and we say, that the measurement value is between 98 and 102 Volts.

27.2.2 Resolution

The smallest change in a measurement variable to which an instrument will respond.

27.2.3 Range

The input range of an measuring device is specified by the minimum and maximum values of input variable (*Xmin to Xmax*) , for example: from -10 to +150 ^{o}C (for the measurement device with temperature input).

The output range of an measuring device is specified by the minimum and maximum values of output variable (*Ymin to Ymax*) , for example: from 4 to +20 mA (for the measurement element with current output).

27.2.4 Span

The input span of a measuring devices is specified by the difference between maximum Xmax and minimum Xmin values of input variables: (Xmax - Xmin). For example, for a measuring devices with input range from -10 ^{o}C to +150 ^{o}C the input span is: +150 ^{o}C - (-10 ^{o}C) = 160 ^{o}C.

The output span of a measuring devices is specified by the difference between maximum Ymax and minimum Ymin values of output variables: (Ymax - Ymin). For example, for a measuring devices with output range from 4 to +20 mA span is: +20 mA - 4 mA = 16 mA.

27.2.5 Precision

It is a measure of consistency or repeatability, i.e successive reading do not differ. Precision is defined as the capability of an instrument to show the same reading when used each time (reproducibility of the instrument). An instrument which is precise may not be necessarily accurate. Difference between accuracy and precision can be explained by example of a shooter aiming at the target (Fig. 27.1). If all the shots are hit at the particular point it is said to have high precision.

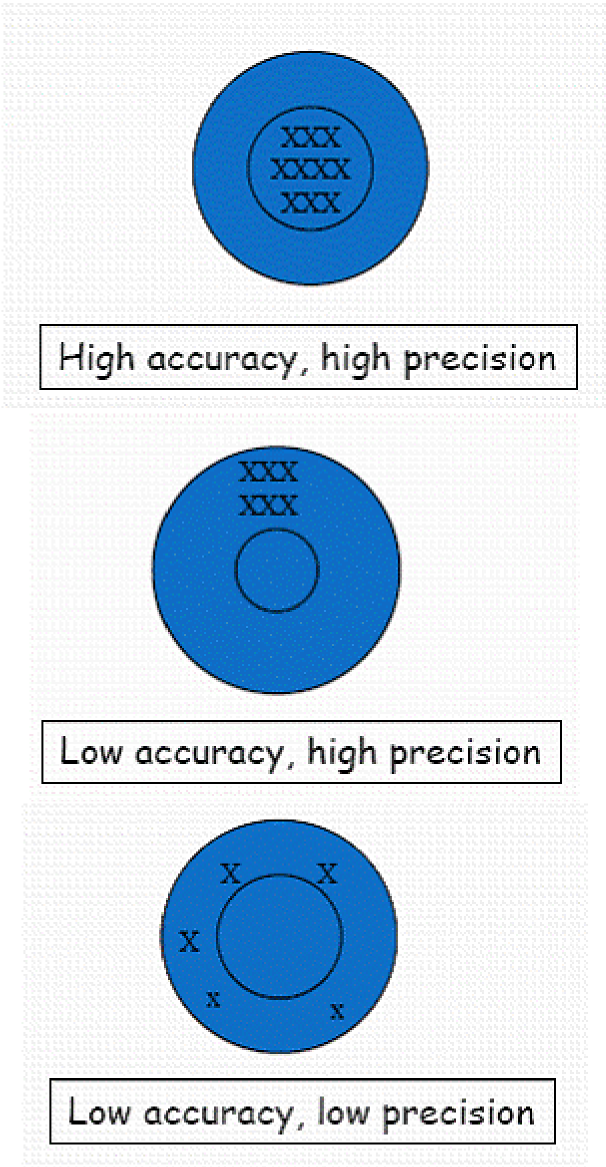


Fig. 27.1 Accuracy and precision

27.2.6 Bias

Constant error which occurs during the measurement of an instrument. This error is usually rectified through calibration.

27.2.7 Linearity

- Maximum deviation from linear relation between input and output.
- The output of an instrument has to be linearly proportionate to the measured quantity.
- Normally shown in the form of full scale percentage (% fs).
- The graph shows the output reading of an instrument when a few input readings are entered.

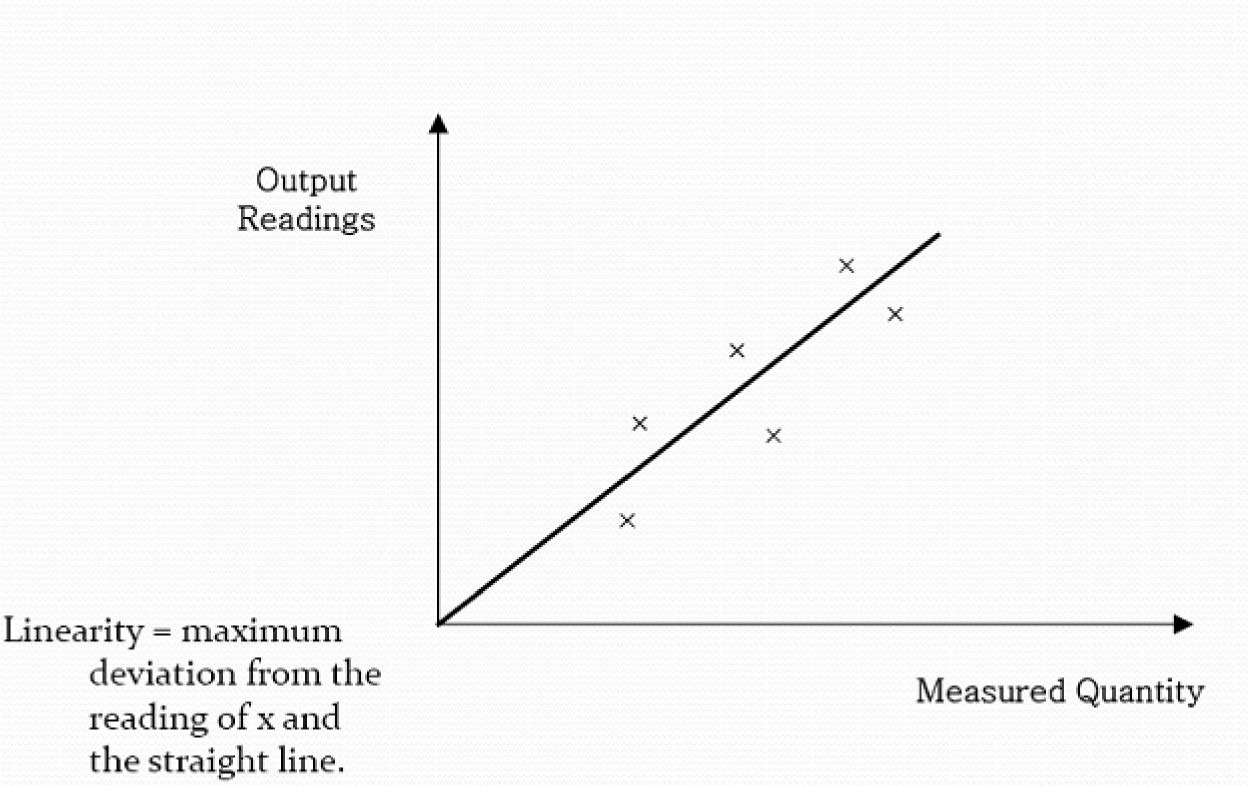


Fig. 27.2 Linearity

27.2.8 Sensitivity

Sensitivity is defined as the ratio of change in output (response) towards the change in input at a steady state condition.

$$Sensitivity\ (k) = \frac{\Delta\theta_o}{\Delta\theta_i}$$

Where,

$\Delta\theta_o$= Change in output

$\Delta\theta_i$= Change in input

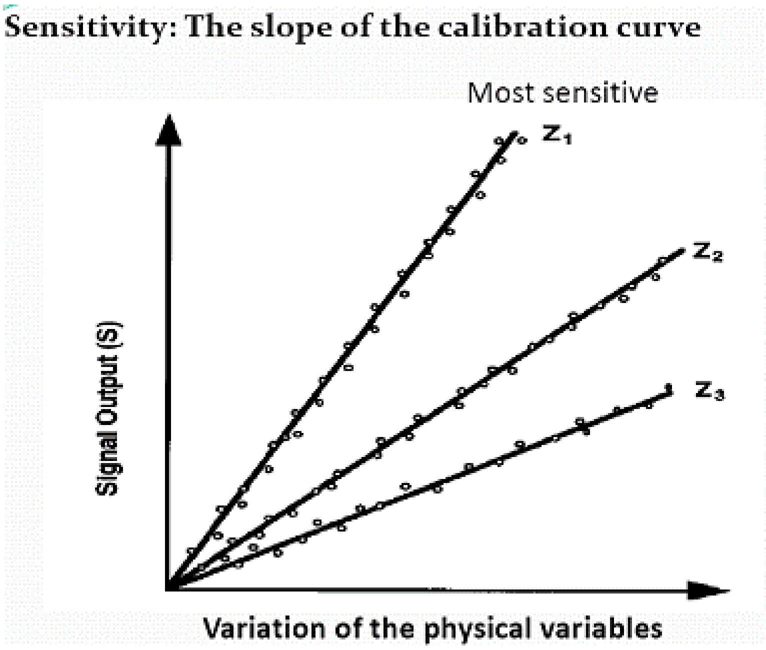


Fig. 27.3 Sensitivity

27.2.9 Threshold

When the reading of an input is increased from zero, the input reading will reach a certain value before change occurs in the output. The minimum limit of the input reading is 'threshold'.

27.2.10 Expected value

It is the desired value or the most probable value that is expected to obtain.

27.2.11 Error

It is the deviation of the true value from the desired value. Also, Error (e) is the difference between the measured value and the true value of a variable.

e = measured value - true value

27.2.12 Accuracy

- True Value is the exact value of a variable.
- Measured Value - value of variable as indicated by measurement system
- Accuracy - closeness of agreement between the measured value and the true value.

27.3 Dynamic Characteristics

Previous characteristics assume a steady state conditions. The time response shows the behavior of the sensor or the instrument at system to the changes in the magnitude of interest by observing the signal output with time. The step response is used as a basic test and for characterizing the system. The dynamic characteristics of an instrument are:

- Speed of response
- Dynamic error: The difference between the true and measured value with no static error.
- Lag – response delay

- Fidelity – the degree to which an instrument indicates the changes in the measured variable without dynamic error (faithful reproduction).

Lesson 28

CLASSIFICATION OF INSTRUMENTS

28.1 Introduction

The instrument principally used to measure electrical quantities like current, voltage, energy, power etc are known as electrical instruments. Tests and measurement are important in design, performance evaluation, repair and maintenance of electrical equipments systems and circuits. To measure electrical quantities like current, voltage, resistance etc it is necessary to transform these quantities into a visible indication.

28.2 Analogue and digital instruments

There are basically two types of instruments:

a) **Analogue:** Magnitude of the electric quantity is indicated by the position of a pointer moving over a graduated scale.

Fig. 28.1 Analogue measuring device

b) **Digital:** When the electrical quantity is indicated in form of decimal number.

Fig. 28.2 Digital measuring device

28.3 Classification of Measuring Instruments

Electrical instruments can be classified on the basis of

28.3.1 Function

a) **Indicating instruments:** Such instrument directly display the value of electrical quantity immediately at the time when measurement is taken. E.g. Voltmeter, ammeter.

Fig. 28.3 Indicating device

b) **Recording instruments:** Such instruments are used to record electrical quantities during a period of time. A pen plots the data on a paper. Digital recording instruments or data loggers are also available.

Fig. 28.4 Recording device (Chart type)

c) **Integrating instruments:** These instruments measure the total quantities of electricity in a given time. The best example is energy meter (Fig. 28.5). The data measured and recorded by such instrument is cumulative.

Fig. 28.5 Integrating instruments (energy meter)

28.3.2 Type mounting

a) **Switch board mounted:** Such instruments are mounted permanently on the switch board. These are not completely covered and terminals are placed on the back of the instruments for connections.

Fig. 28.6 Switchboard or panel mounted instruments

b) **Portable devices:** These are small in size and handy to be carried around easily. Portable devices are useful for onsite/multi location testing and measurement. Few portable are designed in a manner that it can also be mounted on the switch board.

Fig. 28.7 Portable device for current and voltage measurement

28.3.3 Principle of operations

a) Moving iron instruments
b) Moving coil instruments
c) Induction instruments
d) Hot wire instruments
e) Electrostatic instruments
f) Electrolytic instruments

28.3.4 Current type

a) A.C. instruments
b) D.C. instruments

28.3.5 Electrical quantity to be measured

a) Voltmeter-Voltage
b) Ammeter-Current

c) Wattmeter-Power

d) Watt Hour meter-Energy measurements

Lesson 29

PRINCIPLES OF ELECTRICAL MEASUREMENT SYSTEM

29.1 Element of a Generalized Measurement System

There are three elements of any electrical measurement system.

1. Deflecting element
2. Controlling element
3. Damping element

29.2 Deflecting Element

The electrical quantity like current, voltage or power produces the deflecting torque. The deflecting torque carries the pointer to move. There are different mechanisms for deflection like:

a. Coil and soft iron core arrangement.
b. Moving coil and fixed coil system.
c. Moving iron and coil system.
d. Others.

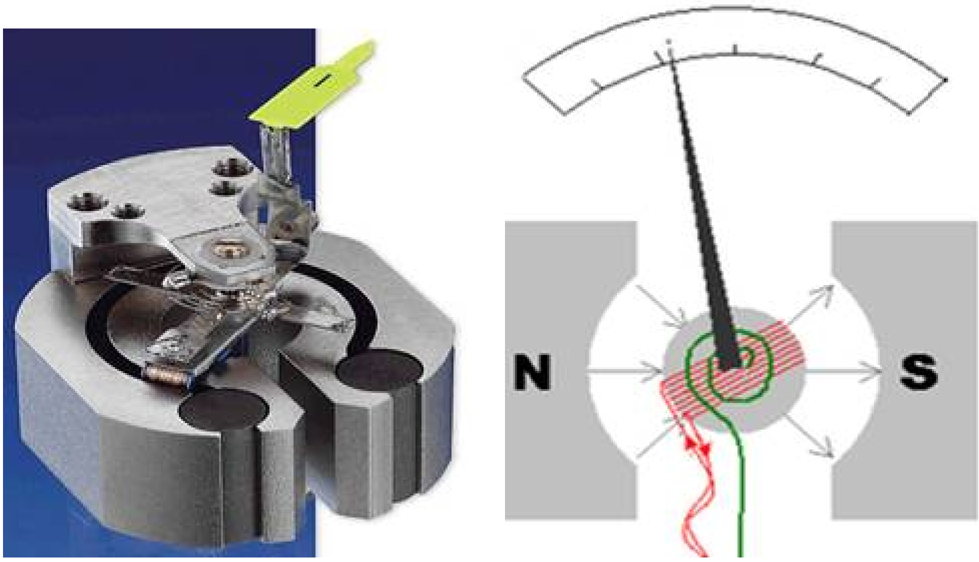


Fig. 29.1 Deflecting element

29.3 Controlling Element

It controls the deflection of the pointer according to the magnitude of the electrical quantities (e.g. current, voltage etc). If controlling device is not provided the pointer will immediately move to maximum position as soon as the instrument starts measuring any electrical quantity. The function of the controlling device is also to bring back pointer to zero position, if the magnitude of measured quantity becomes zero. Controlling devices are of two types:

1. Spring Control
2. Gravity Control

29.3.1 Spring control

Two spiral spring made of non magnetic material wound in opposite ends is used for controlling deflection. As the pointer moves one spring gets winded and other is unwound, thus two springs provides controlling torque. The torsion torque of a spiral spring is proportional to the angle of twist, therefore the controlling torque is directly proportional to the deflection of the pointer.

$$T_C \propto \theta$$

Where

T_C = Controlling Torque

θ = Deflection of pointer

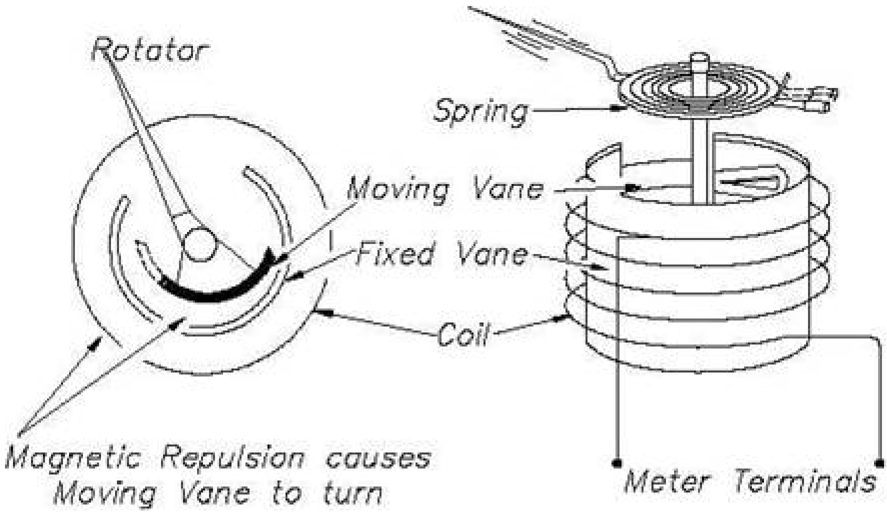


Fig. 29.2 Control element (spring)

29.3.2 Gravity control

To provide controlling torque two weights are attached:

a. *Balance Weight* – It balance the weight of the pointer.

b. *Control Weight* – It provides the controlling torque.

Here the controlling torque is directly proportional to the sin of the angular deflection i.e.

$$T_C \propto \sin\theta$$

The control weight is attached to the pointer spindle in a way that its position can be altered. The controlling torque can be varied by changing the distance of the control weight from the pointer axle.

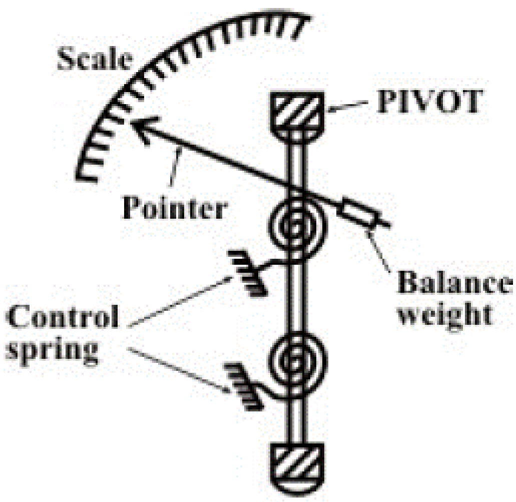


Fig. 29.3 Gravity control by balance weight

29.4 Damping Element

The pointer of the measuring instrument will move by the deflection and controlling mechanism. The pointer will keep moving to and fro (oscillates) and will come to rest after a long period. Thus it has to wait for long to take the reading from the measuring instrument and it will also result inaccurate result.

To overcome this problem a damping element is provided in the instrument. A damping torque is applied to the pointer by this damping device which brings the pointer to rest. Oscillation / vibration of the pointer is eliminated and reading from the instrument can be taken immediately.

Different methods of damping are as follows:

1. Air friction damping
2. Fluid friction damping
3. Eddy current damping

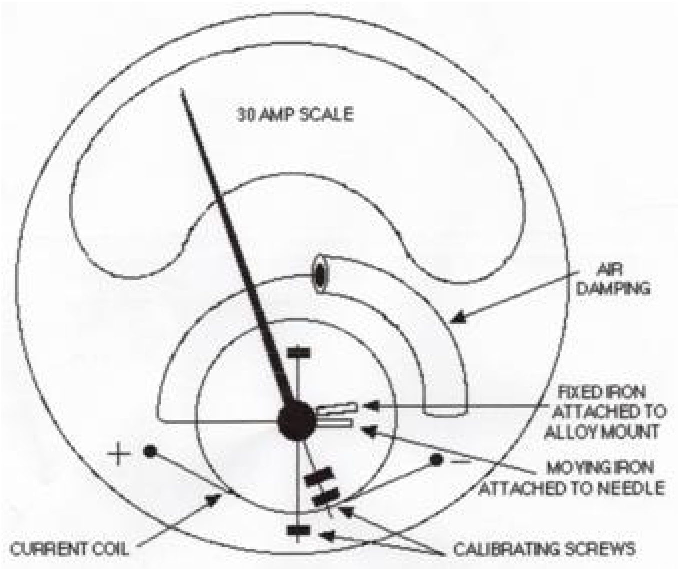


Fig. 29.4 Damping element (Air damping)

Lesson 30

ENERGY MEASUREMENT

30.1 Introduction

It is important to understand power and power measuring method before starting energy measurement. Power and energy are related but are different. Power is the rate at which energy is transferred, used, or transformed. For example, the rate at which a light bulb transforms electrical energy into heat and light is measured in watts—the more wattage, the more power, or equivalently the more electrical energy is used per unit time. The instantaneous electrical power P delivered to a component is given by

$$P(t) = V(t) \times I(t)$$

Where,

P(t) = instantaneous power, measured in watts (joules per second)

V(t) = potential difference (or voltage drop) across the component, measured in volts

I(t) = current through it, measured in amperes

30.2 Power Measurement in 3-Phase Circuits

Power in a 3-phase load (star or delta connected) can be measured in the following methods:

30.2.1 Three-wattmeter method

Fig 30.1 shows three watt meters connected in the following manner:

- Current coil is connected to one line
- Potential coil is connected between that line and some common point.

The sum total of the readings of the three watt meters gives the total power consumed. This method can be used with balanced and unbalanced load. If neutral wire is available then common point should be at the neutral wire.

$$\text{Total power} = W_1+W_2+W_3$$

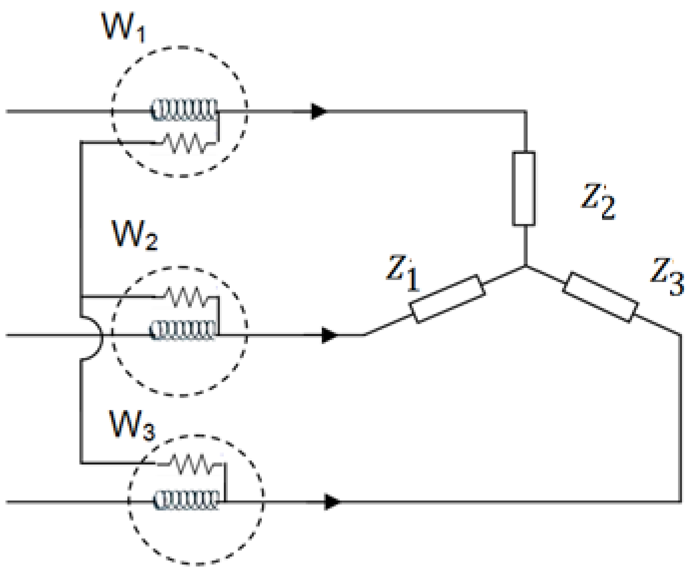


Fig. 30.1 Connection diagram for Three Wattmeter method

30.2.2 Two-wattmeter method

Two watt meters are connected (Fig. 30.2) such that:

- Current coils of two watt meters are connected in any two lines and
- Potential coil of each joined to the third line.

The sum total of the readings of the two watt meters gives the total power consumed. This method can be used with balanced and unbalanced load. Precaution in this method is that if neutral wire is available it should not carry any current. And if it is not so then the neutral of the load should be disconnected from the neutral of the source.

Total power = $W_1 + W_2$

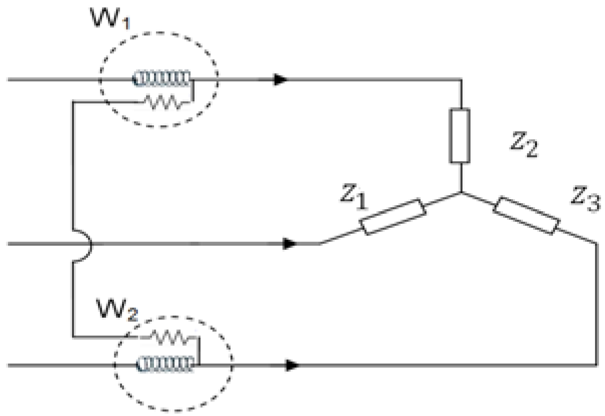


Fig. 30.2 Connection diagram for Two Wattmeter method

From the two wattmeter readings ϕ and thus load power factor Cos ϕ can be determined by the following equation:

$$\tan\phi = \sqrt{3}\frac{W_2 - W_1}{W_2 + W_1}$$

Where,

W_1 = Watt meter reading (Lower value)

W_2 = Watt meter reading (Higher value)

Thus,

Power factor (pf) = Cos ϕ

30.2.3 One-wattmeter method

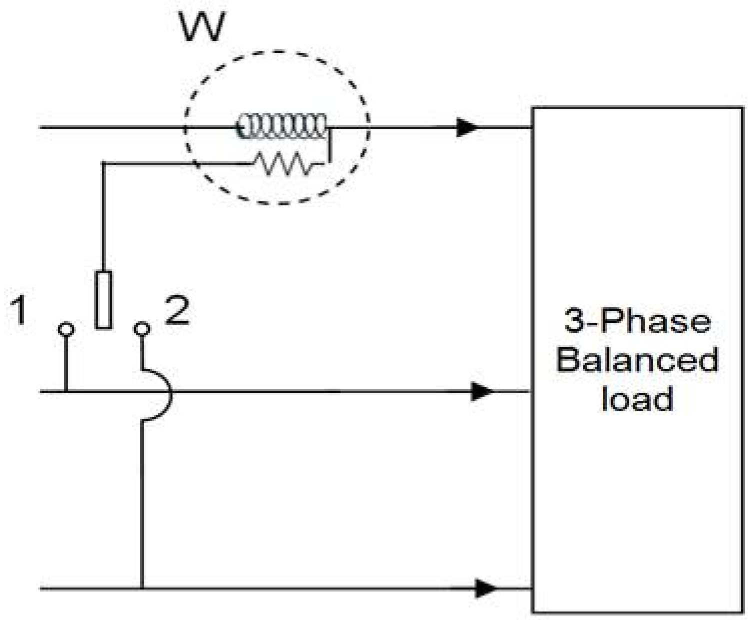


Fig. 30.3 Connection diagram for one wattmeter method

One wattmeter method is applicable to balanced load. The total circuit power is given by multiplying the wattmeter reading by three. Advantage of this method is simplicity in connection. The current coil of the wattmeter is connected in any one line and the potential coil is connected alternately between this and the other two lines. Sum of the two readings gives the total power taken up by the load.

30.3 Energy Measurement

The energy meter is an electrical measuring device, which is used to record Electrical Energy Consumed over a specified period of time in terms of units. Electricity meters operate by continuously measuring the instantaneous voltage (volts) and current (amperes) and finding the product of these to give instantaneous electrical power (watts) which is then integrated against time to give energy used (joules, kilowatt-hours etc.).

1. Voltage coil - many turns of fine wire encased in plastic, connected in parallel with load.
2. Current coil - three turns of thick wire, connected in series with load.
3. Stator - concentrates and confines magnetic field.
4. Aluminum rotor disc.
5. Rotor brake magnets.
6. Spindle with worm gear.
7. Display dials - note that the 1/10, 10 and 1000 dials rotate clockwise while the 1, 100 and 10000 dials rotate counter-clockwise.

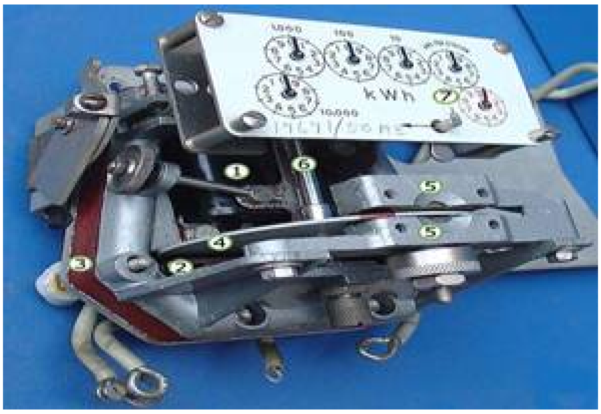


Fig. 30.4 Energy Meter

30.3.1 Electromechanical meters

The most common type of electricity meter is the electromechanical induction watt-hour meter. The electromechanical induction meter operates by counting the revolutions of an aluminium disc which is made to rotate at a speed proportional to the power. The number of revolutions is thus proportional to the energy usage. It consumes a small amount of power, typically around 2 watts.

The metallic disc is acted upon by two coils. One coil is connected in such a way that it produces a magnetic flux in proportion to the voltage and the other produces a magnetic flux in proportion to the current. The field of the voltage coil is delayed by 90 degrees using a lag coil. This produces eddy currents in the disc and the effect is such that a force is exerted on the disc in proportion to the product of the instantaneous current and voltage. A permanent magnet exerts an opposing force proportional to the speed of rotation of the disc. The equilibrium between these two opposing forces results in the disc rotating at a speed proportional to the power being used. The disc drives a register mechanism which integrates the speed of the disc over time by counting revolutions, much like the odometer in a car, in order to render a measurement of the total energy used over a period of time. The type of meter described above is used on a single-phase AC supply. Different phase configurations use additional voltage and current coils.

The aluminum disc is supported by a spindle which has a worm gear which drives the register. The register is a series of dials which record the amount of energy used. The dials may be of the cyclometer type, an odometer-like display that is easy to read where for each dial a single digit is shown through a window in the face of the meter, or of the pointer type where a pointer indicates each digit. With the dial pointer type, adjacent pointers generally rotate in opposite directions due to the gearing mechanism.

The amount of energy represented by one revolution of the disc is denoted by the symbol kWh which is given in units of watt-hours per revolution. Three-phase electromechanical induction meter, metering 100 A 230/400 V supply. Horizontal aluminium rotor disc is visible in center of meter.

In an induction type meter, creep is a phenomenon that can adversely affect accuracy, that occurs when the meter disc rotates continuously with potential applied and the load terminals open circuited. A test for error due to creep is called a creep test.

30.3.2 Electronic meters

Electronic meters display the energy used on an LCD or LED display, and can also transmit readings to remote places. In addition to measuring energy used, electronic meters can also record other parameters of the load and supply such as maximum demand, power factor and reactive power used etc. They can also support time-of-day billing, for example, recording the amount of energy used during on-peak and off-peak hours.

Lesson 31

MAXIMUM DEMAND CHARGE

31.1 Important Terms and Definitions

31.1.1 Demand

The rate at which electric energy is used in any instant or average over a period of time. Usually expressed in kilowatts (kW) or kilovolt-amperes (kVA).

31.1.2 Kilovolt amperes (kVA)

A measure of electrical load on a circuit or system. This unit is used to measure apparent electric power. For billing purposes maximum demand measured in kilowatts (kW) is converted to kilovolt amperes (kVA) by dividing by the power factor. Maximum demand and capacity charges are billed using kVA rather than kW.

31.1.3 Kilowatt

A measure of electrical power. One kilowatt (kW) equals 1,000 watts.

31.1.4 Kilowatt hour

A measure of electrical energy. One kilowatt hour (kWh) of energy is the energy produced by one kilowatt acting for one hour. Electricity meters record in kilowatt hours and electrical consumption is billed on kilowatt hours.

31.1.5 Load factor

Ratio of average energy demand (load) to maximum demand (peak load) during a specific period. Usually stated as a percentage, or number of hours used.

31.1.6 Maximum demand (MD)

The measure of the highest peak of electricity flow into the site during a half-hour period, in the period of a month. Measured in either kW or kVA.

31.1.7 Power factor

The ratio of active or real power in kilowatts (kW), to apparent power in kilovolt amperes or kVA. Power Factor is normally expressed as a figure between zero and one. Unity power factor is 100% (or 1.0) power factor which is the highest available. In practice 0.99 is the highest.

31.1.8 Trivector meter

Trivector meter can measure active power, reactive power, apparent power i.e. with the help of a single meter we can measure kVA, kW, kVAR. The power triangle is sum of (kW, kVAR, kVA) and the meter which gives readings all of the above variables is called TRI vector meter.

31.2 Billing of Electricity

The electricity billing by utilities for medium & large enterprises, in High Tension (HT) category, is often done on two-part tariff structure, i.e. one part for capacity (or demand) drawn and the second part for actual energy drawn during the billing cycle. Capacity or demand is in kVA (apparent power) or kW terms. The reactive energy (i.e.) kVArh drawn by the service is also recorded and billed for in some utilities, because this would affect the load on the utility. Accordingly, utility charges for maximum demand, active energy and reactive power drawn (as reflected by the power factor) in its billing structure. In addition, other fixed and variable expenses are also levied. The tariff structure generally includes the following components:

a) *Maximum demand Charges*

These charges relate to maximum demand registered during month/billing period and corresponding rate of utility.

b) *Energy Charges*

These charges relate to energy (kilowatt hours) consumed during month / billing period and corresponding rates, often levied in slabs of use rates. Some utilities now charge on the basis of apparent energy (kVAh), which is a vector sum of kWh and kVArh.

c) *Power factor* penalty or bonus rates, as levied by most utilities, are to contain reactive power drawn from grid.

d) *Fuel cost* adjustment charges as levied by some utilities are to adjust the increasing fuel expenses over a base reference value.

e) *Electricity duty charges* levied w.r.t units consumed.

f) *Meter rentals*

g) *Lighting and fan power consumption* is often at higher rates, levied sometimes on slab basis or on actual metering basis.

h) *Time of Day (TOD)* rates like peak and non-peak hours are also prevalent in tariff structure provisions of some utilities.

i) *Penalty for exceeding contract demand*

j) *Surcharge if metering is at LT side in some of the utilities*

Analysis of utility bill data and monitoring its trends helps energy manager to identify ways for electricity bill reduction through available provisions in tariff framework, apart from energy budgeting. The utility employs an electromagnetic or electronic trivector meter, for billing purposes. The minimum outputs from the electromagnetic meters are

- Maximum demand registered during the month, which is measured in preset time intervals (say of 30 minute duration) and this is reset at the end of every billing cycle.
- Active energy in kWh during billing cycle
- Reactive energy in kVARh during billing cycle and
- Apparent energy in kVAh during billing cycle

It is important to note that while maximum demand is recorded, it is not the instantaneous demand drawn, as is often misunderstood, but the time integrated demand over the predefined recording cycle. *As example, in an industry, if the drawl over a recording cycle of 30 minutes is:*

250 kVA for 4 minutes
360 kVAfor 12 minutes
410 kVAfor 6 minutes
380 kVA for 8 minutes

The MD recorder will be computing MD as:

$$\frac{(250 \times 4) + (360 \times 12) + (410 \times 6) + (380 \times 8)}{30} = 360.67\ kVA$$

The month's maximum demand will be the highest among such demand values recorded over the month. The meter registers only if the value exceeds the previous maximum demand value and thus, even if, average maximum demand is low, the industry / facility has to pay for the maximum demand charges for the highest value registered during the month, even if it occurs for just one recording cycle duration i.e., 30 minutes during whole of the month. A typical demand curve is shown in Figure 31.1 the demand varies from time to time.

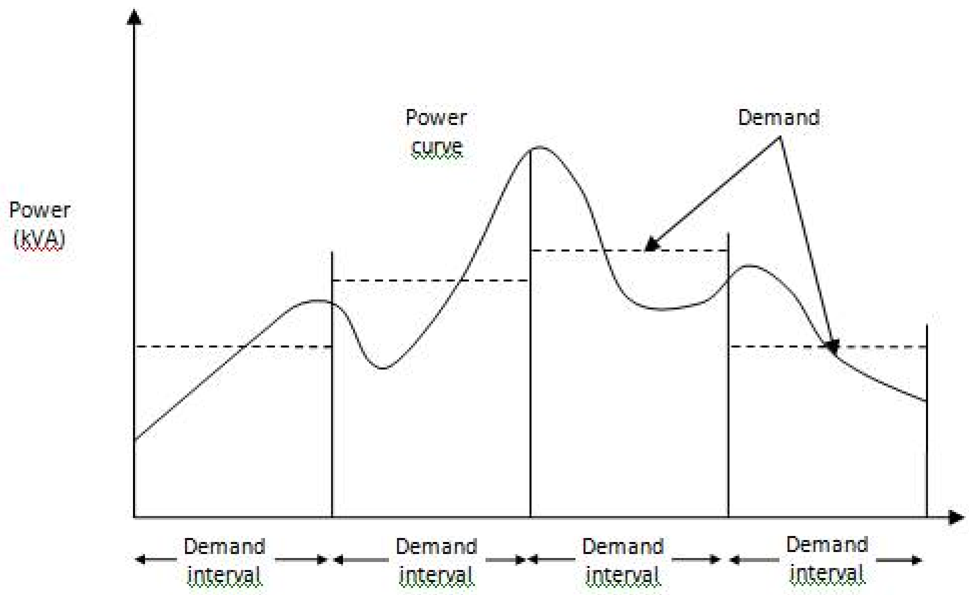


Fig. 31.1 Maximum demand curve

As can be seen from the Figure 31.1 the demand is measured over predetermined time interval and averaged out for that interval as shown by the horizontal dotted line. Fig. 31.2 shows the peak demand during 24 hour operation of a plant.

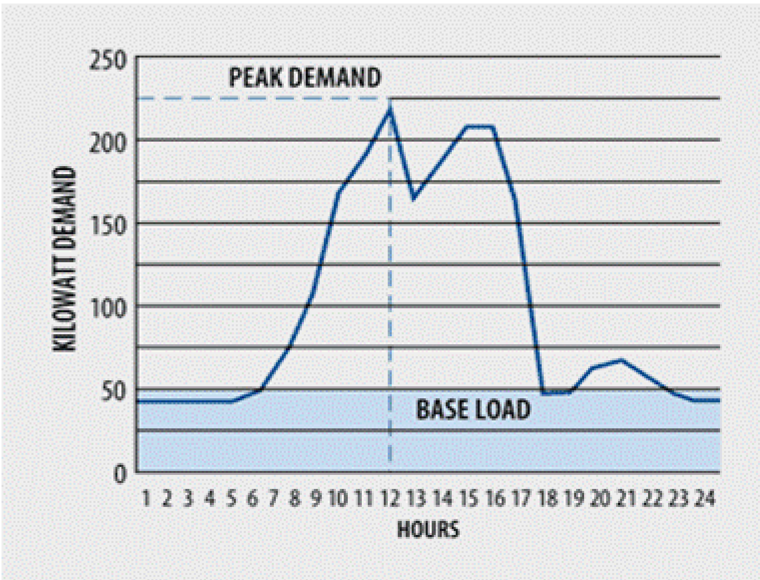


Fig. 31.2 Peak demand during a 24 hour operation

Most electricity boards have changed over from conventional electromechanical trivector meters to electronic meters, which have some excellent provisions that can help the utility as well as the industry. These provisions include:

- Substantial memory for logging and recording all relevant events
- High accuracy up to 0.2 class
- Amenability to time of day tariffs
- Tamper detection /recording
- Measurement of harmonics and Total Harmonic Distortion (THD)
- Long service life due to absence of moving parts
- Amenability for remote data access/downloads

Trend analysis of purchased electricity and cost components can help the industry to identify key result areas for bill reduction within the utility tariff available framework along the following lines.

Table 31.1 Purchased electrical energy trend

Month & Year	MD Recorded kVA	Billing Demand* kVA	Total Energy Consumption kWh	Energy Consumption During Peak Hours (kWh)	MD Charge Rs./kVA	Energy Charge Rs./kWh	PF	PF Penalty/ Rebate Rs.	Total Bills Rs.	Average Cost Rs./kWh
Jan.										
Feb.										
Dec.										

31.3 Need for Electrical Load Management

In a macro perspective, the growth in the electricity use and diversity of end use segments in time of use has led to shortfalls in capacity to meet demand. As capacity addition is costly and only a long time prospect, better load management at user end helps to minimize peak demands on the utility infrastructure as well as better utilization of power plant capacities.

The utilities (State Electricity Boards) use power tariff structure to influence end user in better load management through measures like time of use tariffs, penalties on exceeding maximum demand, night tariff concessions etc. Load management is a powerful means of efficiency improvement both for end user as well as utility.

As the demand charges constitute a considerable portion of the electricity bill, from user angle too there is a need for integrated load management to effectively control the maximum demand.

31.4 Step by Step Approach for Maximum Demand Control

31.4.1 Load curve generation

Presenting the load demand of a consumer against time of the day is known as a 'load curve'. If it is plotted for the 24 hours of a single day, it is known as an 'hourly load curve' and if daily demands plotted over a month, it is called daily load curves. A typical hourly load curve for an engineering industry is shown in Figure 31.3. These types of curves are useful in predicting patterns of drawl, peaks and valleys and energy use trend in a section or in an industry or in a distribution network as the case may be.

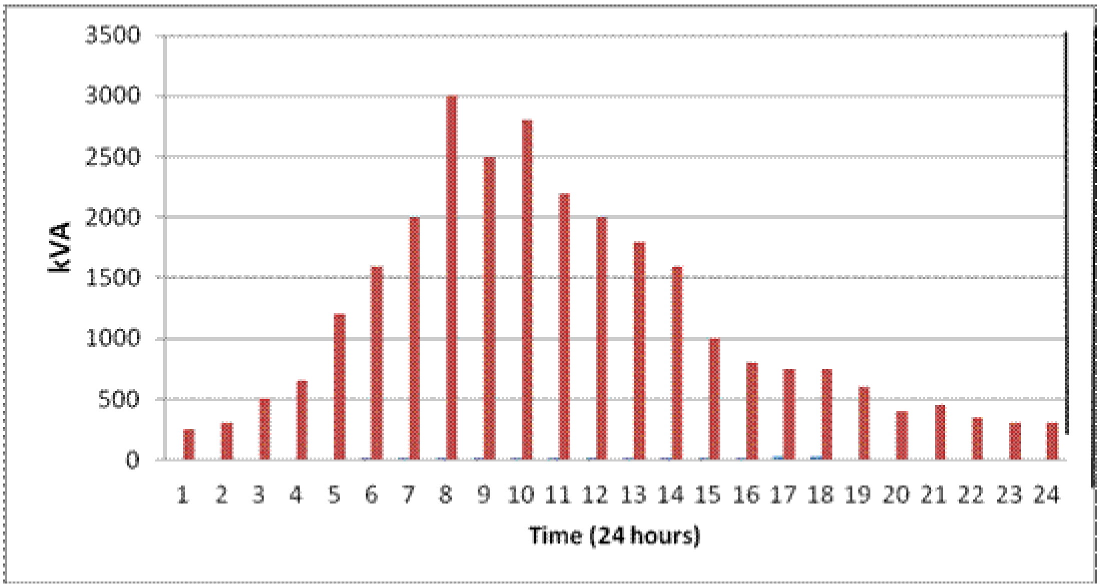


Fig. 31.3 Hourly load curve

31.4.2 Rescheduling of loads

Rescheduling of large electric loads and equipment operations, in different shifts can be planned and implemented to minimize the simultaneous maximum demand. For this purpose, it is advisable to prepare an operation flow chart and a process chart. Analyzing these charts and with an integrated approach, it would be possible to reschedule the operations and running equipment in such a way as to improve the load factor which in turn reduces the maximum demand.

31.4.3 Storage of Products/in process material/ process utilities like refrigeration

It is possible to reduce the maximum demand by building up storage capacity of products/ materials, water, chilled water / hot water, using electricity during off peak periods. Off peak hour operations also help to save energy due to favorable conditions such as lower ambient temperature etc. Example: Ice bank system is used in milk & dairy industry. Ice is made in lean period and used in peak load period and thus maximum demand is reduced.

31.4.4 Shedding of non-essential loads

When the maximum demand tends to reach preset limit, shedding some of non-essential loads temporarily can help to reduce it. It is possible to install direct demand monitoring systems, which will switch off non-essential loads when a preset demand is reached. Simple systems give an alarm, and the loads are shed manually. Sophisticated microprocessor controlled systems are also available, which provide a wide variety of control options like:

- Accurate prediction of demand
- Graphical display of present load, available load, demand limit
- Visual and audible alarm
- Automatic load shedding in a predetermined sequence
- Automatic restoration of load
- Recording and metering

31.4.5 Operation of captive generation and diesel generation sets

When diesel generation sets are used to supplement the power supplied by the electric utilities, it is advisable to connect the D.G. sets for durations when demand reaches the peak value. This would reduce the load demand to a considerable extent and minimize the demand charges.

31.4.6 Reactive power compensation

The maximum demand can also be reduced at the plant level by using capacitor banks and maintaining the optimum power factor. Capacitor banks are available with microprocessor based control systems. These systems switch on and off the capacitor banks to maintain the desired Power factor of system and optimize maximum demand thereby.

31.5 Electrical energy conservation in dairy processing plant

1. Power System

- Transformer loading
- Determination of plant load & load factor analysis
- Improving power factor
- Identification and minimsing transformer and system distribution losses
- Demand management & controls
- Parallel operation of DG/TG sets with grid
- Use of harmonic filters near equipments generating harmonics to reduce total harmonic distortion

2. Motors

- Correct sizing of motors/capacity utilisation
- Conduct motor load survey and check for lightly loaded motors
- Downsizing with an energy efficient motor
- Use of Energy-efficient motors (4-5% more efficiency)
- Speed control using VFD (Decrease of speed by 10% will save about 19% energy)
- Ensuring and recording efficiency of rewound motors
- Shift from standard delta to star operation for motors operated below 40% of rated capacity.

3. Fans & Pumps

4. Refrigeration & A.C.

- Arresting cold air leakage
- Reducing refrigeration load by keeping diffusers outside the room.
- Monitoring system performance
- Ensuring proper refrigerant charge
- Checking for refrigerant contamination
- Automated controls
- Segregation of refrigeration systems
- Efficient piping design and insulation
- Minimizing heat sources in cold storage areas
- Use of vapour absorption machine (VAM)
- Operating ice bank system at night when atmospheric temperature is low

5. Lighting

- Illumination measurement
- Automatic controls/timers e.g. day light linked control
- Use of translucent sheets in roof
- Lighting energy savers with voltage correction
- Replacement with energy efficient lamps (CFL)
- Electronic ballast
- Lamp/retrofit/reflector selection

6. Compressed Air

- Prevention of leaks in compressed air system
- Restoration of generation capacity of air compressor

- Use high efficiency impeller along with cone
- Impeller derating using small diameter impeller
- Use of energy efficient hollow FRP impeller with aerofoil design in cooling towers
- Reduce compressor delivery pressure wherever possible (A reduction of 1 kg/cm2 air pressure would result in 9% input energy saving)

7. Water conservation

- Reuse of water from coolers, heat exchangers, evaporators etc
- Condensate recovery

References

BEE. 2005. Bureau of Energy Efficiency (BEE) guide book. Electrical system In: Energy Efficiency in Electrical Utilities, pg. 5-15.

Lesson 32

LOAD FACTOR AND POWER FACTOR CORRECTION

32.1 Power Factor Basics

32.1.1 Active & reactive power

Active power, measured in kilowatt (kW), is the real power (shaft power, true power) used by a load to perform a certain task. However, there are certain loads like motors, which require another form of power called reactive power (kVAR) to establish the magnetic field. Although reactive power is virtual, it actually determines the load (demand) on an electrical system. The utility has to pay for total power (or demand) as depicted in Figure 32.1.

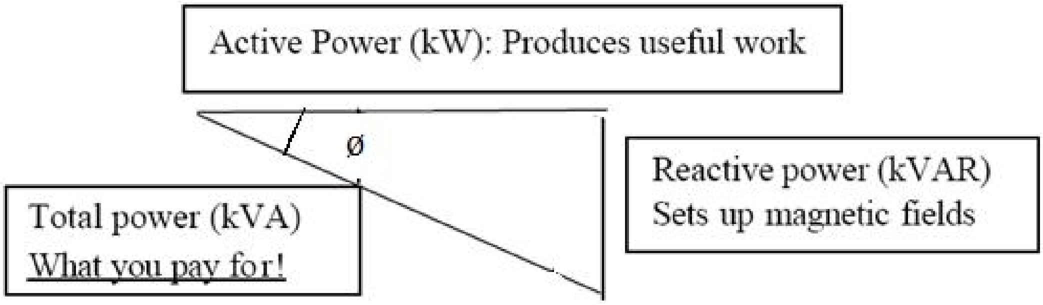


Fig. 32.1 Active, reactive and total power

The vector sum of the active power and reactive power is the total (or apparent) power, measured in kVA (kilo Volts-Amperes). This is the power sent by the power company to customers. Mathematically it may be represented as:

$$kVA = \sqrt{(kW)^2 + (kVAR)^2}$$

The power factor is the ratio between active power (kW) and total power (kVA), or the cosine of the angle between active and total power. A high reactive power will increase this angle and as a result the power factor will be lower (See Figure 32. 2).

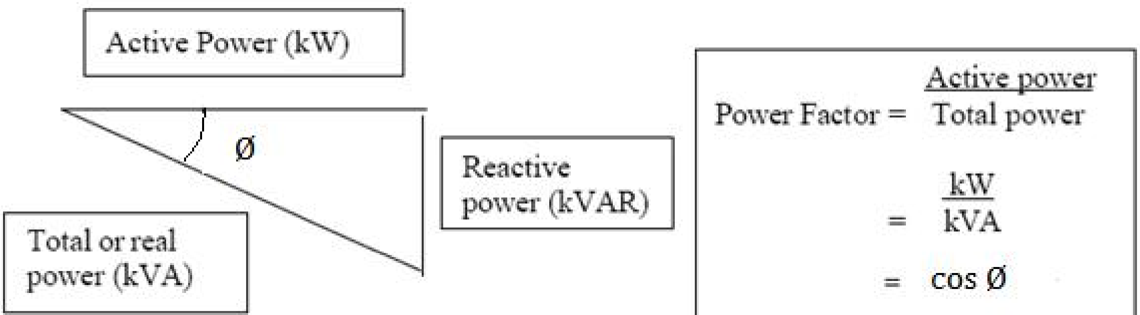


Fig. 32. 2 Relationship between active, reactive and total power

The power factor is always less than or equal to one. Theoretically, if all loads of the power supplied by electricity companies have a power factor of one, the maximum power transferred equals the distribution system capacity. However, as the loads are inductive and if power factors range from 0.2 to 0.3, the electrical distribution network's capacity is stressed. Hence, the reactive power (kVAR) should be as low as possible for the same kW output in order to minimize the total power (kVA) demand.

32.2 Disadvantages of Low Power Factor

Considering fixed power and voltage, the load current is inversely proportional to the power factor. Smaller the power factor, higher is the load current and *vice-versa*.

$$I_L = \frac{P}{V_L \cos \emptyset} \qquad (single\ phase\ supply)$$

$$I_L = \frac{P}{\sqrt{3} V_L \cos \emptyset} \qquad (Three\ phase\ supply)$$

Large current due to poor power factor results in the following disadvantages:

32.2.1 Large *kVA* rating of equipment

The electrical machinery such as motors, A.C. generators, transformers, distribution and control system etc. are rated in kVA. Because the power factor is not known when the machine is manufactured in the factory.

$$kVA = \frac{kW}{\cos \emptyset}$$

kVA rating of the equipment is inversely proportional to power factor which implies smaller the power factor, the larger is the *kVA* rating. At low power factor *kVA* rating of the equipment required is more which makes the equipment larger and costly.

1. **Large copper losses**: The large current drawn by the machine because of poor power factor causes more I^2R losses.
2. **Poor voltage management**: The large current at low power factor causes greater voltage drops in the electrical distribution network and system. This causes improper functioning of the electrical machines.

32.3 Improving Power Factor (PF)

The solution to improve the power factor is to add power factor correction capacitors to the plant power distribution system. They act as reactive power generators, and provide the needed reactive power to accomplish kW of work. This reduces the amount of reactive power, and thus total power, generated by the utilities.

32.4 The advantages of PF improvement by Capacitor Addition

a) Reactive component of the network is reduced and so also the total current in the system from the source end.

b) I^2R power losses are reduced in the system because of reduction in current.

c) Voltage level at the load end is increased.

d) kVA loading on the source generators as also on the transformers and lines upto the capacitors reduces giving capacity relief. A high power factor can help in utilising the full capacity of your electrical system.

32. 5 Cost Benefits of PF Improvement

Costs of PF improvement are in terms of investment need for capacitor addition. The benefits to be quantified for feasibility analysis are:

a) Reduced kVA (Maximum demand) charges in utility bill

b) Reduced distribution losses (kWh) within the plant network

c) Better voltage at motor terminals and improved performance of motors

d) A high power factor eliminates penalty charges imposed when operating with a low power factor

e) Investment on system facilities such as transformers, cables, switchgears etc for delivering load is reduced.