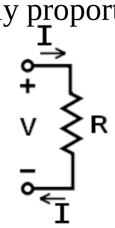
Module-1

1.DC CIRCUITS:

1.1 Ohm's Law. And its limitations

Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference or voltage across the two points, and inversely proportional to the resistance between them.

The mathematical equation that describes this relationship is:



I = V / R

where I is the current through the resistance in units of amperes, V is the potential difference measured across the resistance in units of volts, and R is the resistance of the conductor in units of ohms. More specifically, Ohm's law states that the R in this relation is constant, independent of the current.

Limitations of Ohm's Law:

(a) It does not hold true for non-linear devises such as semiconductor and zener diodes.

(b) It is not applicable to non-metallic conductors, such as silicon carbide, where the following relation is applicable;

$$V = K I^m$$

where K and m are constants.

(c) Ohm's law cannot be applied to arc-lamps

(d) It does not hold good where the temperature rise is rapid in some metals.

1.2 Kirchoff's Law

(i) Kirchhoff's current law (KCL):

This law is also called Kirchhoff's point rule, Kirchhoff's junction rule (or nodal rule), and Kirchhoff's first rule.

The principle of conservation of electric charge implies that:

At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.

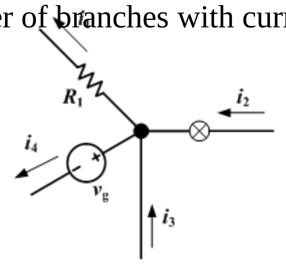
or

The algebraic sum of currents in a network of conductors meeting at a point is zero. (Assuming that current entering the junction is taken as positive and current leaving the junction is taken as negative).

Recalling that current is a signed (positive or negative) quantity reflecting direction towards or away from a node, this principle can be stated as:

$$\sum_{k=1}^{n} I_k = 0$$

n is the total number of branches with currents flowing towards or away from the node.



The current entering any junction is equal to the current leaving that junction. $i_1 + i_4 = i_2 + i_3$

(ii) Kirchhoff's voltage law (KVL):

This law is also called Kirchhoff's second law, Kirchhoff's loop (or mesh) rule, and Kirchhoff's second rule.

The principle of conservation of energy implies that

The directed sum of the electrical potential differences (voltage) around any closed circuit is zero.

or

More simply, the sum of the emfs in any closed loop is equivalent to the sum of the potential drops in that loop.

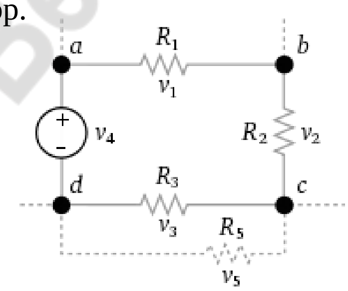
or

The algebraic sum of the products of the resistances of the conductors and the currents in them in a closed loop is equal to the total emf available in that loop.

Similarly to KCL, it can be stated as:

$$\sum_{k=1}^{n} V_k = 0$$

Here, n is the total number of voltages measured.



The sum of all the voltages around the loop is equal to zero. $v_1 + v_2 + v_3 - v_4 = 0$

1.3 (a) Electrical Work, (b) Electrical Power and (c) Electrical Energy.

(a) Electric work:

In an electric circuit, there is movement of electrons which constitutes flow of current. This movement of electrons results in transfer of charge. Electrical work is done when there is a transfer of charge. The unit of such electrical work is joule.

One joule of electrical work done is that work done in moving a charge of 1 coulomb through a potential difference of 1 volt.

Thus, if V = Potential difference in volts

And Q = Charge in coulombs

Then, electrical work, W = V x Q joules

Now, I = Q/t

Therefore W = VIt joules

where, t = time in seconds

(b) Electric power:

Electrical power is the rate at which electrical energy is done in an electric circuit. The SI unit of power is the watt.

Therefore, Electrical power , P = electrical work done / Time

= w/t = VIt / t

= VI joules/sec, i.e watts..

The Power consumed in an electrical circuit is one watt if potential difference applied across the circuit is 1 volt which causes 1 ampere of current to flow through the circuit.

P = V x I (watts)

1 watt = 1 volt x 1 ampere

1 watt = 1 joule/sec

where *P* is the electric power, *V* the potential difference, and *I* the electric current.

In the case of resistive (Ohmic, or linear) loads, Joule's law can be combined with Ohm's law (*I* = *V/R*) to produce alternative expressions for the dissipated power:

$$P = I^2 R = V^2 / R$$

where *R* is the electrical resistance.

(c) Electrical Energy:

Electrical energy is that amount of electrical work done in an electrical circuit.

Therefore, Electrical energy = Power x time

i.e., W = VIt joules, i.e watt-sec

The unit if electrical energy is joule or watt-sec

Energy consumed by an electric circuit is 1 watt-sec or joule when it utilizes power of 1 watt for 1 sec.

As the watt sec is a very small unit, electrical energy is measured in larger units, viz the watt-hour and kilowatt-hour (kWh) (which is the commercial unit of energy).

1. **If the total power dissipated in the circuit shown is 18 watts, find the value of R and its current.**

Solution:

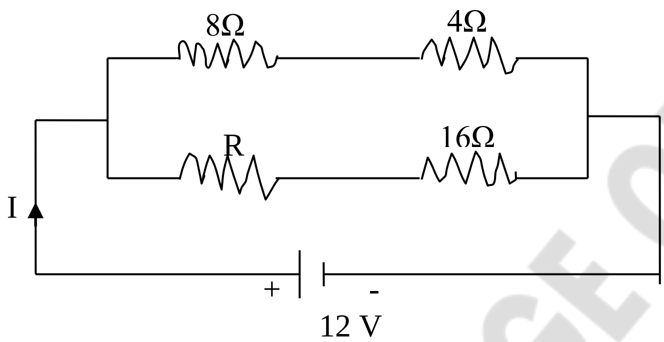
Total power dissipated, P = 18 watts

$P = V^2/ R_{eq}$

Where R_{eq} = Equivalent resistance of the circuit

Therefore, $18 = 12^2/R_{eq}$

$R_{eq} = 8\Omega$



Also, $R_{eq} = (8R)/(8+R) + (4x16)/(4+16)$

$8 = (8R)/(8+R) + (64)/(20)$

$= [160 R + 64 (8+R)] / [20(8+R)]$

$160 (8+R) = 160 R + 512 + 64 R$

$1280 + 160 R = 160 R + 512 + 64 R$

$768 = 64 R$

Therefore, R = **12Ω**

Total current, $I = V/R_{eq} = 12/8$ = **1.5 A**

2. **A resistance of 10Ω is connected in series with two resistance each of 15Ω arranges in parallel. What resistance must be shunted across this parallel combination so that the total current taken shall be 1.5 A with 20 V applied?**

Solution:

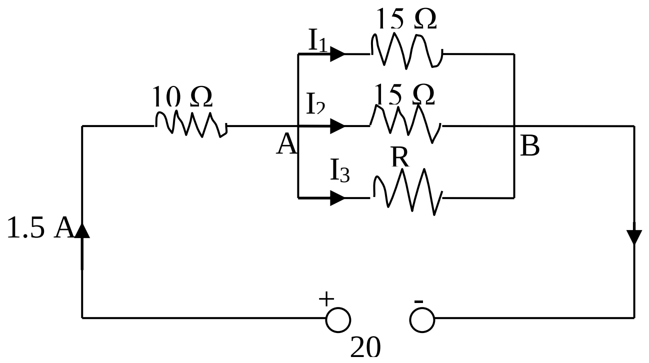
The circuit combination is as shown in figure.

The value of R is required to be found.

Drop across 10 Ω resistor = 1.5 x 10 = 15 V

Drop across parallel combination, V_{AB} = 20-15 = 5 V

So, Voltage across each parallel resistance is 5 V.



I_1 = 5/15 = 1/3 A

I_2 = 5/15 = 1/3 A

I_3 = 1.5 – (1/3 + 1/3) = **5/6 A**

Therefore, I_3R = 5/6 A

I_3R = 5

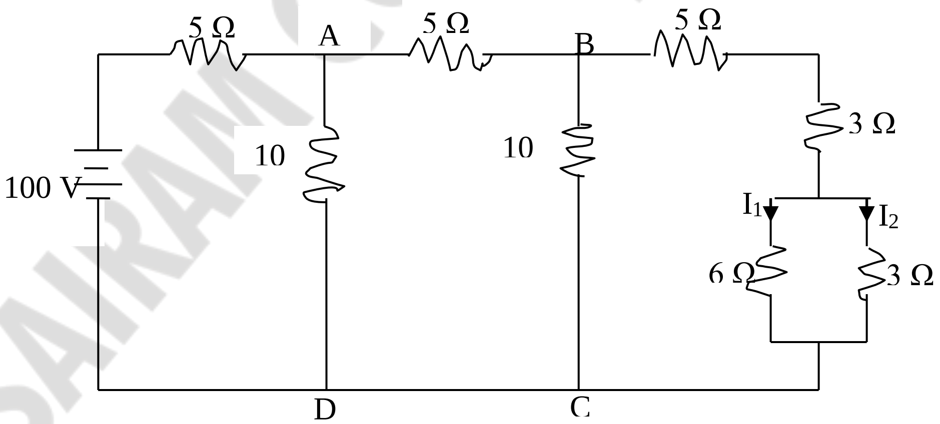
or (5/6)R = 5

or R = **6 Ω**

3. In Circuit shown in figure, determine

(i) The current supplied by the 100 V source

(ii) The voltage across the 6 Ω resistor.



Solution:

(a) As 6Ω and 3Ω are in parallel, their equivalent resistance is

(6x3) / (6+3) = **2 Ω**

(b) This is in series with the 3 Ω and 5 Ω resistors,

Therefore, Total Resistance, R_t = 2+3+5 = **10 Ω**

(c) R_t comes in parallel with the 10 Ω resistor between B and C.

Therefore, Their equivalent resistance,

R_e = (10x10) / (10+10) = **5 Ω**

(d) R_e comes in series with the 5 Ω resistor between A and B,

Therefore, combined resistance, R_c = 5 + 5 = **10 Ω**

(e) R_c comes in parallel with the 10 Ω resistor between A and B,

Therefore, equivalent resistance, R_{eq} = (10x10) / (10+10) = **5 Ω**

(f) R_{eq} is in series with the other 5 Ω resistor

Therefore, Total circuit resistance R_{tcr} = 5+5 = 10 Ω

Therefore, current supplied by battery = 100/R_{tcr} = 100/10 = 10A

At A, the current divides equally between AB and AD.

Therefore, current in AB = 5A

Again, at B, the current is equally divided.

Therefore, current in BE = 5/2 = 2.5 A

Current again divides at E. The current of 2.5 A divides in the ratio 3:6 or 1:2 in the 6 Ω and 3 Ω branch resistors.

Therefore, current in the 6 Ω resistor = (2.5x1) / 3 = **2.5/3 A**

Therefore, Voltage drop across the 6 Ω resistor = (2.5/3) x 6 = **5 V.**

4. A current of 20 A flows through two ammeters A and B in series. The potential difference across A is 0.2 V and across B is 0.3 V. Find how the same current will divide between A and B when they are in parallel.

Solution:

The two ammeters A and B can be considered as resistors of R_A and R_B ohms.

Therefore, R_A = 0.2/20 = 0.01 Ω and R_B = 0.3/20 = 0.015 Ω

The total current through the parallel combination still remains 20 A. Therefore,

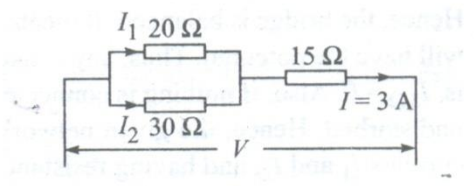
I_A = I. R_B / (R_B+ R_A) = 20 x 0.015 / (0.015+0.01) = **12 A.**

And Therefore, I_B = I – I_A = 20 -12 = **8 A.**

5. A circuit consists of two parallel resistors having resistances of 20 Ω and 30 Ω respectively, connected in series with a 15 Ω resistor. If the current through 15 Ω resistor is 3 A, find (i) the current in 20 Ω and 30 Ω resistors, (ii) the voltage across the whole circuit, and (iii) the total power consumed in all resistors.

Soultion:

The circuit arrangement is shown in figure.



(i) The current in 20 Ω resistor,

$I_1 = 3 \times 30 / (20+30) = \mathbf{1.8\ A}$

The current in 30 Ω resistor,

$I_2 = 3 \times 20 / (20+30) = \mathbf{1.2\ A}$

(ii) The voltage across the whole circuit, $V = I_1 \times 20 + I \times 15$

$= 1.8 \times 20 + 3 \times 15 = \mathbf{81\ V}$

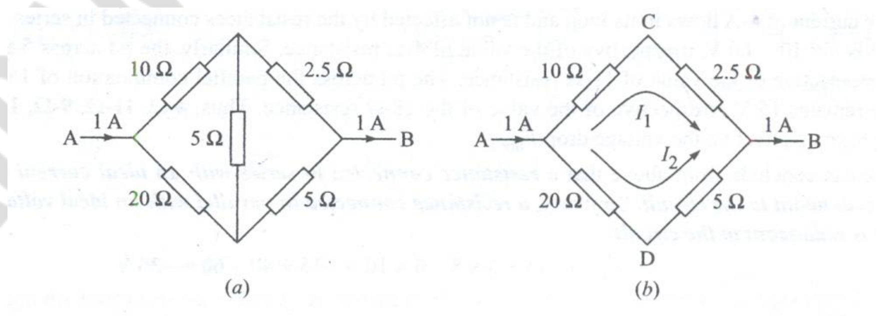
(iii) The total power, $P = VI = 81 \times 3 = \mathbf{243\ W}$

$P_{20\Omega} = 1.8^2 \times 20 = \mathbf{64.8\ W}$

$P_{30\Omega} = 1.2^2 \times 30 = \mathbf{43.2\ W}$

$P_{15\Omega} = 3^2 \times 15 = \mathbf{135\ W}$

6. **Find the currents in all resistors of the network shown in fig. Also find the voltage across AB.**



Solution:

The given network is a Wheatstone bridge. Checking the ratio of the two adjacent sides, we find that

$10/2.5 = 20/5$

Hence, the bridge is balanced. It means whatever may be the current entering terminal A, the points C and D in figure (b) will have the potential. Thus, any resistance connected between these points will have no current flowing through it. That is, $I_{5\Omega} = 0$. Also, if nothing is connected between C and D as shown in figure (b), the currents in other resistors remains undisturbed. Hence, the given network is equivalent to that shown in figure (b). It has two parallel branches carrying currents I_1 and I_2, having resistances,

$$R_1 = 10+2.5 = 12.5\ \Omega \quad \text{and} \quad R_2 = 20+5 = 25\ \Omega$$

By current divider rule, we get

$$I_1 = I \times R_2 / (R_1 + R_2)$$

$$= 1 \times 25 / (12.5 + 25) = 2/3\ A$$

And $\quad I_2 = 1 - I_1 = 1 - (2/3) = 1/3\ A$

Thus, the current through different resistors are

$I_{10\Omega} = I_{2.5\Omega} = \mathbf{(2/3)\ A}$

$I_{5\Omega} = \mathbf{0\ A}$

$I_{20\Omega} = I_{5\Omega} = \mathbf{(1/3)\ A}$

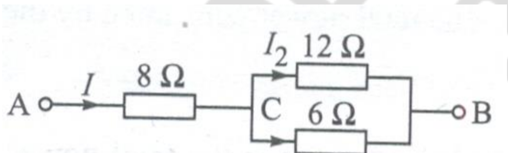
Going from A to B along the upper branch, the voltage across AB is given as

$$V_{AB} = I_2\,(10 + 2.5) = 2/3 \times 12.5 = \mathbf{8.33\ V}$$

7. An 8-ohm resistor is in series with a parallel combination of two resistors 12 ohm and 6 ohms. If the current in 6-ohm resistor is 5 A, determine the total power dissipated in the circuit.

Solution:

The circuit arrangement is shown in figure.



The voltage across CB, $V_{CB} = I_1 R = 5 \times 6 = 30$ V

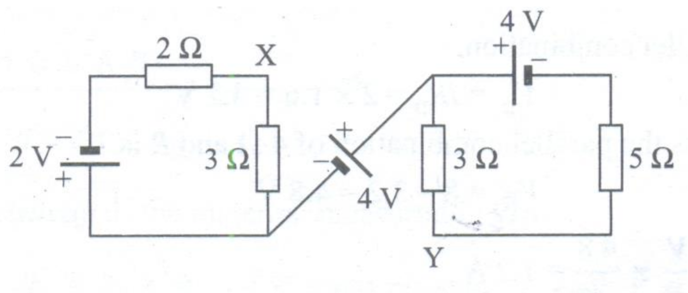
Therefore, $\quad I_2 = V_{CB} / R = 30/12 = 2.5$ A $\quad$ and

$$I = I_1 + I_2 = 5 + 2.5 = 7.5\ A$$

Total resistance of the circuit, $R_{AB} = 8 + 12 \parallel 6 = 12\ \Omega$

The total power, $\quad P = I^2 R_{AB} = 7.5^2 \times 12 = 675$ W

8. **Obtain the potential difference V_{xy} in the circuit shown**.



Solution:

The current in left-hand loop, $I_1 = 2 / (2+3) = 0.4$ A (anticlockwise)

The current in right-hand loop, $I_2 = 4 / (5+3) = 0.5$ A (anticlockwise)

The voltage V_{xy} is the voltage of point x with respect to point y. To find this voltage, we start from y and transverse a path to x to find the total voltage rise,

$$V_{xy} = 3 \times I_2 - 4 - 3 \times I_1 = 3 \times 0.5 - 4 - 3 \times 0.4 = \mathbf{-3.7\ V}$$

9. A resistance R is connected in series with a parallel circuit comprising two resistances of 12Ω and 8 Ω respectively. The total power dissipation in the circuit is 70 W when the applied voltage is 20 V. Calculate R.

Solution:

When 20 V is applied to the circuit, the total power dissipation is 70 W. Therefore, the total resistance R_T of the circuit,

$$R_T = V^2/P = 20^2 / 70 = 5.71\ \Omega$$

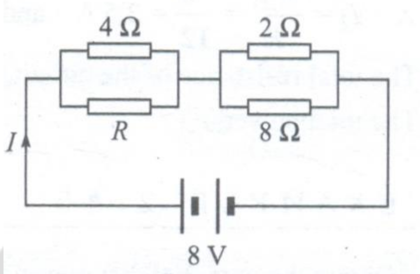
The resistance of the parallel circuit, $R_P = R_1 \times R_2 / (R_1 + R_2)$

$= 12 \times 8 / (12 + 8) = 4.8\ \Omega$

Therefore, the resistance R connected in series is

$$R = R_T - R_P = 5.71 - 4.8 = \mathbf{0.91\ \Omega}$$

10. The total power consumed by the network shown in figure is 16 W. Find the value of R and the total current.



Solution:

Since the total power consumed by the network is 16 W which is supplied by the 8=V battery, the current I is given as

$$I = P/V = 16/8 = 2\ A$$

The parallel combination of 2 Ω and 8 Ω is

$$R_P = R_1 \times R_2 / (R_1 + R_2)$$

$$= 2 \times 8 / (2 + 8) = 1.6\ \Omega$$

The voltage drop across this parallel combination,

$$V_P = IR_P = 2 \times 1.6 = 3.2\ V$$

Therefore, the voltage drop across the parallel combination of 4Ω and R is

$$V_R = 8-3.2 = 4.8\ V$$

The current in 4 Ω resistor, $I_1 = V/R = 4.8 / 4 = 1.2$ A

Therefore, the current through R, $I_2 = I - I_1 = 2 - 1.2 = 0.8$ A

Finally, the value of $R = V/I = 4.8 / 0.8 = 6\ \mathbf{\Omega}$

ELECTROMAGNETISM:

1.4 expression for the energy stored in a magnetic field

When a coil is connected to an electrical energy source, the current gradually increases from zero to its final value I. Due to the current in the inductances (L) part of the coil, a magnetic field is established. The energy stored in the inductance as magnetic field is given by

$$W = \tfrac{1}{2} LI^2 \qquad \text{-----------} \quad (1)$$

In addition to this energy stored in the magnetic field, some energy is dissipated as heat due to the current flowing in the resistance (R) part of the coil.

Once, the field is established and the current has attained its steady value, no more energy is required to maintain the magnetic field. On the other hand, whenever the circuit is broken, the magnetic field collapses and the energy stored is used to generating the induced emf or current.

The expression for the energy stored in inductance given in (1) can be modified by using the expression

$$L = \frac{N^2 \mu A}{l}$$

This equation can be written as

$$L = \frac{\mu_0 \mu_r A N^2}{l}$$

Hence, the energy stored in the magnetic field is

$$W = \tfrac{1}{2} LI^2 = \tfrac{1}{2} \mu_0 \mu_r A N^2 I^2 / l$$

$$= \tfrac{1}{2} \mu_0 \mu_r A l N^2 I^2 / l^2 \quad = \quad \tfrac{1}{2} \mu_0 \mu_r (Al)(NI/l)^2$$

Since, Al represents the volume of the magnetic field, and NI/l represents the magnetic field intensity (H),

We have

$$W = \tfrac{1}{2} \mu_0 \mu_r (Al)(NI/l)^2 = \tfrac{1}{2} \mu_0 \mu_r H^2 \ (\text{Volume})$$

Thus, the energy stored per unit volume is given as

$$W_u = \tfrac{1}{2} \mu_0 \mu_r H^2$$

Since, the magnetic flux density, $B = \mu_0 \mu_r H$, the above expression can be modified as

$$W_u = \tfrac{1}{2} \mu_0 \mu_r H^2 = \tfrac{1}{2} BH$$

$$W_u = B^2 / 2 \mu_0 \mu_r \quad \text{joules/m}^3$$

1.5 **difference between self and mutual inductance.**

Self Inductance:

If dc current flows through a coil of wire of zero resistance and if the magnitude of the current increases with time the following events occur. Since the current is increasing, so does the magnetic flux Φ linking the coil. By Faraday's law, a voltage is induced which appears across the terminals of the coil. Since an electric circuit exists, the induced voltage tends to produce current which, by Lenz's law, should be opposite in direction to the parent current. The polarity of the induced voltage must therefore be as shown in figure.

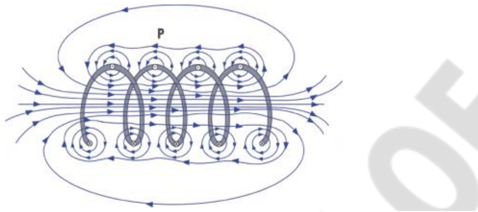


Fig : Voltage induced in a current carrying conductor

or $N\Phi = Li$ --------- (i)

The constant of proportionality, L, is known as self-inductance. Coils possessing the property of self-inductance are known as inductors.

From Eqn. (i), the unit of inductance is weber/amp. This is known as a Henry (H).

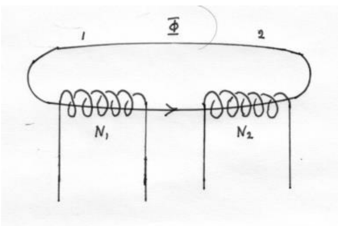
Mutual Inductance:

Suppose flux Φ from a coil A links another coil B which is in another electric circuit. Further, let this flux have a non-zero time derivatives. A voltage will be induced in coil B which is proportional to the time rate of change of flux which links it. Similar to equation (i), we write that

$N\Phi = Mi$ ---------- (ii)

In equation (ii), NΦ is the total flux linkage of coil B and I is the current in coil A. The voltage induced in coil B is therefore d/dt [NΦ] or M. di/dt. The constant M has the units of inductance and is known as inductance. Normally, m is equal to zero if none of the flux from coil a links coil B.

Consider two coils A and B placed near to each other as shown figure.



Let the coil A carry the current I_1 and produces a flux Φ_1 in the winding. This flux link with the coil B entirely if there is no magnetic leakage. As Φ_1 is changing or varying with time the flux linking with coil B also changes and induces an emf Em. in the coil B.

$$E_m = N_2 (d\Phi_1) / dt$$

$$= N_2 (d\Phi_1) / dt \times dI_1/dt$$

$$= N_2 \Phi_1 / I_1 \times dI_1/dt$$

$$E_m = M\, dI_1/dt \quad \text{where } M = (N_2 \Phi_1 / I_1)$$

M is called coefficient of mutual inductance or mutual inductance between the coils A and B and is defined as te number of flux linkages of one coil due to unit current in the other coil.

$$M = N_2 \Phi_1 / I_1 = N_1\Phi_2/ I_2$$

1.6 magnetic flux, magneto motive force and Reluctance. Bring out the relation between them.

Magnetic flux (Greek letter Φ (phi):

The total number of magnetic lines of force in a magnetic field is called magnetic flux.

The unit of magnetic flux in the C.G.S. system is Maxwell. One Maxwell is equal to one magnetic line of force, i.e

1 maxwell = 1 line of force.

The SI unit of magnetic flux is the weber.

1 weber = 10^8 magnetic lines of force or 10^8 maxwells.

Magneto motive force:

M.M.F is defined as the magnetic force, which creates magnetic flux in a magnetic material.

Its unit is 'ampere turns' (AT)

$$Mmf = N \times I$$

where N is the number of turns of wire in the coil and I is the current in the wire.

Another equation for M.M.F is

M.M.F = Flux x Reluctance

Or $NI = \Phi \times S$ or $\Phi = NI / S$

Reluctance:

Reluctance is the property of a magnetic material by virtue of which it opposes the creation of magnetic flux in it. The unit is ampere-turn per weber (AT/Wb). The Reluctance of a magnetic material is directly proportional to the length of the magnetic material and inversely proportional to the area of cross-section.

$$S \;\alpha\; l/A = 1/\mu \,.\, l/A = l / (\mu_0 \mu_r A)$$

$$S = mmf / \Phi$$

Where, μ = a constant known as the absolute permeability of the magnetic material.

$$= \mu_0 \mu_r$$

Where μ_0 = permeability of free space or air and μ_r = relative permeability of the magnetic material.

("S") is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.

(a) Self inductance and (b) Mutual Inductance. Define the unit in which each is measured.

Solution:

Refer Question no. (2)

1.7

(i) Absolute permeability

(ii) Relative permeability

Absolute Permeability(μ_0):

In electromagnetism, permeability is the measure of the ability of a material to support the formation of a magnetic field within itself. In other words, it is the degree of magnetization that a material obtains in response to an applied magnetic field. Magnetic permeability is typically represented by the Greek letter μ. The ratio of the magnetic flux density to the intensity of the magnetic field in a medium.

$$\mu = B/H \quad (H/m)$$

where H = magnetizing force

In SI units, permeability is measured in the henry per metre ($H\,m^{-1}$), or newton per ampere squared ($N\,A^{-2}$). The permeability constant (μ_0), also known as the magnetic constant or the permeability of free space, is a measure of the amount of resistance encountered when forming a magnetic field in a classical vacuum. The magnetic constant has the exact (defined) value $\mu_0 = 4\pi\times10^{-7} \approx 1.2566370614...\times10^{-6}\ H\cdot m^{-1}$ or $N\cdot A^{-2}$).

Relative permeability(μ_r) :

For defining the relative permeability of a magnetic material, the permeability of free space or air is taken as reference. Thus the relative permeability of free space or air is taken as unity.

Thus $\mu_r = 1$ for free space or air.

For any other magnetic material, the relative permeability is defined as the ratio of the flux induced in the magnetic material of a particular shape and size to the flux density induced in free space or air of the same shape and size, when the same magnetizing force is applied. Thus,

$$\mu_r = B/B_0$$

μ_r is dimensionless and hence it is a pure number.

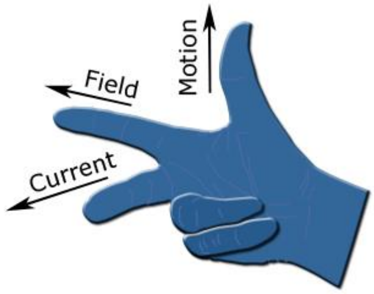
1.7 Fleming's Right Hand Rule.

Fleming's right hand rule (for generators) shows the direction of induced current when a conductor moves in a magnetic field.

The right hand is held with the thumb, first finger and second finger mutually perpendicular to each other {at right angles}, as shown in the diagram .

- The Thu**m**b represents the direction of **M**otion of the conductor.

- The **F**irst finger represents the direction of the **F**ield. (north to south)
- The Se**c**ond finger represents the direction of the induced or generated **C**urrent (the direction of the induced current will be the direction of conventional current; from positive to negative).



- One particular way of remembering the rule is the "FBI" acronym for **F**orce (or otherwise motion), **B** as the magnetic field sign and **I** as the current. The subsequent letters correspond to subsequent fingers, counting from the top. Thumb -> F; First finger -> B; Second finger -> I

1.9 definitions

(a) M.M.F

(b) Magnetic field Intensity

(c) Flux density

Solution:

(a) MMF: Refer Question no. (3)

(b) Magnetic field intensity:

The force experienced on a unit (one weber) N-pole at a distance of 'd' meters from another pole of strength 'm' webers in a medium of relative permeability μ_r is given by

$$F = \frac{m \times 1}{4\pi \mu_0 \mu_r d^2} \text{ newtons}$$

And this is called the magnetic field strength or field intensity (H) at that point. Its units are either newtons/weber or ampere-turns/metre.

Thus, the magnetic field strength or field intensity (also sometimes called magnetising force or intensity of magnetic field) at any point is defined as the force experienced by a unit north pole, when placed at that point.

Thus $$H = \frac{m}{4\pi \mu_0 \mu_r d^2} \text{ newtons/weber}$$

The force experienced by a pole of 'm' webers placed in a uniform magnetic field of Intensity H newtons/weber will be equal to mH newtons.

Magnetising force may also be defined as the number of ampere turns produced per unit length of the magnetic path. Thus,

$$H = NI / l \quad \text{(AT/m)}$$

(c) Flux density:

The magnetic flux density at any point is given by the flux passing per unit area at that point, through a plane that is at right angles to the flux.

If Φ wb. is the total magnetic flux passing through an area of A m^2, then

$$\text{Flux density } B = \Phi/A \quad (Wb/m^2)$$

2.1 **Lenz's Law.**

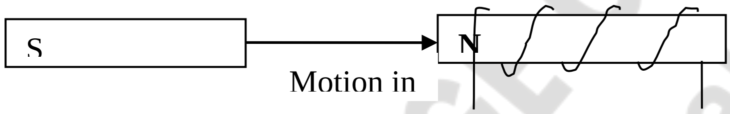
Lenz's Law:

This law gives the direction of induced e.m.f. and hence current and is stated as follows:

The direction of induced e.m.f. and hence current is such that it opposes the cause producing it.

Explanation:

Let the n-pole of a magnet approach a coil shown in figure.



It is obvious that the flux linking the coil changes and consequently e.m.f is induced in the coil. This induced e.m.f. sends current through the coil.

As per Lenz's law, the direction of this induced current in this coil is such that it opposes the cause producing it. the cause which is producing the induced current is the motion of the magnet. Therefore, induced current should flow in such a direction in the coil so that it develops polarities which opposes the motion of the magnet. This is possible only if the left face of the induced current is readily by applying Fleming Right hand Rule.

2.2 **relation between self – inductance, mutual Inductance with the coefficient of coupling.**

2.3

Refer Question no. (2)

We have

The emf induced in the second coil due to the flux Φ_1

$M_{12} = N_2 \Phi_2 / I_1$

Similarly, the emf induced in the first coil due to the flux Φ_2

$M_{21} = N_1 \Phi_1 / I_2$

$M_{12} \times M_{21} = N_2 \Phi_2 / I_1 \quad x \quad N_1 \Phi_1 / I_2$

$= N_2 \Phi_2 / I_2 \quad x \quad N_1 \Phi_1 / I_1$

$M_{12} \times M_{21} = L_1 L_2$

If $M_{12} = M_{21} = M$

Therefore, $M^2 = L_1 L_2$

$M = \sqrt{(L_1 L_2)}$

If K's fraction of Φ_1 is linked with coil 2. Then $\Phi_2 = K\, \Phi_1$

Similarly if K's fraction of Φ_2 is linked with coil 1. Then $\Phi_1 = K\, \Phi_2$

$M_{12} = N_2\, \Phi_2 / I_2 \;=\; N_1 K\, \Phi_1 / I_2 \;=\; K N_1\, \Phi_1 / I_2$

$M_{21} = N_2\, \Phi_1 / I_1 \;=\; N_2 K\, \Phi_2 / I_1 \;=\; K N_2\, \Phi_2 / I_1$

$M_{12} = M_{21} = K N_1\, \Phi_1 / I_2 \;\; x \;\; K N_2\, \Phi_2 / I_1$

$= K^2 N_1\, \Phi_1 / I_1 \;\; x \;\; N_2\, \Phi_2 / I_2$

$= K^2 (L_1 L_2)$

If $M_{12} = M_{21} = M$

$M^2 = K^2 (L_1 L_2)$

$K^2 = M^2 / L_1 L_2$

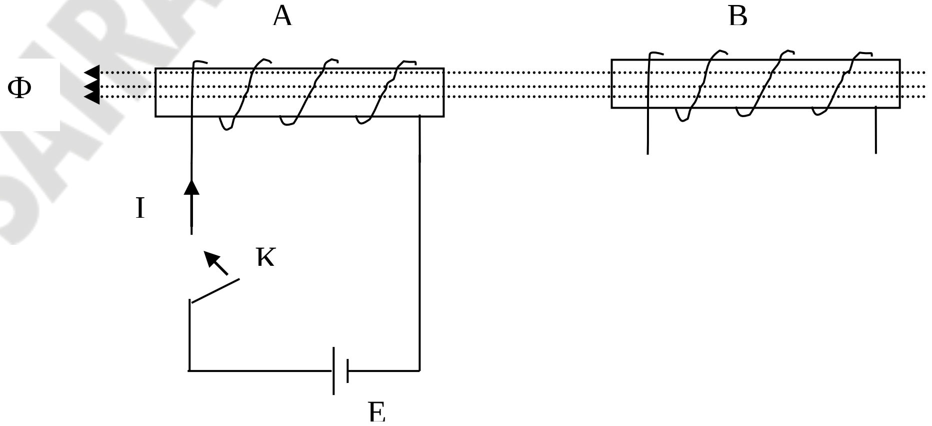
$K = M / \sqrt{(L_1 L_2)}$

Where K is called coefficient of magnetic coupling.

2.4 **differentiate between statically induced emf and dynamically induced emf.**

Statically Induced EMF:

In this case, the conductor is held stationary and the magnetic field varied. It may be self induced or mutually induced.



Consider, as shown in figure, two coils A and B wound over a magnetic specimen. Coil A is energized using a battery of strength E volts. If switch K is initially closed, then a steady current of I amp. will flow through the coil A. It produces a flux of Φ wb. Let us assume that this entire flux links coils A and B. When the switch is suddenly opened, the current reduces to zero. Hence, the flux linking both the coils becomes zero. As per Faraday's law, emfs are induced in both the coils A and B. Such emfs are known as statically induced emfs. Staatically induced emfs is also known as "transformer emf". It can be classified into two categories, namely, self induced emf and mutually induced emf.

Self Induced emf:

If a single coil carries a current, a flux will set up in it. If the current changes the flux will change. This change in flux will induce an emf n the coil. This kind of emf is known as 'self induced emf".

In other words, self induced emf is the emf induced in a circuit when the magnetic linking it it changes the flux being produced by current in the same circuit.

The magnitude of this self induced emf is $e = d\Phi/dt$

The direction of this indued emf would be such as to oppose any change of flux which is the very cause of its production. Hence, it is also known as the opposing or counter emf of self induction.

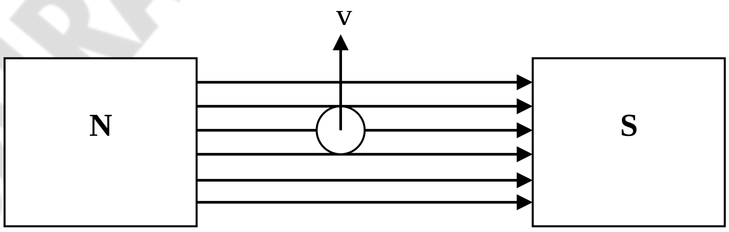
Mutually Induced emf:

It is the emf induced in one circuit due to change of flux linking it, the flux being produced by current in another circuit.

Referring to the figure, when a change in current through coil A is created, we find that the flux linking coil B changes. Hence, an emf is induced in coil B which is mutually induced emf. The same phenomenon can be observed in coil A when coil B is energized.

Dynamically Induced EMF:

When the magnetic field is stationary and the conductor is in motion, the e.m.f. induced is called dynamically induced emf.



Example:dc generator works on the principle of dynamically induced emf in the conductors which are housed in a revolving armature lying within magnetic field.

Let us take a conductor of length l meters moving at right angles to a uniform magnetic field of B wb/m^2 with a velocity of v metres/sec. let the conductor move through a small distance dx in dt seconds. So, the area swept = l x dx

Flux cut = Flux density x area swept

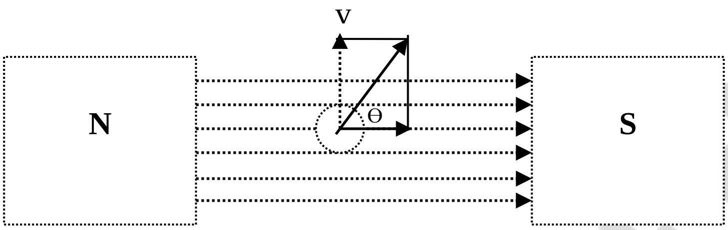
As per Faraday's Laws of Electromagnetic Induction, the e.m.f. 'e' induced in the conductor is given by

$$e = \frac{\text{Flux cut}}{\text{time}} = \frac{Bl\,dx}{dt}$$

$$= Bl\,dx/dt$$

Or $e = B\,l\,v$ volts

Second case:



Suppose the conductor moves at an angle Θ with the direction of the magnetic field as shown figure, then velocity v may be resolved into two components:

(a) $v \cos \Phi$, parallel to the field

(b) $v \sin \Phi$, perpendicular to the field.

The component $v \cos \Phi$, being parallel to the field, does not induce any voltage. But, component $v \sin \Phi$ produces e.m.f., and is given by

$$V = B\,I\,v \sin \Phi \text{ volts}$$

3 **Find the inductance of a coil of 200 turns wound on a paper core tube of 25 cm length and 5 cm radius. Also calculate energy stored in it if current rises from zero to 5 A (μ_r for paper = 1).**

Solution:

Area $A = \pi d^2 / 4 = \pi/4 \times (2 \times 0.05)^2 - 7.855 \times 10^{-3}\ m^2$

Now, reluctance, $S = l / (\mu_o \mu_r A)$

$= 0.25 / [(4\pi \times 10^{-7}) \times 1 \times (7.855 \times 10^{-3})]$

$= 2.532 \times 10^7$ AT/Wb

Now, $L = N^2/S$

Or $L = 200^2 / (2.532 \times 10^7)$

$=$ **1.579×10^{-3} Henry**

Energy stored in the coil,

$W = ½ L I^2$

$= ½ \times (1.579 \times 10^{-3}) \times 5^2$

= 0.01973 Joules

4 **A coil consists of 750 turns and a current of 10 A in the coil gives rise to a magnetic flux of 1200 µWb. Calculate the e.m.f. induced and the energy stored when the current is reserved in 0.01 sec**.

Solution;

Given $N = 750$, $I = 10$ A and $\phi = 1200\ \mu Wb = 1200 \times 10^{-6}$ Wb

Also, rate of change of current,

$dI/dt = 10-(-10) / 0.01 = 2000$ Amps/sec

Now, Self Inductance, $L = N \phi / I$

$= 750 (1200 \times 10^{-6}) / 10 = 0.09$ H

(a) Self-Inductance e.m.f., $e_L = L. dI/dt$

$= 0.09 \times 2000 =$ **180 Volts**

(b) Energy stored, $W = ½ LI^2$

$= ½ \times 0.09 \times 10^2 =$ **4.5 Joules**

5 **An air-cored solenoid has a length of 50 cm and a diameter of 2 cm. Calculate its inductance if it has 1000 turns and also find the energy stored in it if the current rises from zero to 5 amps.**

Solution:

No. of turns of coil, $N = 1000$

Length of solenoid, $l = 50$ cm $= 0.5$ m

Area of cross-section, $A = \pi/4 (2 \times 10^{-2})^2 = \pi/1000\ m^2$

Relative permeability, $\mu_r = 1$

Therefore, Inductance of solenoid, $L = N^2 A \mu_o \mu_r / I$

$= \{1000 \times 1000 \times \pi/1000 \times (4\pi \times 10^{-7}) \times 1\} / 0.5$

$=$ **0.0007 H**

Energy stored in magnetic field $= ½ LI^2$

$= ½ \times 0.0007 \times 5^2 =$ **0.00875 J**

6 **A coil of resistance 150Ω is placed in a magnetic field of 0.1 m Wb. The coil has 500 turns and a galvanometer of 450 Ω is connected in series with it. The coil is moved in 0.1 sec from the given field to another field of 0.3 m Wb. Find the average induced emf and the average current through the coil**.

Solution:

The induced emf in the coil,

$E_{av} = N\ d\phi/dt$

$= 500 \times (0.3 – 0.1)$mWb / 0.1s = **1 V**

The average current, $I_{av} = E_{av} / R_T = 1 / (150+450) =$ **1.67 mA**

7 **A coil consists of 600 turns and a current of 10 A in the coil gives rise to a magnetic flux of 1 milliweber. Calculate (i) the self-inductance, (ii) the energy stored, and (iii) the emf induced when is reserved in 0.01 second.**

Solution:

(i) The self-inductance, $L = N\phi / I = 600 \times 1 \times 10^{-3} / 10 =$ **0.06 H**

(ii) The energy stored, $U = ½ LI^2 = ½ \times 0.06 \times 10^2 =$ **3 J**

(iii) The induced emf, $e = -L.\ di/dt = [-0.06 \times (-10)-10] / 0.01 =$ **120 V**

8 **A coil consists of 750 turns. A current of 10 A in the coil gives rise to a magnetic flux of 1200 μWb. Determine the inductance of the coil and the average emf induced in the coil when this current is reversed in 0.01 sec.**

Solution:

(i) The self-inductance, $L = N\phi / I = 750 \times 1200 \times 10^{-6} / 10 =$ **0.09 H**

(ii) The induced emf, $e = -L.\ di/dt = [-0.09 \times (-10)-10] / 0.01 =$ **180 V**

9 **Two identical coils of 1200 turns each are placed side by side such that, 60% of the flux produced by one coil links the other. A current of 10 A in the first coil sets up a flux of 0.12 mWb. If the current in the first coil changes from +10 A to -10 A in 20 ms, ind (i) the self inductance of the coil, (ii) the emf induced in both the coils.**

Solution:

(i) The self inductance of the two identical coils is given as

$$L = N\phi / I = 1200 \times 0.12 \times 10^{-3} / 10 = 1.44 \text{ H}$$

(ii) Since only 60% of the flux produced by one coil links the other coil, the coefficient of coupling, k=0.6

Therefore, the mutual inductance M between the two coils is calculated as given below

$$K = M/ \sqrt{(L_1L_2)}$$

$$M = k \sqrt{L_1L_2} = k. \sqrt{(L.L)} = k. L = 0.6 \times 1.44 = 0.864 \text{ H}$$

The induced emfs in two coils are given as

$$e_1 = L.\ di_1 /dt = L (I_2 – I_1) / \Delta t = [1.44 \times (-10)-10] / 20 \times 10^{-3}$$
$$= \mathbf{1440\ V}$$

and $$e_2 = M.\ di_1 /dt = M (I_2 – I_1) / \Delta t$$
$$= [0.864 \times (-10)-10] / 20 \times 10^{-3} = \mathbf{864\ V}$$

Module – 2

DC MACHINES:

INTRODUCTION

An electrical machine deals with the energy transfer either from mechanical to electrical form or electrical to mechanical form. This process is called electro-mechanical energy conversion.

An electrical machine which converts mechanical energy into electrical energy is called as electrical generator.

An electrical machine which converts electrical energy into mechanical energy is called as electrical motor.

Such electrical machines may be related to an electrical energy of an alternating type called A.C. machines or may be related to a electrical energy of direct type called D.C. machines. The D.C. machines are classified as

→ D.C. generators

→ D.C. motors

2.1 **derivation of induced E.M.F. of a D.C. Machine**

E.M.F. Equation of D.C. Generator:

Let ϕ = Flux/pole in webers

Z = Total number of armature conductors or coil sides on armature

= No. of slots x No.of conductors/slot

P = Number of generator poles.

A = Number of parallel paths in the armature

N = Rotational speed of armature in revolutions per minute(r.p.m)

E = e.m.f. induced in any parallel path in armature.

Generated e.m.f. E_g = emf generated in any of the n parallel paths

Average emf generated/conductor = d ϕ/dt volts(because n=1)

During one revolution of armature in a p-pole generator, each armature conductor cuts the magnetic flux p times.

Flux cut by one conductor in one revolution = ϕ P Weber

Flux cut by each conductor per second = Flux cut by the conductor per revolution X No. of revolutions of armature per second.

= ϕP x N/60 Weber

As per Faraday's laws of Electromagnetic Induction ,emf generated per conductor

= d ϕ/dt = ϕPN/60 volts

The number of conductors in series between a positive brush and a negative brush is equal to the total number of conductors dividing by the number of parallel paths,

No. of armature conductors per parallel path = Z/A

The generated emf , E_g = emf generated per conductor x No. of conductors in each parallel path.

Or

$E_g = \phi PN/60 \times Z/A$-----------(i)

For a simplex wave-wound Generator

No.of parallel paths, A=2

Equation (i) becomes $E_g = \phi PN/60 \times Z/2 = \phi ZPN/120$ volts

For Simplex Lap wound Generator

No.of parallel paths,A=P

Equation (i) becomes $E_g = \phi PN/60 \times Z/P = \phi ZN/60$ volts

So rewriting equation (i), the general equation for emf generated is

$E_g = \phi ZN/60 \times P/A$ volts-----------------(ii)

A=2 for simplex wave winding

A=P for Lap winding

Also putting equation (ii) in another form,

$E_g = 1/2\Pi\ (2\Pi\ N/60) \times \Phi Z(P/A)$ volts

$= \omega\ \Phi Z/2\ \Pi x(P/A)$ volts

where ω is in rad/sec.

2.2) Back Emf& its significance

Back EMF in a D.C.Motor:-

As soon as the armature of a DC shunt Motor starts rotating, dynamically induced emf is produced in the armature conductors. The direction of the induced emf as found by Fleming's right hand rule is such that it opposes the applied voltage as shown in figure. This induced emf is known as back emf E_b. it has the same value as that of the notionally induced emf in the generator.

So, $E_b = \phi ZN/60 \times P/A$ volts

where N is in rpm.

The applied voltage V has to force current through the armature against the back emf. The electrical work performed in overcoming this opposition is converted into mechanical energy developed in the armature.

Value of back emf; Voltage & current relations:-

The back emf E_b is always less than the applied voltage V, although the difference is small when the motor is running under normal conditions.

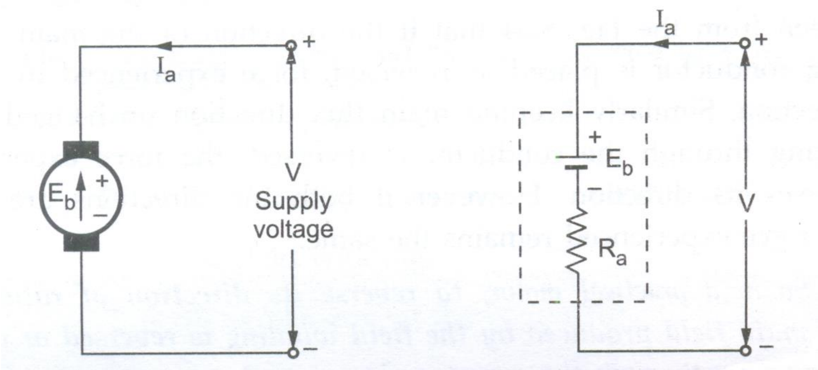
The net voltage across the armature circuit=V- E_b

If the armature resistance is R_a'

Armature current,I_a=(Net voltage in armature circuit/Armature Resistance)

Or $I_a=(V-E_b)/R_a$

Since V and R_a are usually fixed, the value of E_b will determine the armature current drawn by the motor. If the speed of the motor is high,



Back emf in a DC motor Equivalent circuit

$E_b = \phi ZN/60 \times P/A$ is large and hence the motor will draw less armature current and vice-versa.

Significance of Back-emf:-

Due to the presence of back emf, the dc otor becomes a self-regulating machine i.e. the motor is made to draw as much armature current as is just sufficient to develop the torque required by the load.

When the motor runs on no load, a small amount of torque is required to overcome the friction and windage losses. So, a small amount of armature current flows and the back emf is almost equal to the applied voltage.

If load is suddenly brought on to the motor, the first effect is to slow down the armature. Therefore, the speed at which the armature conductors move through the field is reduced and so there is a fall in the back emf E_b. the decreased emf allows a larger current to flow through the armature, and a larger current means an increased driving torque. Thus, the driving torque increases as the speed of the motor reduces, and the motor will stop slowing down when the armature current is just sufficient to produce the reduced torque required by the load.

Taking another case, when the load on the motors is decreased, the driving torque is momentarily in excess of the requirement, so that the armature is accelerated. As the armature speed increases, the back emf

E_b also increases and causes the armature current I_a to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.

So, we conclude that back emf in a DC motor regulates the flow of armature current i.e. it automatically alters the armature current to meet the load requirement.

2.3) working principle of operation of

(a) a generator

(b) a motor

WORKING PRINCIPLE OF A D.C. MACHINE AS A GENERATOR:

Whenever a conductor is moved in a magnetic field such that it cuts across lines of flux, dynamically induced e.m.f. is produced in it according to Faraday's laws of Electro magnetic Induction.The magnitude of this induced e.m.f. In the conductor is given by the equation,

$$e = Blv \sin\theta$$

where l= length of the portion of the conductor with in the magnetic field.

V=velocity of the conductor

B = magnetic flux density

θ = angle between direction of movement of the conductor &the direction of the magnetic field

This e.m.f. causes a current to flow in the conductor if the circuit is closed.

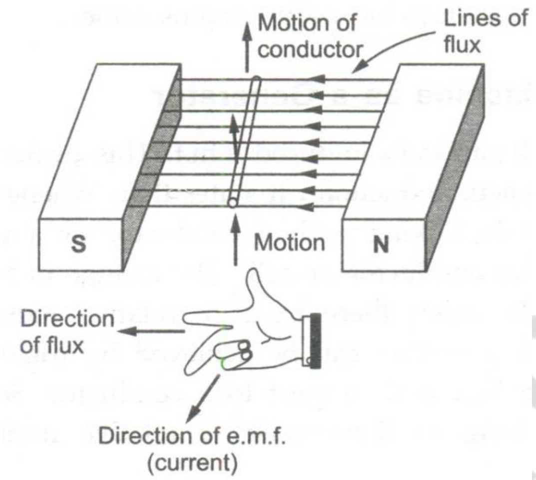
Thus, electrical power developes in the conductor. If the conductor does not move or if it is moved parallel to the lines of flux, no e.m.f. is induced in it,and hence no power is generated. Hence it is clear that, for the generation of e.m.f there should be relative motion between the conductor and the magnetic field.

Hence, a generating action has the following requirements:

(i) The conductor (or coil), (ii) The flux, (iii) The relative motion between the conductor and the flux. In a practical generator,the conductors are rotated to cut the magnetic flux,keeping the flux stationary. In order to obtain a large voltage as the output,several conductors are joined together in a particular manner,to form a winding. Such a winding is known as the armature winding of a DC machine. The part on which the winding is placed is called as the armature of the DC machine. The conductor situated on the armature are rotated by some external device called a prime mover. Some of prime movers are used are steam engine,diesel engine,water turbines etc., . The magnetic field is produced by a current carrying winding known as a field winding. The direction of the induced e.m.f may be obtained by using fleming's right hand rule as given below.

Fleming's Right Hand Rule:

If three fingers of a right hand, namely the thumb, index finger and a middle finger outstressed so that every one of them is at right angles with other two ,and if in this position,the index finger points on the direction of lines of flux,the thumb in the direction of the relative motion of the conductor with respect to the flux,then the outstressed middle finger gives the direction of the e.m.f induced in the conductor. This will mainly gives the direction of the current set up by the e.m.f induced in the conductor when a closed path is provided to it.



Working Principle of DC Machine as a Motor:

It's operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule which is as follows

1. Hold a thumb, first finger and a second finger of the left hand in such a way that they are at right angle at each other.

2. If the forefinger represents the direction of the field and a second finger the direction of the current, then the direction of the force is indicated by the thumb.

The magnitude of this force is given by

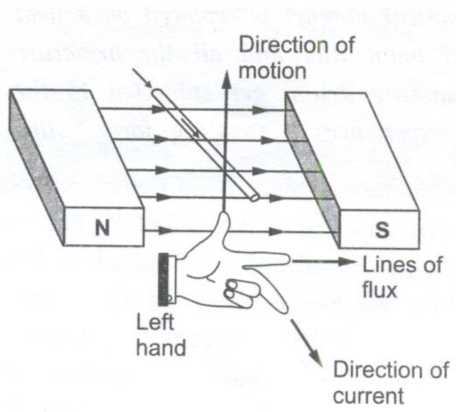
$F = B\,I\,l$ newtons

where B = Field strength in Tesla(wb/m2)

I = current flowing through the conductor(A)

l = length of the conductor in m

In a practical DC motor, the field winding produces the required magnetic field; the current carrying aremature conductors are placed in magnetic field and so experiences a force. As conductors are placed in slots which are on the periphery , the individual force experienced by the conductor acts like a twisting or turning force on the armature which is called a torque. The torque is a product of the force and the radius at which this force acts. We shall now consider the motoring action in some detail.



Consider a DC motor having north and south poles, represented by N and S as shown in figure. Here, conductors are placed uniformly in the slots of the armature.

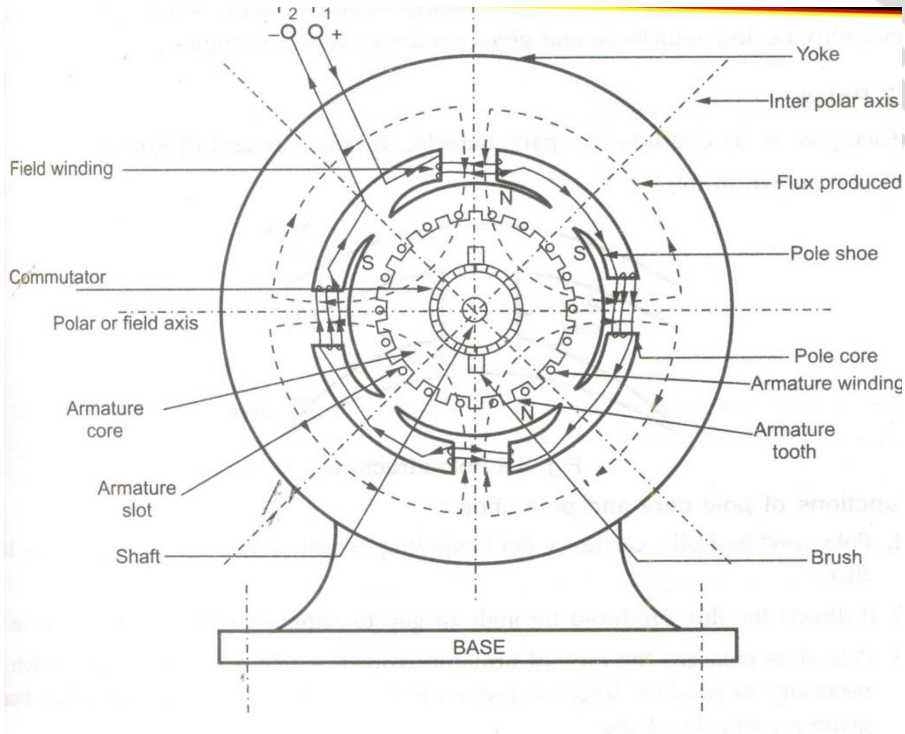
For the purpose of explaining the principle of working of a DC motor, only two conductors a and b, which come under the influence of N and S pole respectively, are considered. This two conductors are joined together by an end connection at the rear end of the armature, and to the commutator segments at the front end of the armature. When a DC supply is made available at the motor terminals, current pases through the conductors a and b via the commutator. The +ve sign marked on conductor a, shows that the current is flowing inverse and the –ve sign marked on conductor b shows that the current is flowing outwards. Horizontal dotted lines indicate the lines of magnetic force which originate from the north pole N and terminate on the south pole S as shown in figure.

As per the Fleming's left hand rule, a conductor a is subjected to a force F acting in downward directions and the conductor b experiences an equal force F acting in the upward direction. As the two conductors are connected together the two equal and opposite forces F acting on them constitute a couple , which rotates the armature in the anti clockwise direction through an angle 90 degree. And the conductor a and b occupy the positions a1 and b1 respectively.

In this new position, these conductors experiences a force F in opposite direction along the same line, and hence the torque experienced by them is zero. Had the armature contained just these two conductors, the armature would have stopped in the position a1,b1. However, as a armature has a several other conductors, which are uniformely distributed in the slot of the armature and which are interconnected, they experiences a torque in the anti clockwise direction.

As it is necessary that armature experiences a continuous anti clockwise torque, the direction of current in the conductors a and b must be reversed as soon as they cross the position a1 and b1 respectively. Otherwise the armature would experience a pulsating torque in the clockwise direction in the position a1,b1. This reversal of current in conductor a nd b , after they cross the position a1 and b1 respectively is brought about by the commutator thus making the armature experience a continuous anti clockwise torque resulting in continuous rotation of armature in the anti clockwise direction.

2.4)*CONSTRUCTION OF A DC MACHINE:*



The figure shows the basic structure of a dc machine (a motor or a generator). The machine has following important parts.

Stator Magnetic Structure:

The figure shows the magnetic structure of a 4 pole dc machine. Its main components are described below

(i) *YOKE:* It is the outermost cylindrical part which serves two purposes. First, it acts as a supporting frame for the machine, and the second, it provides the path for magnetic flux. It is made up of cast iron,cast steel, or forged steel, usually, small machines have cast iron yokes.

(ii) *Poles:* The machine has salient poles. The pole cores are fixed inside the yoke, usually by bolts. The cross section of the pole is rectangular. By attaching a pole show, the end of the pole is made to have a cylindrical surface. The cross sectional area of the pole shoe is considerably larger than that of the pole core to leave as little interpole space as possible. This is done to reduce the leakage flux. The poles are made up pf cast steel, or forged steel. Each pole carries a field coil(or exciting coil) small machines are generally use permanent magnets.

(iii) *Field Coils:* The field coils are wond on the pole cores and are supported by the pole shoes. All coils are identical and are connected in series such that on excitation by a dc source, alternate N and S poles are made. Thus, a machine always has even number of poles. The magnetic flux distribution approximates a square wave as shown in figure for the four pole structure. The flux is taken positive in the radially invert direction. Note that the yoke carries one of the pole flux φ . Therfore, the cross section of the yoke should be selected accordingly.

Rotor:

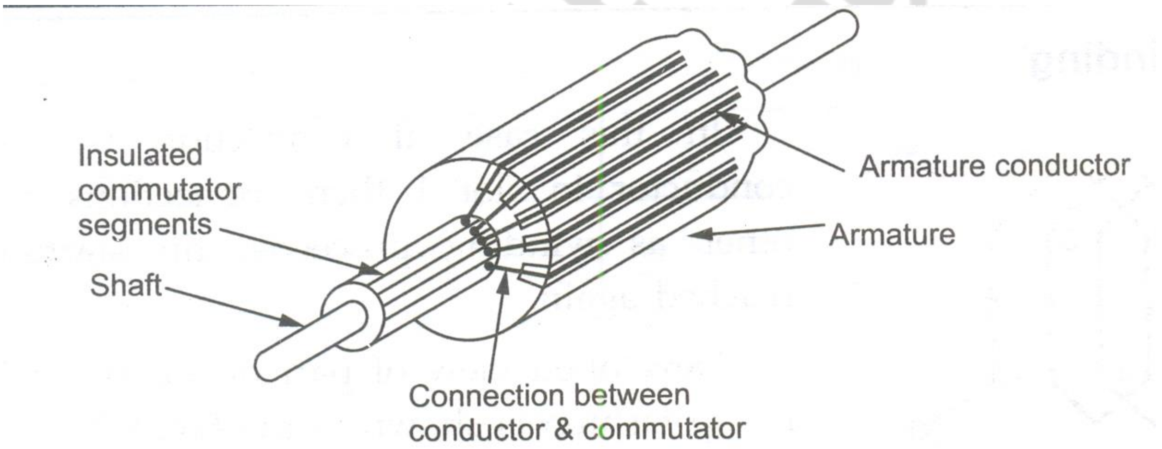
The rotor is a inner cylindrical part having armature and commutator- brush arrangement. It is mounted on the shaft of the motor.

(i) Armature:

The armature core consists of steel laminations, each about 0.4-0.6mm thick, insulated from one another. The purpose of laminating the core is to reduce the eddy current loss. Slots are stamped on the periphery of the laminations to accommodate the armature winding. The top of the slots has a groove in which a wedge can be fixed. After the winding conductors are put into the slots, the wedge is inserted. The wedge prevents the conductors from flying out due to the centrifugal force when the armature rotates. The actual length of the armature is same as that of the poles on the yoke. The term conductor refers to the active portion of the winding namely the part which cuts the flux when the rotor rotates, thereby generating an alternating emf .

(ii) Commutator

It consists of a large number of wedged-shaped copper segments are bars, assembled side by side to form a ring. The segments are insulated from one another by thin mica sheets. Each segment is connected to a coil-end of the armature winding, as shown in the figure. The radial line represents the active lines of the rotor conductors. The commutator is a part of the conductor and participate in its rotation.



(iii) Brushes:

Two stationary brushes, made of carbon, are pressed aginst the commutator with the help of a spring fitted in a brush gear. The brush-commutator system provides to related function : (i) Electrical connections is made with the moving rotor, and (ii) A study or direct voltage is obtained from the alternating emf generated in the rotating conductors.

5) characteristics of speed/ load for d.c. shunt & series motor. &APPLICATION

DC Motor Characteristic:

DC motor characteristic depict the relationship between the following quantities:

(i) Torque and Armature current or Ta/Ia characteristic (also called electrical characteristic)

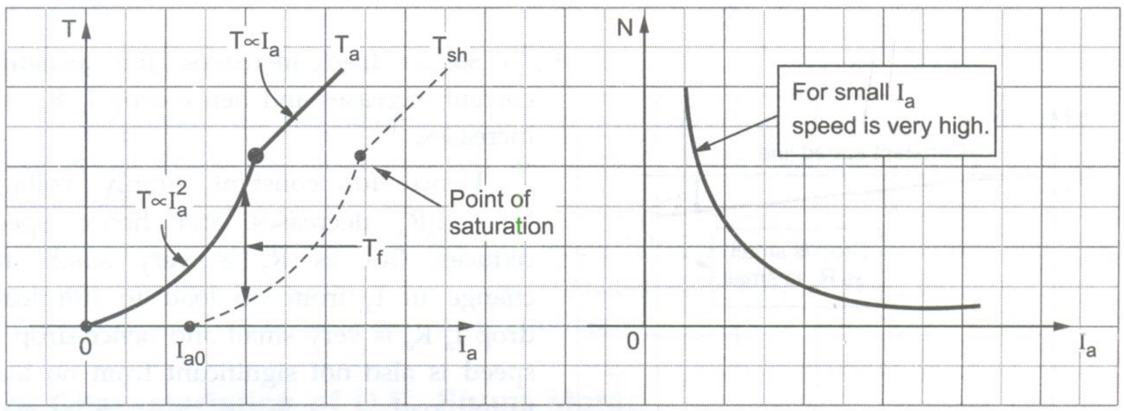
(ii) Speed and Armature current i.e N/Ia characteristic.

(iii) Speed and Torque or N/Ta characteristic (also called mechanical characteristic). This also can be ascertained from (i) and (ii) above.

Characteristic of Series Motor:

In a series wound motor, the field winding is connected in series with the armature as shown in the figure. The series field winding consists of a few turns of thick wire having low resistance. It is apparent that the same current flows through the both the field winding and the armature. If the mechanical load on the motor increases, the armature current also increases. Therefore, the flux in the series motor increases with the increase in the armature current and vice versa.

1. Ta/Ia characteristic: We know that Ta α ϕ Ia . Also, in a series motor, as the field windings also carry armature current, ϕ α Ia till the point of magnetic saturation is reached.



At light loads, Ia and Hence ϕ, is small. But, as Ia increases, Ta increases as the square of the current in a parabolic manner, till the point of saturation a is reached. After saturation, is practically independent of Ia, hence Ta α Ia, and so the characteristic becomes the straight line (portion AB of the characteristic).

The shaft torque Tsh is less than the armature torque because of stray losses, a dotted curve depicting it in the figure.

So, we reach the conclusion that, on heavy loads, before the onset of magnetic saturation, the armature torque is proportional to the square of the armature current. Therefore, if a large starting torque is required for accelerating heavy masses quickly; (e.g, In electrical locomotive, hoist etc.) series motor are ideal.

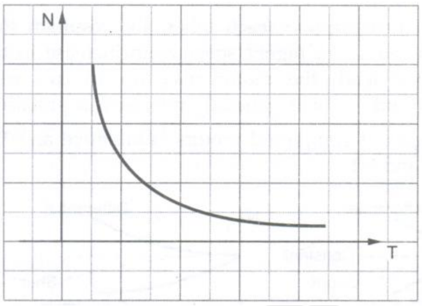
2. N/Ia characteristics: We know that changes in speed can be determined from the formula :

N α Eb/ϕ

Variatrion of Eb for different load currents is so negligible that Eb may be treated as a constant. If Ia is increased, flux too increases. So, speed is inversely proportional to the armature current. As shown in figure

When there is a heavy load, Ia is large. But when the load, and consequently Ia, slumps to a low value, the speed becomes dangerously high. Hence, a series motor should invariably be started with some mechanical load in it , to prevent excessive speed and damage due to the heavy centrifugal forces produced.

3. N/Ta characteristic: The N/Ta characteristic of a series motor is shown in figure. From the curve, it is apparent that the series motor develops a high torque at low speed and vice versa. This is because an increasing torque requires an increase in armature current, which is also the field current. The result is that the flux is strengthened and hence speed and speed drops(as N α 1/ ϕ) Similarly, at low torque, the motor speed is high.

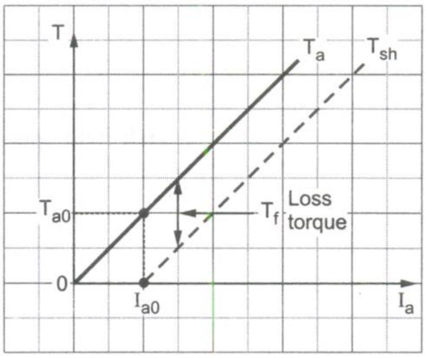


Characteristic of Shunt Motor:

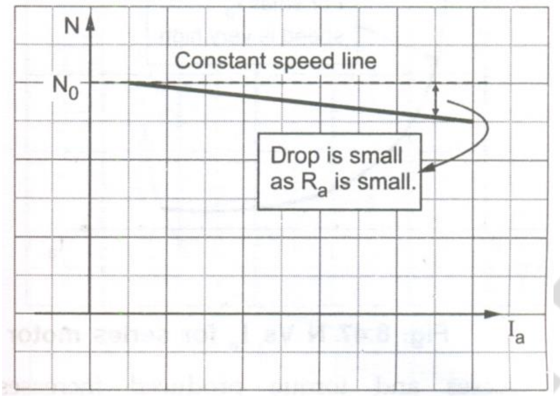
In the shunt wound motor, a field winding is connected in parallel with the armature, as shown in figure. The line current I divides into two parallel paths: Ish close in the shunt field current and Ia in the armature circuit. It is to be kept in the mind that the field current is constant, since the field winding is directly connected to the supply voltage V, which is assume to be constant. Hence, the flux in the shunt motor is approximately constant.

1. Ta/ Ia characteristic : As we assume the flux ϕ to be practically constant (neglecting armature reaction) we see that Ta α Ia. This implies that the statistics is practically a straight line to the origin.

The shaft torque vs armature current is also shown (dotted) . It is clear from the curve that a large armature current is required to start a heavy load. Therfore, a shunt motor should not be started on heavy load.



2. N/ Ia characteristic: We have seen that N α Eb/ϕ. As ϕ is assumed to be constant, N α Eb. As Eb is also practically constant, the speed too is practically constant, as indicated by dotted line AB.



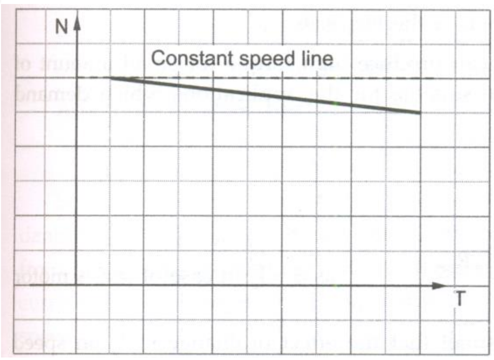
However, to be accurate, both Eb and ϕ decreases with increase in load. But Eb decreases somewhat more than ϕ so that, all considered, there is some decrease in speed, the drop ranging from 5 to 15% of full load, depending on certain other conditions. Thus, the actual speed curve will be somewhat dropping, as shown by line AC.

It may be noted that the characteristic does not have a point of zero armature current, because a small current (no load current Io) is necessary to maintain the rotation of the motor at no load.

As there is no mark change in the speed of a shunt motor, during the transition from no load to full load, it may be connected to the load which can be suddenly disconnected without fear of excessive speeding. Because of this virtue of constant speed, shunt motor can be usefully employed for the driving shafts, lathe, machine tools and other application where an approximately constant speed is desired.

3.N/Ta characteristic; This curve is obtained by plotting the the values of N and Ta for various armature currents Ia. It may be seen that speed falls somewhat as the load torque increases.

This characteristic can be also deduced from the other two characteristic just described. The N/Ta characteristic is of great importance is determining this type of motor is best suited to drive a given load.



Characteristic of a Compound Motors:

(a) Characteristic of a Cumulative Compound Motors

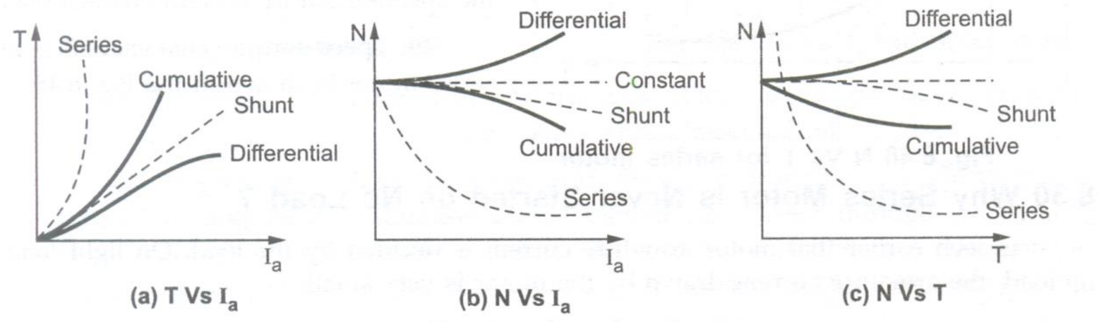


Figure shows the connections for this type of motors. As the armature current is increased, the series flux increases, thus increasing the total flux of the motor. AS a result of this, the torque is increased. The increase of torque Ta with armature current Ia is shown by the Ta/Ia characteristic curve OA of figure. This increase of Ta with Ia is greater than what it is in the case of shunt motor (dotted curve OB) and less than what it is in the case of a series motor (dotted curve OC). Obviously, this type of motor develops a high torque with sudden increase in the load.

We have just discussed that, with the increase of Ia, the series flux, and hence the total flux, increase. This leads to the decrease the motor speed starting from the particular value given by the point A at No-load. The variation of N with Ia is given by the N/Ia characteristic AB of figure. Again, it must be borne in mind that this decreases in speed is greater than what it would be in the case of a shunt motor(given by the dotted curve AC), but less than what it would be in the case of a series motor. (shown by dotted line AD).

As series excitation assist shunt excitation, the N/Ta characteristic curve AB will lie between that of a shunt motor(dotted line AC) and of series motor(dotted line AD) as shown in figure.

Applications of Cumulative Compound Motors:

This motors are employed in cases where series characteristic are desired and where the load may be removed completely. Typical examples are certain types of coal- cutting machines, which are frequently required to make deep cuts. The shunt windings will ensure that the speed will not become excessive, and the series winding will cater to the heavy loads. In many instances, fly wheels are used in conjunction with such motors, where temporary heavy load occurs, as in the case of rolling mills. The fly wheel supplies its stored energy when the motor tends to slow down due to sudden heavy load. When the load is removed, the motor speed increases and a fly wheel again stores up kinetic energy, which is required to be released again when the situation demands.

(b) Characteristic of Differential Compound Motors.

The connection diagram is shown in figure. Since the series field opposes the shunt field, the total motor flux is decreased as load is applied to the motor. This results in the motor speed remaining all most constant or even increasing with increase in load (as N α Eb/ϕ). This is shown by the N/Ia characteristic of figure (curve AB). Point A indicates no-load speed. For purpose of comparison curve AC is for shunt motor, where the speed remains practically constant with increase in load. Curve AD is for series motor, where speed reduces with load.

Again, the total field is the difference between the shunt and series field . Ths increase with Ia (curve OA), but not as rapidly as would be the case for a series motor (curve OB). Curve OC gives this relationship for a shunt motor. This Ta/Ia characteristic for differential compound motor are given in figure.

Now, coming to the N/Ta characteristic for the differential compound motor there is a slight increase in motor torque with increase in speed, as indicated by curve OA. For comparison purposes, OB and OC are the curves for shunt and series motor respectively.

Applications of series motors:

1) High starting torque .No load condition is dangerous.
2) Variable speed
3) Cranes
4) Hoists, elevators
5) Trolleys
6) Conveyors
7) Electric locomotives

Applications of shunt motor:

1) speed is fairly constant and medium starting torque
2) blowers and fans
3) centrifugal and reciprocating pumps
4) lathe machines
5) machine tools
6) milling machines
7) drilling machines

Applications of cumulative compound motor:

1) high starting torque no load condition is allowed
2) rolling mills
3) punches
4) shears
5) heavy planers
6) elevators

2.6) Derivation armature torque & shaft torque developed in

a D.C. motor

The turning or twisting force about an axis is called torque. Consider a wheel of radius ’R’ meters acted upon by a circumferential force F newtons.

The wheel is rotating at a speed of N rpm

Then angular speed of the wheel is $\omega = 2\Pi N/60$ rad/sec

So work done in one revolution is,

W = F x distance traveled in one revolution

= F x 2ΠR joules

P = power developed=work done/ time

$$= F \times \frac{2\Pi R}{\text{Time for one rev}} = \frac{F \times 2\Pi R}{(60/N)} = (F \times R) \times (2\Pi N/60)$$

$P = T \times \omega$ watts

T = torque in N – m

ω = angular speed in rad / sec

Let Ta be the gross torque developed by the armature of the motor. It is also armature torque. The gross mechanical power developed in the armature is E_b, I_a, as seen from the power equation. So if speed of motor is N rpm

Power in armature = armature torque x ω

$$E_b I_a = T_a \times (2\Pi N/60)$$

But E_b in a motor is given by

$$E_b = \Phi PNZ / 60A$$

$$\frac{\Phi PNZ \times I_a}{60\,A} = T_a \times \frac{2\Pi N}{60}$$

$$T_a = \frac{1\ \Phi I_a \times PZ}{2\Pi A}$$

$$T_a = 0.159\ \Phi I_a . \frac{PZ}{A} \text{ N - m}$$

This is the torque equation of a d.c motor

The torque which is available at the shaft for doing the useful work is known as load torque or shaft torque denoted as T_{sh}.

$$T_a = T_f + T_{sh}$$

The shaft torque magnitude is always less than the armature torque.

Net output of motor = $P_{out} = T_{sh} \times \omega$.

2.7) necessity of starter for a d.c. motor .

All the d.c. motor are basically self starting motors. Whenever the armature and the field winding of a d.c. motor receive supply, motoring action takes place. So d.c. motor does not require any additional device to start it.

At the starting instant the speed of the motor is zero, (N=0). As speed is zero, there cannot be any back emf. As $E_b \alpha N$ and N is zero at start.

$I_a R_a$ at start = zero

The voltage equation of d.c. motor is

$$V = E_b + I_a R_a$$

So at start, $V = I_a R_a$ as $E_b = 0$

$$I_a = V/ R_a.$$

Consider a motor having full load input power as 8000W. the motor rated voltage be 250V and armature resistance is 0.5Ω

Then at start E_b= 0 and motor operated at 250V supply

$I_a = V/ R_a = 250 / 0.5 = 500A$

While its full load current = $I_{FL} = \frac{\text{Power input on full load}}{\text{Supply voltage}} = 8000 / 250 = 32A$

So at start motor is showing a tendency to draw a armature current which is 15 – 20 times more than the full load current. Such high current is dangerous for the machine.

1) In a constant voltage system, such high flow of current may cause line voltage fluctuations. This affects the performance of the other equipment connected to the same line.

2) Such high armature current blows out the fuses, it'll burn the insulation of the armature winding.

3) Due to such high torque the shaft and other accessories are subjected to large mechanical stresses. These stresses cause permanent mechanical damage to the motor.

To restrict this high starting armature current, a variable resistance is connected in series with the armature at start. This resistance is called starter or starting resistance. So starter is current limiting device. In the beginning the entire resistance is in series with the armature and then gradually cuts off as motor gather speed, producing the back emf. In addition to the starting resistance, there are some protective devices provided in a starter.

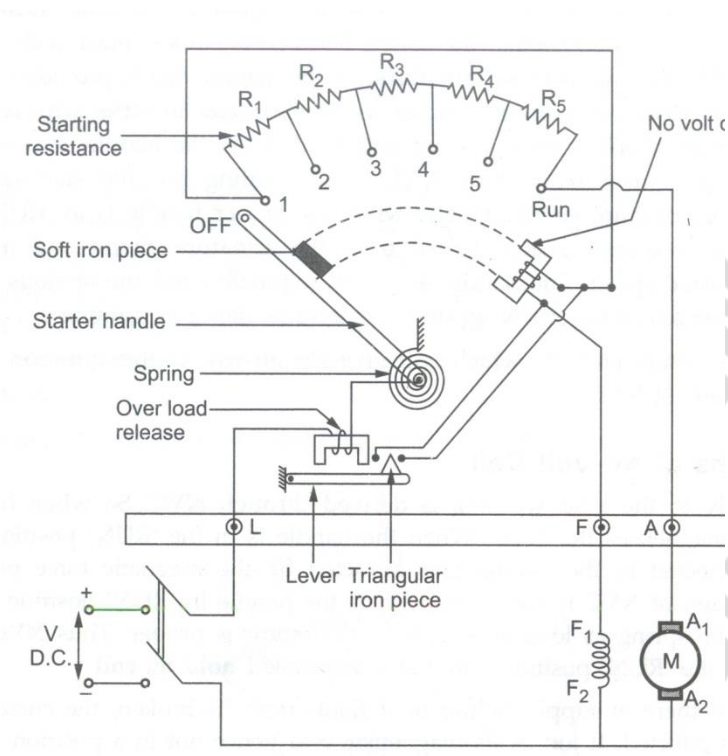
THREE POINT STARTER :

The starter is basically a variable resistance, divided into number of sections. The contact points of these section are called studs and brought out separately shown as OFF , 1,2,… upto RUN. There are three main points of the starter :

1. 'L' → Line terminal to be connected to positive of supply.

2. 'A' → To be connected to the armature winding.

3. 'F' → To be connected to the field winding.



Point ‘l’ is for the connected to an electromagnet called OVERLOAD RELEASE(OLR). The second end of a ‘OLR’ is connected to a point where handle of the starter is pivoted. This handle is free to move from its other side against the force of the spring. This spring bring back the handle to the off position another parallel path is derived from the stud ‘1’, given to the another electromagnet called NO VOLT COIL(NVC). The NVC is further connected to terminal F. the starting resistance is entirely in series with the armature. The OLR and NVC are the two protecting devices of the starter.

OPERATION:

Initially the handle is in off position. The dc supply to the motor is switched ON then handle is slowly moved against the spring force to make a contact with stud number ‘1’. At this point field winding gets supply through the parallel path provided to starting resistance through NVC. While entire resistance comes in series with the armature and armature current which is high at start gets limited. As the handle moved further it goes on making contact with studs 2,3,4. etc cutting out the starting resistance from the armature circuit. Finally when the starter handle is in RUN position the entire starting resistance get removed from the armature circuit and the motor starts operating with normal speed.

2.8) A series motor should never be started without a load

The motor armature current is decided by the load. On light load, or

No load ,the armature current drawn by the motor is very small.

In case of a d.c. series motor ,$\phi \alpha I_a$

And on no load as Ia is small hence flux produced is also very small

$$N \alpha 1/\phi$$

So on no load as flux is very small, the motor tries to run at dangerously

High speed which may damage the motor mechanically. This can be seen from the speed-armature current and the speed-torque charactertics that on low armature current and low torque condition motor shows a tendency to rotate with dangerously high speed.

That's why series motor should never be started on no load. For this reason it is not selected for belt drives as breaking or slipping of belt causes to throw the entire load off on the motor with no load which is dangerous.

2.9) Schematic representations of series , shunt , compound motors.

In each case , write the voltage & current equations?

Solution:

The dc motors are classified depending upon the way of connecting the field winding with the armature winding. The different types of dc motors are shunt motors, series motors and compound motors.

The compound motors are further classified as short shunt compound and long shunt compound motors.

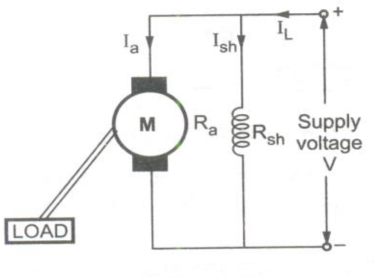
D.C. SHUNT MOTOR:

In this motor the field winding is connected across the armature winding and the combination is connected across the supply.

Let R_{sh} be the resistance of the shunt field winding

R_a be the resistance of armature winding.

The value of R_a is very small while R_{sh} is quite large. Hence shunt field winding has more number of turns with less cross-sectional area.



DC Shunt Motor

As long as supply voltage is constant, which is generally the flux produced is also constant. Hence DC shunt motor is called constant flux motor.

VOLTAGE AND CURRENT RELATIONSHIP:

The voltage across armature and field winding is same equal to the supply voltage V.

The total current drawn from the supply is denoted as line current I_L.

$I_L = I_a + I_{sh}$

$I_{sh} = V/R_{sh}$

$V = E_b + I_a R_a + V_{brush}$

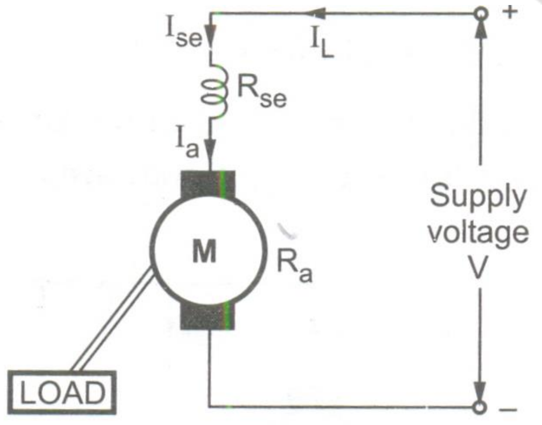
V_{brush} is generally neglected

Now flux produced by the field winding is proportional to the current passing through it i.e I_{sh}.

$\Phi \propto I_{sh}$

DC SERIES MOTOR:

In this type of motor, the series field winding is connected in series with the armature and the supply



DC Series Motor

Let R_{se} be the resistance of the series field winding.

The value of R_{se} is very small and it is made of small number of turns having large cross-section area.

VOLTAGE AND CURRENT RELATIONSHIP:

Let I_L be the total current drawn from the supply

So $I_L = I_{se} = I_a$

$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$

$V = E_b + I_a(R_a + R_{se}) + V_{brush}$

Supply voltage has to over come the droop across series field winding in addition to E_b and drop across armature winding.

In series motor entire armature current is passing through the series field winding.

So flux produced is proportional to the armature current.

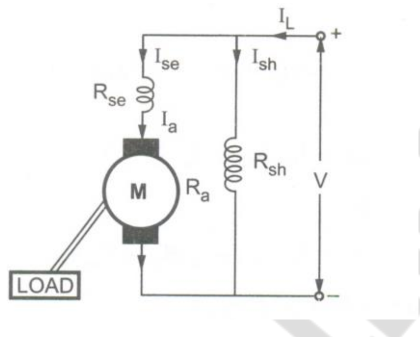
$$\Phi \propto I_{se} \propto I_a \qquad \text{for series motor}$$

DC COMPOUND MOTOR:

The compound motor consists of part of the field winding connected in series and part of the field winding connected in parallel with armature. It is further classified into short shunt compound and long shunt compound motor.

LONG SHUNT COMPOUND MOTOR:

In this motor, the shunt field winding is connected across the combination of armature and the series field winding as shown in fig.



Long Shunt Compound motor

Let R_{se} be the resistance of the series field and R_{sh} be the resistance of shunt field winding. The total current drawn from supply is I_L.

So $\quad I_L = I_{se} + I_{sh}$

$$I_{se} = I_a$$

$$I_L = I_{sh} + I_a$$

$$I_{sh} = V / R_{sh}$$

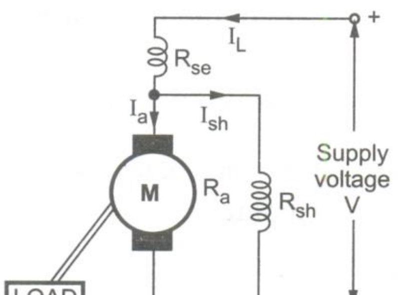
$$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$$

$$I_{se} = I_a$$

$$V = E_b + I_a(R_a + R_{se}) + V_{brush}$$

SHORT SHUNT COMPOUND MOTOR:

In this motor, the shunt field is connected purely in parallel with armature and the series field is connected in series as shown in fig.



$$I_L = I_{se}$$

The entire line current is passing through the series field winding.

$$I_L = I_{sh} + I_a$$

The drop across the shunt field winding is calculated from the voltage equation.

$$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$$

But $I_{se} = I_L$

$$V = E_b + I_a R_a + I_L R_{se} + V_{brush}$$

Drop across shunt field winding is,

$$\rightarrow \quad V - I_L R_{se} = E_b + I_a R_a + V_{brush}$$

$$I_{sh} = \frac{V - I_L R_{se}}{R_{sh}} = \frac{E_b + I_a R_a + V_{brush}}{R_{sh}}$$

Compound motor can be classified into two more types

1) cumulatively compound motor

2) differential compound motor

If the two field windings are wound in such a manner that the fluxes produced by the two always help each other, the motor is called cumulatively compound.

If the fluxes produced by the two field windings are trying to cancel each other that is they are in opposite direction the motor is called differential compound.

10. The armature of an 8-pole dc generator has 480 conductors. The magnetic flux and the speed of rotation are such that the average emf generated in each conductor is 2.1 V, and each conductor is capable of carrying a full-load current of 200A. Calculate the terminal voltage on no load. The output current on full load and the total power generated on full-load. When the armature is

(a) lap wound (b) wave-wound.

Solution:

a) With the armature lap –wound ,the number of parallel paths, A=P=8

Therefore the no of conductors per path is

$Z/A = 480/8 = 60$

The terminal voltage on no load $E = e \times (Z/A) = 2.1 \times 60 = 126V$

The output current on full load

I_L = Full load current per conductor x no. of parallel paths

$= 200 \times 8 = 1600A$

the total power generated on full load,

$P_0 = I_L \times E = 1600 \times 126 = 201600$ W = 201.6kW

b) With the armature wave-wound, the number of parallel paths, A=2

$E = e \times (Z/A) = 2.1 \times 480/2 = 504v$

The o/p current on full load I_L $200 \times 2 = 400$ A

The total power generated on full load,

$P_0 = I_L \times E = 400 \times 504 = 201600$ W =201.6KW

11. A 4 pole ,1200 rpm dc generator has a lap-wound armature having 65 slots and 12 conductors per slot.If the flux per pole is 0.02 wb, determine the emf induced in the armature.

Solution:

The total number of conductors Z= 65 x 12 = 780

For lap winding ,the number of parallel paths,A = p = 4

The total e.m.f. induced is given by

$$E = \frac{\phi ZNP}{60A} = \frac{0.02 \times 780 \times 1200 \times 4}{60 \times 4} = 312V$$

12. In a given d.c. machine , If p= 8, N= 300 RPM and ϕ= 100 milliweber,

Calculate E_g with winding

(i) lap-connected

(ii) wave-connected

Solution:

$$E_g = \frac{\phi ZNP}{60A} \text{ volts}$$

For simplex lap winding ,the no of parallel paths, A=P and for a wave winding, A=2.

i) for lap connected d.c. machine

$$E_g = \frac{\phi ZNP}{60A}$$

$$= \frac{(100 \times 10^{-3}) \times 400 \times 300 \times 8}{60 \times 8}$$

$$= 200 \text{ volts}$$

ii) for wave connected d.c. machine

$$E_g = \frac{\phi ZNP}{60A}$$

$$= \frac{(100 \times 10^{-3}) \times 400 \times 300 \times 8}{60 \times 2}$$

$$= 800 \text{ volts}$$

13. A 4-pole generator with wave wound armature has 51 slots ,each having 24 conductors. The flux per pole is 0.01 Weber .At what speed must the armature rotate to give an induced emf of 220V.? What will be the voltage developed if the winding is lap & the armature rotates at the same speed?

Solution:

(i) For wave connected Armature

$$E_g = \frac{\phi ZNP}{60A}$$

$$\text{Speed } N = \frac{E_g \times 60 \times A}{\phi ZP}$$

$$= \frac{220 \times 60 \times 2}{0.01 \times (51 \times 24) \times 4}$$

$$= 540 \text{ rpm}$$

(ii) For lap wound armature

here , number of parallel paths A=p=4

speed N = 540 R.P.M

Voltage developed , $E_g = \frac{\phi ZNP}{60A}$

$$= \frac{0.01 \times (51 \times 24) \times 500 \times 4}{60 \times 4}$$

$$= 110 \text{ volts}$$

14) A shunt generator supplies a load of 10 KW at 200 V through a pair of feeders of total resistance 0.05 ohm . Armature resistance is 0.1 ohm .Shunt field resistance is 100 ohm. Find the terminal voltage &generated emf of the generator.

Solution:

Load current , $I = \frac{10000}{200}$

$= 50$ A

Drop in the feeders = 0.05 x 50 = 2.5 V

Terminal voltage , V = 200 + 2.5 = 202.5V

$I_{sh} = \frac{202.5}{R_{sh}}$

$= \frac{202.5}{100}$

$= 2.025$ A

$I_a = I + I_{sh}$

$= 50 + 2.025 = 52.025$A

Generated emf $E_g = V + I_a R_a$

$= 202.5 + (52.025 \times 0.1)$

$= 207.7$ V

15. Find the useful flux per pole on no-load of a 250V ,6 pole shunt motor having a two circuit connected armature winding with 220 conductors . At normal working temperature the overall armature resistance including brushes is 0.2 ohm .The armature current is 13.3 A at the no-load speed of 908 rpm.

Solution:

V= 250 V

P = 6

Z = 220

A = 2

$R_a = 0.2$ ohm

$I_a = 13.3$ A

N = 908 rpm

For a d.c. shunt motor $V = E_b + I_a R_a$

$250 = E_b + 13.3 \times 0.2$

$E_b = 247.34$ V

Back emf E_b is given by $E_b = \frac{\phi ZNP}{60A}$

$$247.34 = \frac{\phi \times 6 \times 908 \times 220}{60 \times 2}$$

$$\Phi = 24.76 \text{ mWb}$$

16. A 240 V ,4 pole ,shunt motor running at 1000 rpm .gives 15 H.P. with an armature current of 50 A and a field current of 1.0 A .The armature winding is wave-connected and has 540 conductors. Its resistance is 0.1ohm and drop at each brush is 1 V. Find

a) useful torque b) total torque c) useful flux per pole

d) rotational losses.

Solution:

V= 240 V, p= 4, N= 1000 rpm , P_{out} = 15 H.P.

I_a = 50 A , I_{sh} = 1 A, R_a = 0.1 ohm

If wave connected A = 2, Z= 540

V_{brush} = 1V/ brush

a) useful torque:

useful torque is shaft torque,

$$T_{sh} = \frac{Pout}{\omega} = \frac{Pout}{(2\Pi N/60)}$$

$$= \frac{15 \times 735.5 \times 60}{2 \times \Pi \times 1000}$$

$$= 105.35 \text{ N-m} \qquad (1 \text{ H.P} = 735.5 \text{ W})$$

b) Total torque is armature torque,

$$T_a = \frac{\text{Power developed by armature}}{(2\Pi N/60)}$$

$$= \frac{E_b I_a}{(2\Pi N/60)}$$

Now $E_b = V - I_a R_a$ – brush drop

$= 240 - (50 \times 0.1) - (1 \times 2) = 233$ V

$$T_a = \frac{233 \times 50}{\frac{(2\Pi \times 1000)}{60}}$$

$= 111.2493$ N-m

$$E_b = \frac{\phi ZNP}{60A}$$

= and A= 2 for wave connection

$$\Phi = \frac{60\ A\ E_b}{PNZ} = \frac{60 \times 2 \times 233}{4 \times 1000 \times 540} = 12.95\ m\ wb$$

c) Rotational losses:

$$\text{Lost torque} = \frac{\text{rotational losses}}{\frac{(2\Pi \times 1000)}{60}} = \frac{(111.2493 - 105.35) \times 2\ \Pi \times 1000}{60}$$

$$= 617.77 \text{ watts}$$

17. A 120 V d.c. shunt motor has an armature resistance of 0.2 ohm and shunt field resistance of 60 ohm .It runs at 1800 rpm .when it takes fullload current of 40 A .Find the speed of the motor while it is operating at half the fullload, with load terminal voltage remaining same.

Solution:

$$I_{sh} = \frac{V}{Rsh} = \frac{120}{60} = 2A$$

$\Phi\ \alpha\ I_{sh}$ here ϕ is constant

$T\ \alpha\ \Phi\ I_a\ \alpha\ I_a$

$$\frac{T_1}{T_2} = \frac{I_{a1}}{I_{a2}}$$

$$\frac{T_1}{0.5T_1} = \frac{I_{a1}}{I_{a2}}$$

$I_{a2} = 0.5\ I_{a1}$

$I_{L1} = I_{sh} + I_{a1}$

$I_{a1} = 40 - 2 = 38A$

$I_{a2} = 0.5 \times 38 = 19\ A$

$E_{b1} = V - I_{a1} R_a = 120 - 38 \times 0.2 = 112.4\ V$

$E_{b2} = V - I_{a2} R_a = 120 - 19 \times 0.2 = 116.2\ V$

$$N\ \alpha\ \frac{E_b}{\Phi}\ \alpha\ E_b$$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} = \frac{116.2}{112.4} \times 1800 = 1860.854 \text{ r.p.m.}$$

18. A 500 V shunt motor has 4 poles and wave connected winding with 492 conductors. The flux per pole is 0.05 Wb. The full load current is 20 amps. the armature and shunt field resistances are 0.1 ohm & 250 ohm respectively. Calculate the speed and the developed torque.

Solution:

$V = 500v$, $P=4$, $Z= 492$, $\Phi = 0.05$ wb , $I_L = 20$ A

$I_{sh} = V/ R_{sh} = 500/250 = 2A$

$I_a = I_L - I_{sh} = 20 - 2 = 18A$

$E_b = V - I_a R_a = 500 – 18 \times 0.1 = 498.2$ V

$E_b = \frac{\phi ZNP}{60A}$ where A= 2 for wave type

$N = \frac{60 \times 2 \times 498.2}{0.05 \times 4 \times 492} = 607.56$ rpm

$T_a = 0.159 \times \phi \times I_a [ZP/A] = 0.159 \times 0.05 \times 18 \times 492 \times \frac{4}{2}$

$= 140.8104$Nm

19. A 4 pole generator with wave wound armature has 51 slots,each having 24 conductors.The flux per pole is 0.01 weber. At what speed must be the armature rotate to give an induced emf of 220V. What will be the voltage developed if the winding is lap and the armature rotates at the same speed?

Solution:

P= 4, A=2, 51 slots ,24 conductors/slot , $\phi = 0.01$ Wb, $E_g = 220V$

$E_g = \frac{\phi ZNP}{60A}$ where Z= 51 x 24 = 1224

$220 = \frac{0.01 \times 4 \times N \times 1224}{60 \times 2}$

N= 539.2156 r.p.m

For Lap wound A = P = 4 and N = 539.2156 r.p.m.

$E'_g = \frac{\phi ZNP}{60A} = \frac{0.01 \times 4 \times 539.2156 \times 1224}{60 \times 4} = 110V$

20. A 4 pole, 220V ,lap connected, D.C. shunt motor has 36 slots, each slot containing 16 conductors. It draws a current of 40 A from the supply. The field resistance and armature resistance are 110 ohm ,0.1 ohm respectively. The motor develops an output power of 6 KW. The flux per pole is 40 mWb. Calculate,

a) the speed

b) the torque developed by the armature and

c) the shaft torque

Solution:

P=4, V=220V, for lap connected A=P = 4, 36 slots,16 conds/slot

$I_{sh} = V/ R_{sh} = 220/ 110 = 2A$

$I_a = I_L - I_{sh} = 40 - 2 = 38A$

$P_{out} = 6$ KW, $\phi = 40$ mwb

$E_b = V - I_a R_a$

$= 220 - 38 \times 0.1 = 216.2$ V

a) $E_b = \dfrac{\phi ZNP}{60A}$ where Z = 36 x 16 = 576

$$216.2 = \frac{40 \times 10^{-3} \times 4 \times N \times 576}{60 \times 4}$$

N = 563.02 r.p.m.

b) $T_a = 0.159 \times \phi \times I_a\,[ZP/A] = 0.159 \times 40 \times 10^{-3} \times 38 \times 4 \times \dfrac{576}{4}$

$= 139.207$ Nm

c) $T_{sh} = \dfrac{Pout}{\omega} = \dfrac{Pout}{(2\Pi N/60)}$

$$= \frac{6 \times 10^3}{\left[\dfrac{2 \times \Pi \times 563.02}{60}\right]}$$

$= 101.7325$ Nm

21. A 4 pole ,lap connected D.C. generator has 600 armature conductors and runs at 1200 r.p.m. This generator has a total flux of 24 Wb in it.

i) Calculate the emf induced in the above dc generator.

ii) Find the speed at which it should be driven to produce the same emf when wave connected.

Solution:

P= 4, for lap A =P= 4, Z = 600 , N = 1200 r.p.m.

$\Phi_T = \phi \times P = 0.24$ Wb

$\Phi = \Phi_T/P = 0.24/ 4 = 0.06$ Wb

i) $E_g = \frac{\phi ZNP}{60A} = \frac{0.06 \times 4 \times 1200 \times 600}{60 \times 4} = \underline{720\ v}$

ii) A =2

$E_g = \frac{\phi ZN'P}{60A} = N' = \frac{60 \times A \times E_g}{\phi ZP}$ x

$N' = \frac{60 \times 2 \times 720}{0.06 \times 4 \times 600}$

$= 600$ r.p.m.

22. A 4 pole, 250 V series motor has wave connected armature with 1254 conductors. The flux per pole is 22 mwb when the motor is taking 50 A . The armature and field coil resistance are respectively 0.3 ohm and 0.2 ohm .Calculate the speed and torque of the motor and also the power developed in watts.

Solution:

$P= 4$, $Z = 1254$, $\Phi = 22$ mwb , $I_a = 50$ A, $A = 2$

$E_g = V – I_a (R_a + R_{se})$

$= 250 – 50(0.3+0.2)$

$= 225$ V

$E_b = \frac{\phi ZNP}{60A}$

$225 = \frac{22 \times 10^{-3} \times 4 \times N \times 1254}{60 \times 2}$

$N = 244.6716$ r.p.m.

$T_a = 0.159 \times \phi \times I_a\ [ZP/A] = 0.159 \times 22 \times 10^{-3} \times 50 \times 4 \times \frac{1254}{2}$

$= 438.65$ Nm

$P_m = T_a \times \omega = T_a \times (2\Pi N/60) = 438.65 \times 2\Pi \times \frac{244.6716}{60}$

$= 11239.068$ W $= 11.239$ KW

$P_m = E_b\ I_a = 225 \times 50 = 11250$ W

23. A 440 V d.c. shunt motor takes an armature current of 20 A and runs at 500rpm
The armature resistance is 0.6 ohm .If the flux is reduced by 30% and the torque

is increased by 40%. What are the new values of armature current and speed ?

Solution:

$V = 440$ V , $I_{a1} = 20$A , $N_1 = 500$ rpm

Φ_1 =original flux

$\Phi_2 = \Phi_1 - 30\% \, \Phi_1$

$= 0.7\, \Phi_1$,

$\Phi_2 / \Phi_1 = 0.7$

T_1 = original torque,

$T_2 = T_1 + 40\%\, T_1$

$= 1.4\, T_1$

$$\frac{T_1}{T_2} = \frac{\Phi_1}{\Phi_2} \times \frac{I_{a1}}{I_{a2}}$$

$T \propto \Phi I_a$

$$\frac{1}{1.4} = \frac{1}{0.7} \times \frac{20}{I_{a2}}$$

$I_{a2} = 40$ A

$$N \propto \frac{E_b}{\Phi} \quad \text{i.e} \quad \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{\Phi_2}{\Phi_1}$$

$$\frac{500}{N_2} = \frac{[V - I_{a1}R_a]}{[V - I_{a2}R_a]} \times 0.7$$

$$\frac{500}{N_2} = \frac{[440 - 20 \times 0.6]}{[440 - 40 \times 0.6]} \times 0.7$$

$N_2 = 694.259$ r.p.m.

24. The field current in a d.c. shunt machine is 2 A and the line current is 20 A At 200 V ,calculate :

i) The generated e.m.f. when working as generator.

ii) Torque in Nm when running at 1500 r.p.m. as motor.

Take the armature resistance as 0.5 ohms

Solution:

i) As a generator :

$V_t = 200$ V , Line current = 20 A

$E_g = V_t + I_a R_a$

$E = 200 + 22 \times 0.5 = 200 + 11 = 211$ volts

ii) Torque when running as motor:

$E_b = V - I_a - R_a = 200 - 18 \times 0.5 = 191$ volts

P_m = Mechanical power developed

$= E_b I_a = 191 \times 18 = 3438$W

Therefore $T = \frac{P_m}{\omega} = \frac{P_m}{(2\Pi N/60)}$

$= \frac{3438}{\frac{(2\Pi \times 1500)}{60}} = \underline{21.887 \text{ NM}}$

25. A separately excited D.C. generator when running at 1000 r.p.m. supplies 50 A at 250 V. Find how much current it will deliver when the speed falls to 800 rpm . Take armature resistance as 0.01 ohm and brush drop of 1V/ brush.

Solution:

For separately excited generator field current is constant.

$N_1 = 1000$ r.p.m., $I_{a1} = 50$ A

$V_{t1} = 250$ V

$E_{g1} = V_{t1} + I_{a1} R_a + 2 \times$ V/brush

$= 250 + 50 \times 0.01 + 2 = 252.5$ V

$E_g \ \alpha \ N\phi \ \alpha \ N$--------- ϕ is constant as I_1 constant

$\frac{E_{g1}}{E_{g2}} = \frac{N_1}{N_2}$ i.e. $E_{g2} = \frac{N_2}{N_1} \times E_{g1}$

$= \frac{800}{1000} \times 252.5 = 202$ V

$I_{L1} = I_{a1} = 50$ A, $I_{L2} = I_{a2}$

$R_L = 250/50 = 5$ ohm

$E_{g2} = V_{t2} + I_{a2} R_a + 2 \times$ V/brush

$202 = V_{t2} + (V_{t2}/5) \times 0.01 + 2$

$V_{t2} = 199.6$V

$I_{a2} = \frac{V_{t2}}{R_L} = \frac{199.5}{5} =$ **39.92A**

26. A series motor runs at 600 r.p.m. when taking 110 A from a 250 V supply. The resistance of the armature circuit is 0.12 ohm, and that of series winding is 0.03 ohm . the useful flux per pole for 110 A is 0.024 Wb, and that for 50 A is 0.0155wb.

Solution:

N_1 =6 r.p.m, I_{a1} = 110 A, V = 250 v, R_a = 0.12ohm

R_{se} = 0.03 ohm , ϕ_1 = 0.024 Wb , & I_{a2}= 50 A , ϕ_2 = 0.0155 Wb

$$E_{b1} = V - I_{a1}(R_a + R_{se}) = 250 - 110(0.12+ 0.03) = 233.5V$$

$$E_{b2} = V - I_{a2}(R_a + R_{se}) = 250 - 50(0.12+ 0.03) = 242.5 V$$

$$N \ \alpha \ \frac{E_b}{\Phi} \quad \text{i.e} \quad \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{\Phi_2}{\Phi_1}$$

$$\frac{600}{N_2} = \frac{233.5}{242.5} \times \frac{0.0155}{0.024}$$

$$N_2 = \frac{600 \times 242.5 \times 0.024}{233.5 \times 0.0155} = \mathbf{964.8407 \ r.p.m.}$$

27. A 250 V d.c. shunt motor has an armature resistance of 0.5 ohm and Shunt field resistance of 250 ohm when driving a load at 600 r.p.m. , the Torque of which is constant , the armature takes 20 A. If it is desired to raise the speed from 600 to 800 r.p.m. , what resistance must be inserted in the field circuit? Assume the magnetization curve to be a straight line.

Solution:

$$I_{sh1} = V / R_{sh} = 250/ 250 = 1A$$

$$E_{b1} = V - I_{a1}R_a = 250 - 20 \times 0.5 = 240V$$

$$T \ \alpha \ \Phi I_a \ \alpha \ I_{sh} I_a$$

$$\frac{T_1}{T_2} = \frac{I_{sh1}}{I_{sh2}} \times \frac{I_{a1}}{I_{a2}} = 1$$

$$\frac{1}{I_{sh2}} \times \frac{20}{I_{a2}} = 1$$

$$I_{sh2} \times I_{a2} = 20 \qquad \text{-------------} \quad (i)$$

$$N \ \alpha \ \frac{E_b}{\Phi} \ \alpha \ \frac{E_b}{I_{sh}}$$

$$\text{i.e} \quad \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{I_{sh2}}{I_{sh1}}$$

$$\frac{600}{800} = \frac{240}{E_{b2}} \times \frac{I_{sh2}}{1}$$

$$\frac{E_{b2}}{I_{sh2}} = 320 \quad \text{------------ (ii)}$$

$E_{b2} = V - I_{a2}\,Ra = 250 - 0.5 \times Ia_2$

$E_{b2} = 250 - 0.5\,(20/I_{sh2})$

Using eq 1 &eq ii $\dfrac{250 - (10/I_{sh2})}{I_{sh2}} = 320$

$I_{sh2} = 0.7389\text{A}, 0.0422\text{ A}$

$I_{sh2} = V/\ R_{sh} + R_x$ i.e. $0.7389 = \dfrac{250}{250 + R_x}$

$R_x =$ **88.3407 ohm**

28. A 4 pole , 1500 r.p.m. d.c. generator has a lap wound armature having 24 slots with 10 conductors per slot . If the flux per pole is 0.04 Wb , Calculate the e.m.f. generated in the armature. What would be the generated e.m.f. if the winding is wave connected?

Solution:

P=4, N= 1500 rpm , Lap A= P, $\phi = 0.04$ Wb

Z = slots x conductors / slot = 24 x 10 = 240

$$E_g = \frac{\phi ZNP}{60A} = \frac{0.04 \times 4 \times 1500 \times 240}{60 \times 4} = 240 \text{ V}$$

If winding is wave connected ,A =2

$$E_g = \frac{0.04 \times 4 \times 1500 \times 240}{60 \times 2} = 480 \text{ V}$$

29. The current drawn from the mains by a 220 V d.c. shunt motor is 4 A on no-load . The resistance field and armature windings are 110 ohms & 0.2 ohm respectively . If the line current on full load is 40A at speed of 1500 rpm .find the no-load speed?

Solution:

$I_{L0} = 4$, V = 220 V , $R_{sh} = 110$ ohm , $R_a = 0.2$ ohm , $I_{FL} = 40$ A

$I_{sh} = V/R_{sh} = 220/\ 110 = 2\text{A}$

$I_{a0} = I_{Lo} - I_{sh} = 4 - 2 = 2\text{A}$

$E_{b0} = V - I_{ao}\,R_a = 220 - 2 \times 0.2 = 219.6 \text{ V}$

$I_{aFL} = I_{FL} - I_{sh} = 40 - 2 = 38$

$E_{bFL} = V - I_{aFL} R_a = 220 - 38 \times 0.2 = 212.4$ V

$N \propto \frac{E_b}{\Phi} \propto E_b$

$\frac{N_o}{N_{FL}} = \frac{E_{bo}}{E_{bFL}}$ i.e. $\frac{N_o}{1500} \times \frac{219.6}{212.4}$

N_o = **1550.8474 r.p.m.**

30. A d.c. series motor is running with a speed of 1000 r.p.m. ,while taking a current of 22 amps from the supply . If the load is changed such that the current drawn by the motor is increased to 55 amps, calculate the speed of the motor on new load. The armature & series winding resistances are 0.3 ohm &0.4 ohm respectively. Assume supply voltage as 250 V.

Solution:

N_1 = 1000 rpm ,I_{a1} = 22 A, I_{a2} = 55A

R_a = 0.3 ohm , R_{se} = 0.4 ohm, V=250V

$E_{b1} = V - I_{a1}(R_a + R_{se}) = 250 - 22 \times (0.3+ 0.4) = 234.6$V

$E_{b2} = V - I_{a2}(R_a + R_{se}) = 250 - 55 \times (0.3+ 0.4) = 211.5$ V

$N \propto \frac{E_b}{\Phi} \propto \frac{E_b}{I_a}$ i.e $\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{I_{a2}}{I_{a1}}$

$\frac{1000}{N_2} = \frac{234.6}{211.5} \times \frac{55}{22}$

N_2 = 360.6138 r.p. m.

31. A 200 V , 4 pole , lap wound ,d.c. shunt motor has 800 conductors on its armature. The resistance of the armature winding is 0.5 ohm & that of the shunt field winding is 200 ohm .The motor takes a current of 21A, the flux/pole is 30 mWb. Find the speed and gross torque developed in the motor.

Solution:

V =200 V, P=4, Lap A =P =4, Z =800

Shunt motor R_a = 0.5 ohm , R_{sh} = 200 ohm, I_L = 21A, ϕ = 30 mWb.

$I_{sh} = V/R_{sh} = 200/200 = 1$A

$I_L = I_{sh} + I_a$ i.e. $I_a = I_L - I_{sh}$

$I_a = 21 - 1 = 20$

$E_b = v - I_a R_a = 200 - 20 \times 0.5 = 190$

$E_b = \frac{\phi ZNP}{}$ i.e 190 = $\frac{30 \times 10^{-3} \times 4 \times N \times 800}{}$ = **475 rpm.**

60A	60 x 4

MEASURING INSTRUMENTS:

Important Questions with Answers

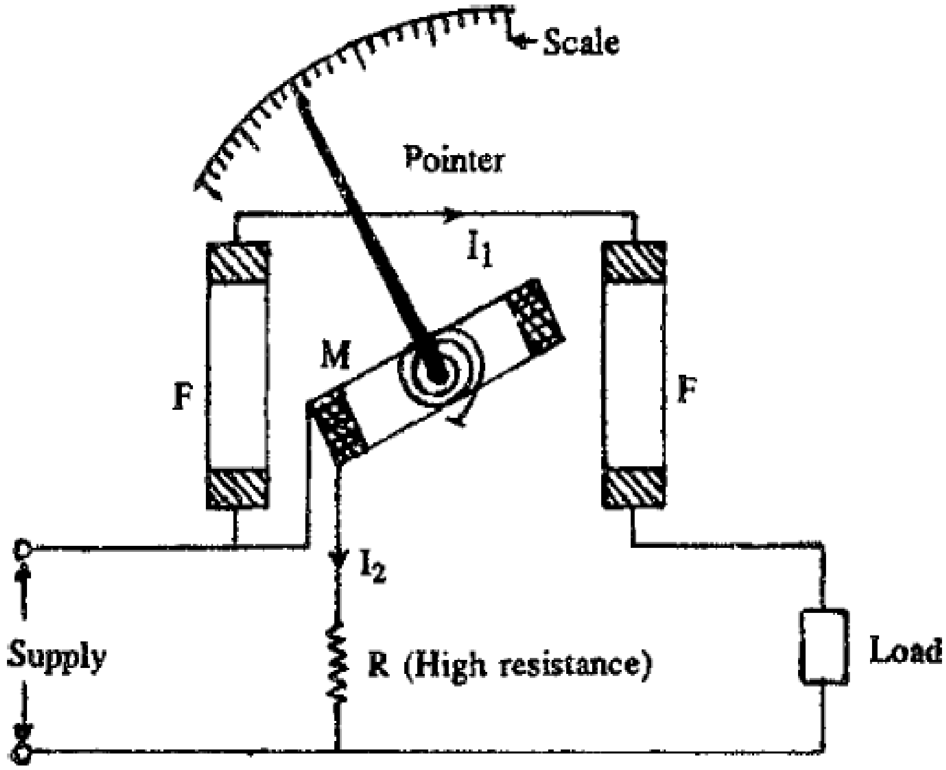
1. **construction and working principle of dynamometer type wattmeter.**

Thus instrument is used to measure power consumption in single phase AC circuits. It consumption in single-phase AC circuits. It consists of two fixed coils (F) and a movable coil (M), as shown in figure. The fixed coil forms the current coil (CC), which carries the entire coil current or a definite fraction of it, and the moving coil (M) forms the voltage coil which carries a current proportional to the voltage.

When current flows simultaneously through both fixed and moving coils, as during a measurement, a torque is produced, and this, acting on the moving coil, tends to turn it. The moving coil is carried on the spindle and hence the spindle also rotates and cause a pointer fixed to it to move over a graduated scale. The deflecting torque produced must depend on both currents and hence we have $T_d \alpha I_1 I_2$.

But $I_2 \alpha V$, the supply voltage

Therefore, $T_d \alpha VI_1$, i.e., the deflecting torque is proportional to the power in the circuit. The controlling torque T_c, is obtained by means of spring control. Therefore we have $T_c \alpha \Theta$ (deflection). At equilibrium, $T_c = T_d$, hence the deflection indicates directly the power consumed.



The damping is generally obtained by means of air friction damping mechanism. Stray magnetic fields can affect the accuracy of these meters unless they are properly shielded. In the case of measurement of power of a high voltage circuit, instrument transformers could be employed.

2. **induction type energy meter.**

A single-phase induction-type energy meter is used to measure the quantity of electrical energy supplied to a single phase circuit in a given time (measured in kilo-watt-hour).

Construction:

A single-phase induction-type energy meter has the following systems/mechanism.

(a) Moving system

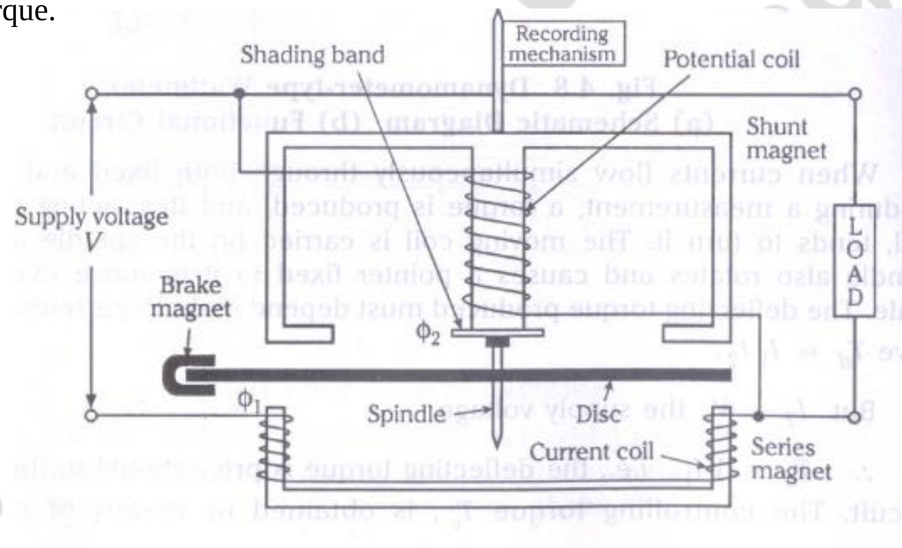
(b) Operating Mechanism

(c) Recording System

(a) Moving System:

The moving system consists of a light aluminium disc mounted on a vertical spindle and supported on a sapphire cup contained in a bottom bearing screw. The bottom pivot, which is usually removable, is of hardened steel, and the end, which is hemispherical in shape, rests in the sapphire cup. The top picot merely serves to maintain the spindle in a vertical position under working conditions and neither supports any weight nor does it expert appreciable thrust in any direction.

There is no pointer and control spring, so that the disc rotates continuously because of the deflecting torque.



(b) Operating Mechanism:

The operating mechanism has the following components:

(i) Series magnet

(ii) Shunt Magnet

(iii) Brake Magnet

i)Series Magnet:

The series magnet consists of a number of U-shaped iron laminations assembled to form a core. Each of its two limbs iswound with a few of heavy gauge wire. The wound coil is called current coil, and is connected in series ith the load to be metered. The series magnet is placed under the aluminium disc, and produced a magnet field proportional to and in phase with the current.

(ii) Shunt Magnet:

The shunt magnet consists of a number of M-shaped iron laminations, assembled together to form a core. A coil having a large number of turns of fine wire is fitted on the middle limb of the shunt magnet. This wound coil is called the potential coil and is connected across the load, so that it carries current proportional to the supply voltage V. The shunt magnet is situated above the aluminium disc, as shown. A copper shading band (also called ‘power factor compensator’) is placed over the central limb in order to ensure a 90^0 phase difference between the flux produced by the supply voltage and the supply voltage itself.

(iii) Brake-Magnet:

The speed of the aluminium disc is controlled by the brake magnet.

(c) Recording Mechanism:

The number of revolutions of the disc is a measure of the electrical energy through the meter and is recorded on dials which are geared to the shaft.

Working:

When the line current flows through the current coil, the series magnet is excited. The alternating flux Φ_1 Produced by it is proportional to and in phase with the line current (if effects of hysteresis and iron saturation are ignored). The potential coil of the shunt magnet is connected across the supply line and carries current proportional to the supply voltage V. The Φ_2 produced by it is proportional to the supply voltage V and lags behind it by 90^0. This phase displacement of exactly 90^0 is brought about by adjusting the copper shading band. Most of the flux Φ_2 crosses the narrow gap between the centre and side-limbs of the shunt magnet.

However, a small quantity, which is the useful flux, passes through the disc. The fluxes Φ_1 and Φ_2 induce e.m.f.s in the disc, which give rise to circulatory produces the driving torque, which causes the disc to rotate.

The speed of the aluminium disc is controlled to the required value by the C-shaped permanent brake magnet. The magnet is mounted so that the disc revolves in the air-gap between the polar extremities. When the peripheral portion of the rotating disc passes through the air-gap of the brake magnet, eddy currents are induced in it, giving rise to the reqired torque. The braking torque $T_B \;\alpha\; \Phi^2 N / R$, where Φ is the flux of the brake magnet, N the speed at which the disc rotates and R is the resistance of the eddy current path. If Φ and R are constant, $T_B \;\alpha\; N$. The spindle is geared to the recording mechanism so that the electrical energy consumed in the circuit is directly registered in kWh.

Theory:

The current coil carries proportional to load, while the potential coil carries current proportional to the voltage.

Therefore, Average deflecting torque, $T_d \;\alpha\;$ Average power

$$\alpha \; VI \cos \Phi$$

Therefore, $T_d = k_1 VI \cos \Phi$

But we have seen that the braking torque T_B is proportional to the speed of the disc N, i.e.,

$$T_B \quad \alpha \quad N$$

Therefore, $T_B = k_2 N$

The disc rotates at a steady speed N when the braking torque equals the deflecting torque i.e.,

$$T_B = T_d$$

Therefore, $k_2 N = k_1 VI \cos \Phi$

Multiplying both sides by time 't', we have

$$k_2 N t = k_1 VI \cos \Phi . t$$

or $N t = k_1 / k_2 VI \cos \Phi . t$

If $k_1 / k_2 = k_3$ and $p = V I \cos \Phi$, then

$$N t = k_3 P t$$

The expression 'Nt' gives the no. of revolutions of the disc in time 't', and the expression 'Pt' represents the energy passing through the meter in time 't'.

Therefore, *the no. of revolutions of the disc α electrical energy passing through the meter*.

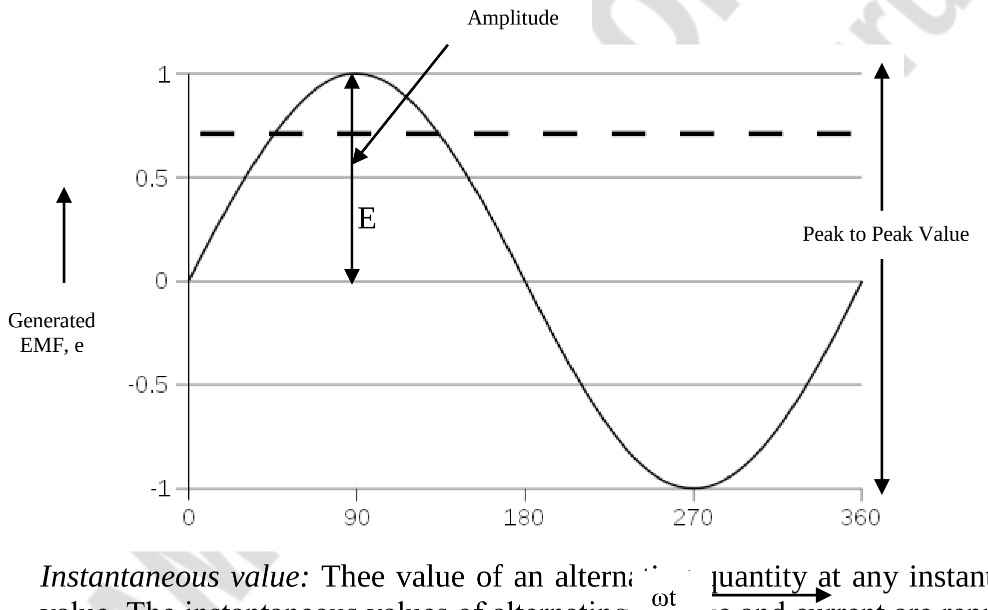
Module – 3

SINGLE PHASE AC CIRCUITS:

1. (i) instantaneous value, (ii) Peak-to-Peak value, and (iii) Peak amplitude.

In alternating current (AC, also ac) the movement of electric charge periodically reverses direction. In direct current (DC), the flow of electric charge is only in one direction.

AC is the form in which electric power is delivered to businesses and residences. The usual waveform of an AC power circuit is a sine wave. In certain applications, different waveforms are used, such as triangular or square waves. Audio and radio signals carried on electrical wires are also examples of alternating current. In these applications, an important goal is often the recovery of information encoded (or modulated) onto the AC signal.



(i) *Instantaneous value:* Thee value of an alternating quantity at any instant called instantaneous value. The instantaneous values of alternating voltage and current are represented by ‘e’ and ‘i’ respectively.

(ii) *Peak-to-peak value*: The peak-to-peak value of an AC voltage is defined as the difference between its positive peak and its negative peak. Since the maximum value of sin(x) is +1 and the minimum value is −1, an AC voltage swings between $+V_{peak}$ and $-V_{peak}$. The peak-to-peak voltage, usually written as V_{pp} or V_{P-P}, is therefore $V_{peak} - (-V_{peak}) = 2V_{peak}$.

(iii) *Peak Amplitude*: The maximum value, positive or negative, which an alternating quantity attains during one complete cycle is called amplitude or peak value or maximum value. The amplitude of alternating voltage and current is represented by E_m and I_m respectively.

2. (i) the form factor and (ii) the peak factor in an ac circuits.

(i) Form Factor:

The ratio of effective value (or r.m.s. value) to average value of an alternating quantity (voltage or current) is called form factor, i.e.,

$$\text{Form factor, } K_f = \frac{\text{r.m.s.value}}{\text{Average value}}$$

For sinusoidal alternating current,

$$K_f = 0.707\ I_m / 0.637\ I_m = 1.11$$

For sinusoidal alternating voltage,

$$K_f = 0.707\ E_m / 0.637\ E_m = 1.11$$

Hence, the R.M.S. value (of current or voltage) is 1.11 times its average value.

(ii) Crest or Peak or Amplitude Factor (K_a):

It is defined as the ratio of maximum value to the effective value (r.m.s value) of an alternating quantity. i.e.,

$$K_a = \frac{\text{maximum value}}{\text{r.m.s value}}$$

For sinusoidal alternating current,

$$K_a = \frac{I_m}{I_m/\sqrt{2}} = 1.414$$

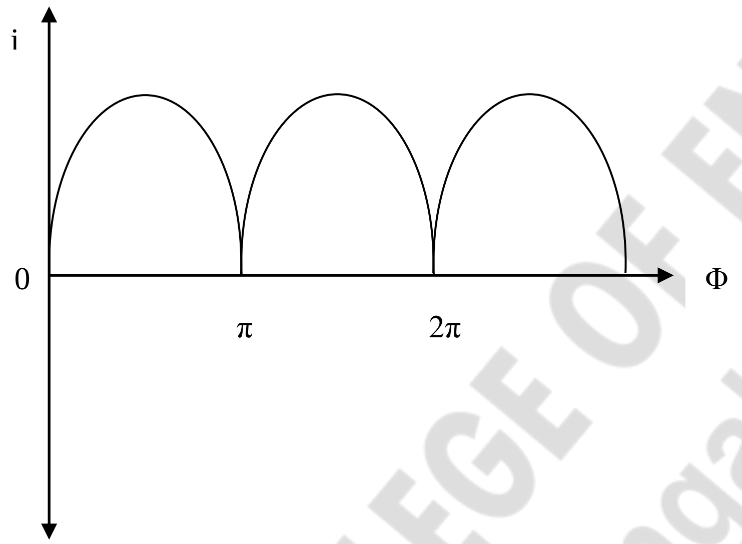
For sinusoidal alternating current,

$$K_a = \frac{E_m}{E_m/\sqrt{2}} = 1.414$$

3. Obtain the form factor of a full – wave rectified wave.

Solution:

Full-wave rectified wave:



$$\text{Mean square value} = \frac{\text{Area under one squared curve}}{\text{Period}}$$

$$\text{Mean square value} = \frac{1}{\Pi}\int_0^{\pi} I_m^2 \sin^2 \Phi \, d\Phi$$

$$= \frac{I_m^2}{\Pi}\int_0^{\pi} \frac{1-\cos 2\Phi}{2}\, d\Phi = \frac{I_m^2}{2\pi}\left(\Phi - \frac{\sin 2\Phi}{2}\right)_0^{\pi}$$

$$= \frac{I_m^2}{2\pi}\left(\pi - \frac{\sin 2\pi}{2} - 0 + \frac{\sin 0}{2}\right)$$

$$= I_m^2 / 2\pi \times \pi = I_m^2 / 2$$

$$\text{RMS value} = I_m / \sqrt{2}$$

Average value:

Average value = <u>Area under the curve for one complete cycle</u>

Period

$$= \frac{1}{\Pi}\int_0^{\pi} I_m \sin\Phi \, d\Phi \quad \text{(since, the given wave is symmetrical)}$$

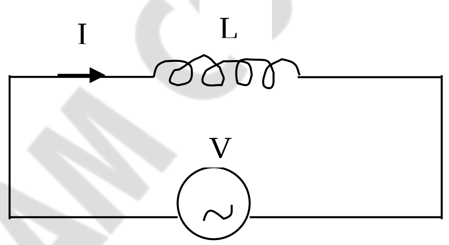
$$= I_m / \pi \; (-\cos\Phi)_0^{\pi} = I_m / \pi \; (1 + 1) = 2 I_m / \pi$$

$$\text{Form factor} = \frac{\text{RMS value}}{\text{Average value}}$$

$$= \frac{I_m / \sqrt{2}}{2 I_m / \pi} = \frac{I_m \times \pi}{\sqrt{2} \times 2 I_m} = 1.11$$

$$\text{Peak factor} = \frac{\text{Peak value}}{\text{RMS value}} = \frac{I_m}{I_m / \sqrt{2}} = \sqrt{2}$$

4.purely inductive circuit lags behind the applied voltage by 90⁰.



Consider the circuit shown in the figure. In this circuit, an alternating voltage is applied across a pure inductor of self inductance L Henry.

Let the applied alternating voltage be

$v = V_m \sin\omega t$ ------- (i)

$v = L. di/dt$

Therefore, $I = 1/L \int v \, . \, dt = 1/L \int V_m \sin\omega t \, dt = V_m / L \; (-\cos\omega t / \omega)$

$= - V_m / \omega L \; \cos\omega t = I_m (\sin\omega t - \pi/2)$ ------- (ii)

Comparing Eqn. (i) and (ii) we can say that the current through an inductor lags the applied voltage by an angle of 90^0

Power:

Instantaneous power $P = v\,i$

$$= V_m \sin \Phi \; I_m (\sin \Phi - \pi/2)$$

$$\text{Average power, } P = -1/\pi \int_0^{\pi} V_m I_m \sin \Phi \cos \Phi \, d\Phi$$

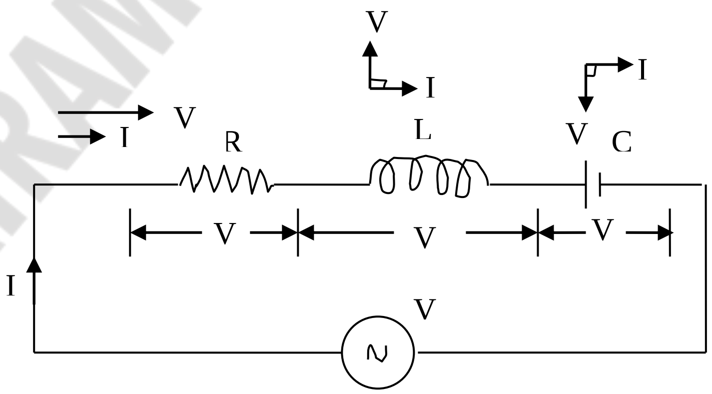
$$= -1/\pi \int_0^{\pi} V_m I_m / 2.\ \sin 2\Phi \, d\Phi = + V_m I_m / 2\pi \left(\cos 2\Phi / 2 \right)_0^{\pi}$$

$$= V_m I_m / 4\pi \; (\cos 2\pi - \cos 0) = 0$$

Thus, a pure inductor does not consume any real power.

5.expression for power in a series RLC circuit.

Consider an a.c circuit containing resistance R ohms, inductance L henries and capacitance C farads as shown in figure.



Let V = r.m.s value of applied voltage

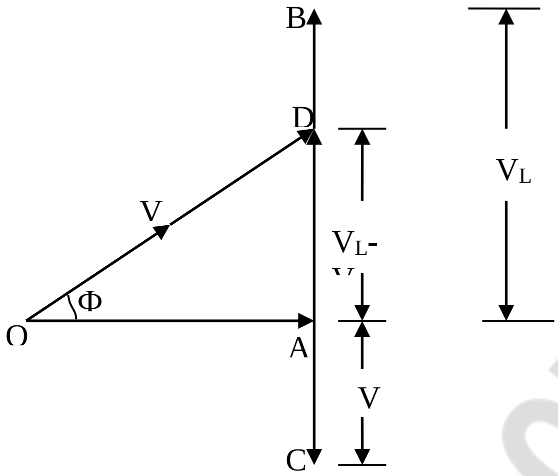
I = r.m.s. value of current

Therefore, Voltage drop across R, $V_R = IR$ (in phase with I)

Voltage drop across L, $V_L = I\,X_L$ (leading I by 90^0)

Voltage drop across C, $V_C = I\,X_C$ (lagging I by 90^0)

Referring to the voltage triangle of figure shown below, OA represents V_R, AB and AC represent inductive and capacitive drops respectively. We observe that V_L and V_C are 180^0 out of phase.



Thus, net reactive across the combination is

$AD = AB – AC$

$= AB – BD$ (Since BD = AC)

$= V_L - V_C$

$= I (X_L – X_C)$

OD, which represents the applied voltage V, is the vector sum of OA and AD.

Therefore, $OD = \sqrt{(OA^2 + AD^2)}$ or $V = \sqrt{[(IR)^2 + (IX_L – IX_C)^2]}$

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

or $$I = \frac{V}{\sqrt{[R^2 + (X_L- X_C)^2]}} = \frac{V}{\sqrt{R^2 + X^2}} = \frac{V}{Z}$$

The denominator $\sqrt{[R^2 + (X_L- X_C)^2]}$ is the impedance of the circuit.

So $(\text{impedance})^2 = (\text{resistance})^2 + (\text{net reactance})^2$

Or $Z^2 = (R^2 + (X_L- X_C)^2 = R^2 + X^2$

Where the net reactance = X

Phase angle Φ is given by

$\tan \Phi = (X_L- X_C) / R = X/R$

Power factor,

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

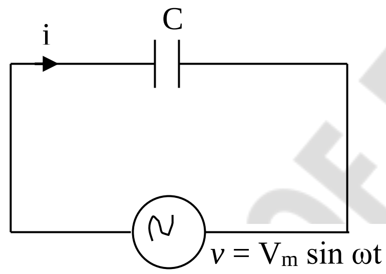
Actual or Real Power, $P = VI \cos \Phi$ (watts)

Reactive or Quadrature power, $Q = VI \sin \Phi$ (VAR)

Complex or apparent power, $S = VI$ (volt amp)

4. pure capacitive does not consume any power.

Consider the circuit shown in figure in which a capacitor of value C farad is connected across an alternating voltage source.



Let the Sinusoidal voltage applied across the capacitance be

$$v = V_m \sin \omega t \quad \text{------------- (i)}$$

The characteristic equation of a capacitor is

$v = 1/C \int i\, dt$

$i = C\, dv/dt = C\, d/dt (V_m \sin \omega t) = \omega C V_m \cos \omega t$

$i = I_m \cos \omega t$ where, $I_m = \omega C V_m$

$i = I_m \sin (\omega t + 90)$ ------------- (ii)

Comparing equation (i) and (ii) we find that there is a phase difference of 90^0 between the voltage and the current in a pure capacitor.

The current in a pure capacitor leads the applied voltage by an angle of 90^0.

Instantaneous power is $p = v\, i$

$p = V_m \sin \Phi \,.\, I_m \cos \Phi$

$p = V_m I_m \sin \Phi \cos \Phi$

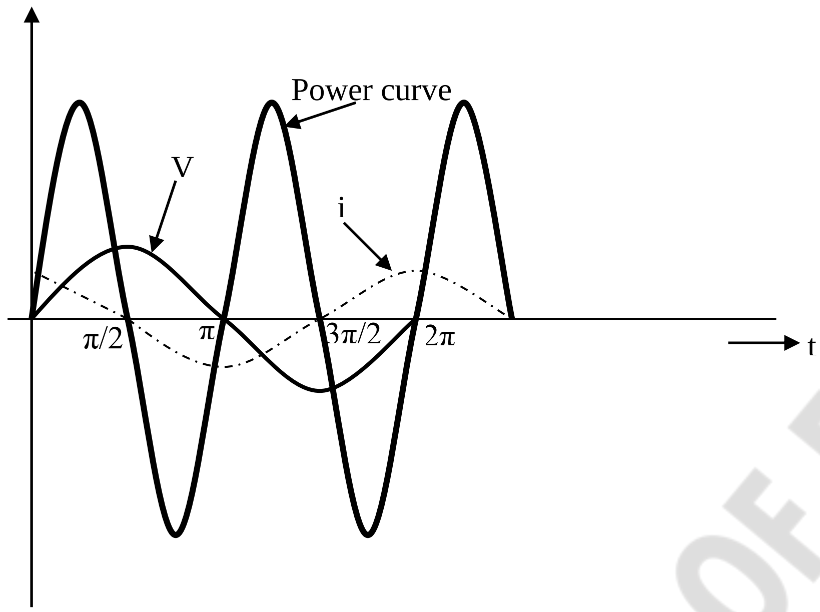
$$\text{Average power}, P = -1/\pi \int_0^\pi V_m I_m \sin \Phi \cos \Phi \,.d\Phi$$

$$= -1/\pi \int_0^\pi V_m I_m / 2.\ \sin 2\Phi\, d\Phi = + V_m I_m / 2\pi \ \left(\cos 2\Phi / 2 \right)_0^\pi$$

$$= V_m I_m / 4\pi \ (\cos 2\pi - \cos 0) = 0$$

Thus, a pure capacitor does not consume any real power.

Wave form Representation:



5. **Two impedances 20∠-45⁰ Ω and 30∠30⁰ Ω are connected in series across a certain AC supply and the resulting current is found to be 10 Amps. If the supply voltage remains unchanged, calculate the supply current when the two impedances are connected parallel.**

Solution:

Case I : Impedance in series

Impedance $Z_1 = 20\angle -45^0 = 20(\cos 45^0 - j \sin 45^0)$

$= 20 (0.707 - j\ 0.707)$

$= 14.14 - j\ 14.14$

Impedance $Z_2 = 30\angle 30^0 = 30 (\cos 30^0 + j \sin 30^0)$

$= 30 (0.866 + j\ 0.5)$

$= 26 + j\ 15$

Total impedance $Z = Z_1 + Z_2$

$= (14.14 - j\ 14.14) + (26 + j\ 15)$

$= 40.14 + j\ 0.86$

Current $I = V/Z = 10$ Amps

Therefore, Voltage applied, $V = 10\ Z$

$= 10 (40.14 + j\ 0.86)$

$= 401.4 + j\ 8.6$

$= 401.5 \angle \tan^{-1} 0.021$

$= 401.5 \angle 0.1^0$

Case II : Impedance in parallel

The same voltage i.e., $401.5\angle 0.1^0$ is applied to the parallel combination of the both the impedances.

Total impedance $Z = Z_1 Z_2 \,/\, (Z_1 + Z_2)$

$= (14.14\text{-}j14.14)(26+j15) / (40.14 + j0.86)$

$= (579.74 - j155.54) / (40.14 + j\,0.86)$

$= (600\angle\tan^{-1} 0.268) / (40.15\angle\tan^{-1} 0.02)$

$= (600\angle\text{-}15^0) / (40.15\angle 0.2^0)$

$= 14.95\angle\text{-}15.2^0$

Here, Current $I = V/Z = (401.5 \angle 0.1^0) / (14.95\angle\text{-}15.2^0)$

$= 26.86 \angle 15.3^0$

6. Two parallel circuits comprising of (i) a coil of resistance of 20Ω and inductance of 0.07 H and (ii) a resistance of 50 Ω in series with a condenser of capacitance 60 µF are connected across 230 V, 50 Hz. Calculate the main current and power factor of the arrangement.

Solution:

Circuit A : (i) a coil of resistance of 20Ω and inductance of 0.07 H)

Inductive Reactance $X_L = 2\pi fL$

$= 2\pi \times 50 \times 0.07$

$= 22\ \Omega$

Impedance of circuit A,

$Z_A = \sqrt{(R_A^2 + X_L^2)}$

$= \sqrt{(20^2 + 22^2)} = 29.7\ \Omega$

Current drawn by circuit A,

$I_A = V/Z_A = 230 / 29.7 = 7.75$ A

Phase angle of circuit A,

$\phi_A = \cos^{-1} R_A / Z_A$

$= \cos^{-1} 20/29.7$

$= \cos^{-1} 0.673$

$= 47.7^0$ (lag) (for inductive circuit)

Circuit B: (ii) a resistance of 50 Ω in series with a condenser of capacitance 60 µF)

Capacitive reactance $X_C = 1 / 2\pi fC$

$= 1 / (2\pi \times 50 \times 60 \times 10^{-6})$

$= 53\ \Omega$

Impedance of circuit B,

$Z_B = \sqrt{(R_B^2 + X_C^2)}$

$= \sqrt{(50^2 + 53^2)}$

$= 72.9\ \Omega$

Current drawn by circuit B,

$I_B = V/Z_B = 230/72.9 = 3.15$ A

Phase angle of circuit B,

$\phi_B = \cos^{-1} R_B / Z_B$

$= \cos^{-1} 0.685$

$= 46.8^0$ lead, as circuit is capacitive.

Active component of resultant current,

$I \cos\phi = I_A \cos\phi_A + I_B \cos\phi_B$

$= (7.75 \times 0.673) + (3.15 \times 0.685)$

$= 5.12 + 2.15 = 7.36$ A

Reactive component of resultant current,

$I \sin\phi = I_A \sin\phi_A + I_B \sin\phi_B$

$= 7.75 \times (-0.739) + 3.15 \times 0.729$

$= -5.72 + 2.30 = -3.42$ A

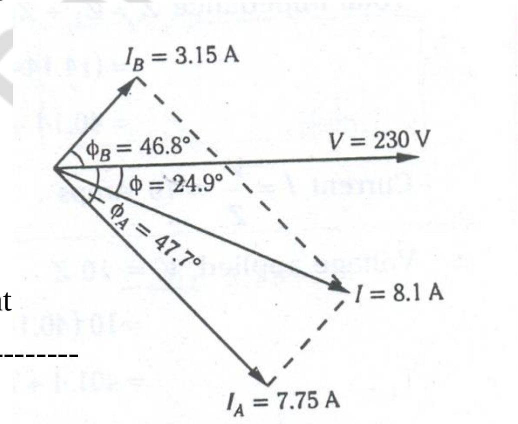
Squaring both sides and adding them

$I^2 = (I\cos\phi)^2 + (I\sin\phi)^2$

$I = \sqrt{[(I\cos\phi)^2 + (I\sin\phi)^2]}$

$= \sqrt{[(7.36)^2 + (-3.42)^2]}$

$= \sqrt{(54.17 + 11.70)} = $ **8.1 A**



Power Factor of the arrangement

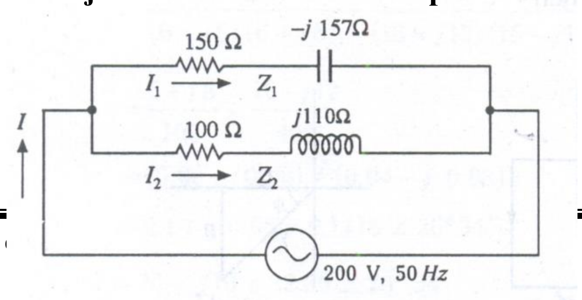
$$= \frac{\text{Active component of resultant current}}{\text{Resultant current}}$$

$= (I\cos\phi) / I = 7.36 / 8.1 = $ **0.908 (lag)**

7. Two impedances $Z_1 = 150 – j\ 157\ \Omega$ and $Z_2 = 100 = j\ 110\ \Omega$ are connected in parallel across 200 V, 50 Hz supply. Find

(i) Branch Currents

(ii) Total current



(iii) Total power

(iv) Draw vector Diagram

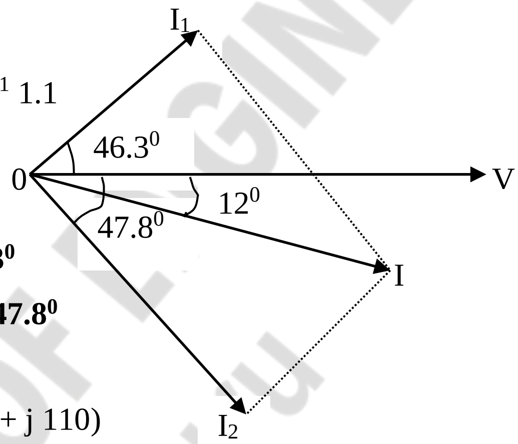
Solution:

Impedance, $Z_1 = 150 - j\,157 = \sqrt{(150^2 + 157^2)}\ \angle -\tan^{-1} 1.046$

$= 217\angle -46.3^0$

Impedance, $Z_2 = 100 - j\,110 = \sqrt{(100^2 + 110^2)}\ \angle -\tan^{-1} 1.1$

$= 148.66\ \angle 47.8^0$



$V = 200\ \angle 0^0$

$I_1 = V / Z_1 = 200\ \angle 0^0 / 217\ \angle -46.3^0 = \mathbf{0.92\ \angle 46.3^0}$

$I_2 = V / Z_2 = 200\ \angle 0^0 / 148.66\ \angle -47.8^0 = \mathbf{1.34\angle -47.8^0}$

The total impedance is given by:

$$Z = \frac{Z_1 Z_2}{Z_1 + Z_2} = \frac{(150 - j\,157)(100 + j\,110)}{250 - j47}$$

Simplifying the numerator and then multiplying both numerator and denominator by (250 + j47), we get

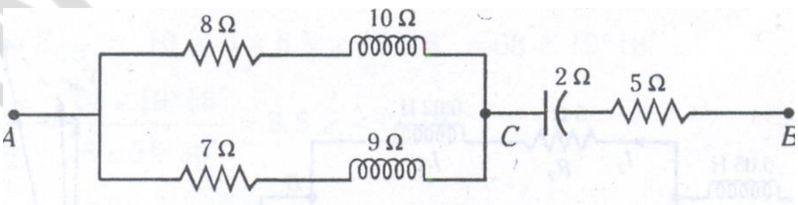
$Z = 124 + j26.5 = \sqrt{(124^2 + 26.5^2)}\ \angle \tan^{-1} 0.212$

$= 126\ \angle 12^0$

Total current $I = V/Z = 200\ \angle 0^0\ /\ 126\ \angle 12^0 = \mathbf{1.58\ \angle -12^0}$

Total power $P = VI \cos\phi = 200 \times 1.58 \times \cos 12^0 = =$ **309 watts**

8. **In the arrangement shown in the figure below calculate the impedance of AB and the phase angle between voltage and current. Also calculate the total power consumed, if the applied voltage between A and B is $200\angle 30^0$ volts.**



Solution:

Impedance in the parallel arms:

$Z_1 = 8 + j10$ and $Z_2 = 7 + j9$

Impedance in the series arm $Z_3 = 5 - j2$

$$Z_{AC} = \frac{(8 + j10)(7 + j9)}{(8 + j10) + (7 + j9)}$$

$$= \frac{-34 + j142}{15 + j19} \cdot \frac{(15 - j19)}{(15 - j19)}$$

$= (2188 + j2776) / 586 = 3.73 + j\,4.73$

Total Impedance $Z_{AB} = 3.73 + j4.73 + Z_3$

$= 3.73 + j4.73 + 5 - j2$

$= 8.73 + j2.73$

$= \sqrt{(8.73^2 + 2.73^2)}\ \tan^{-1}(2.73/8.73)$

$= 9.15 \angle 17.3^0$

$=$ **$9.15\ \Omega$, 17.3^0 lag**

$V = 200\angle 30^0$

$I = V/Z = 200\angle 30^0 / 9.15\angle 17.3^0 = 21.9\angle 12.7^0$

The resistive component contributing to power is 8.73 Ω

Power $= I^2R = (21.9)^2 \times 8.73$

$= 4173$ watts $=$ **4.173 KW**

9. An ac current is given by I = 10 sin ωt + 2 sin 5ωt. Find the rms value of the current.

Solution:

The rms value of an alternating current is defined on the basis of its heating effect. The total heat produced by a non-sinusoidal ac current is the sum of heats produced by is dc component and various harmonics. The given current has no dc component. But it has fundamental, 2nd harmonic and 3rd harmonic. When the given current flows through a resistance R for a time duration t, we have

$H_{total} = H_1 + H_2 + H_3$

$\Longrightarrow$ $I^2_{rms} Rt = I^2_{1rms} Rt + I^2_{2rms} Rt + I^2_{3rms} Rt$

$I^2_{rms} = I^2_{1rms} + I^2_{2rms} + I^2_{3rms}$

$I_{rms} = \sqrt{[(I_{1m}/\sqrt{2})^2 + (I_{2m}/\sqrt{2})^2 + (I_{3m}/\sqrt{2})^2]}$

$= 1/\sqrt{2}\ \{\sqrt{(10^2 + 3^2 + 2^2)}\} =$ **7.517 A**

10. A series RLC circuit is composed of 100 ohm resistance, 1.0 H inductance and 5 μF capacitance. A voltage v(t) = 141.4 cos 377t volts is applied to the circuit. Determine the current and the voltage V_R, V_L and V_C.

Solution:

From the expression of the applied voltage, $V_m = 141.4$ V, $\omega = 377$ rad/s.

Therefore, $V_{(rms\ value)} = V_m/\sqrt{2} = 141.4 / \sqrt{2} = 100$ V.

Let this voltage be the reference phasor. Thus, $V = 100\angle 0^0$ V

$X_L = \omega L = 377 \times 1 = 377\Omega$; $X_C = 1/\omega C = 1/(377 \times 5 \times 10^{-6}) = 530.5\ \Omega$

The complex impedances, $\mathbf{Z_R} = (100 + j0)\ \Omega$; $\mathbf{Z_L} = (0 + j377)\ \Omega$; $\mathbf{Z_C} = (0 - j530.5)\ \Omega$

The total impedance of the circuit, $Z = Z_R + Z_L + Z_C = (100 - j\ 153.5)\ \Omega$

The current, $\mathbf{I = V/Z} = 100\angle 0^0 / (100 - j\ 153.5) = \mathbf{0.546\angle 56.9^0}$ or $I = 0.546$ A

The voltages across each element are given as

$V_R = IZ_R = (0.546\angle 56.9^0) \times (100 + j0) = 54.6\angle 56.9^0$ V or $V_R = 54.6$ V

$V_L = IZ_L = (0.546\angle 56.9^0) \times (0 + j377) = 205.8\angle 146.9^0$ V or $V_L = 205.8$ V

$V_C = IZ_C = (0.546\angle 56.9^0) \times (0 - j530.5) = 289.6\angle -33.1^0$ V or $V_C = 289.6$ V

11. An impedance coil in parallel with a 100μF capacitor is connected across a 200 V, 50 Hz supply. The coil takes a current of 4 A and the power in the coil is 600 W. Calculate (i) the resistance of the coil, (ii) the inductance of the coil and (iii) the power factor of the entire circuit.

Solution;

Given: $I_{coil} = 4$ A, $P_{coil} = 600$ W, V = 200 V, f = 50 Hz, C 100 μF

(i) The power loss in a coil is due to its resistance r. Thus,

$$P_{coil} = I^2_{coil} r$$

$$R = P_{coil} / I^2_{coil} = 600 / 4^2 = \mathbf{37.5\ \Omega}$$

(ii) The impedance of the coil, $Z_{coil} = V / I_{coil} = 200/4 = 50\ \Omega$

But $Z_{coil} = \sqrt{(r^2 + X_L^2)}$

$$X_L = \sqrt{(Z_{coil}^2 - r^2)} = \sqrt{(50^2 - 37.5^2)} = 33\ \Omega$$

Therefore, $L = X_L / 2\pi f = 33 / (2\pi \times 50) = \mathbf{0.1\ H}$

(iii) $X_C = 1/2\pi f = 1/(2\pi \times 50 \times 100 \times 10^{-6}) = 31.8\ \Omega$

Let the two parallel branches be A and B. Then, the complex impedance of these branches,

$\mathbf{Z_A} = r + jX_L = (37.5 + j33)\ \Omega$ and $\mathbf{Z_B} = -jX_C = (0 - j31.8)\ \Omega$

The equivalent impedance of the entire circuit,

$$Z = Z_A \parallel Z_B = Z_A Z_B / (Z_A + Z_B)$$

$$= \frac{(37.5 + j33) \times (0 - j31.8)}{(37.5 + j33) + (0 - j31.8)} = 42.3\angle -50.5^0 \Omega$$

Thus, the power factor angle of the circuit, $\phi = -50.5^0$

Therefore, Power factor = cos (-50.5) = **0.636 (leading)**

12. A non-inductive resistor of 10 ohm is in series with a capacitor of 100μF across a 250 V, 50 Hz ac supply. Determine the current taken by the capacitor and the *pf* of the circuit.

Solution:

Given: R = 10 ohm, C = 100μF, V = 250 V, f = 50 Hz

$X_C = 1/ 22\pi f = 1 / (2\pi \times 50 \times 100 \times 10^{-6}) = 31.8\ \Omega$

The impedance of the circuit, $Z = R - jX_C = (10 - j31.8)\ \Omega$

Taking the applied voltage to be the reference phasor, the current,

$I = V/Z = 250 \angle 0^0 / (10 - j31.8) = 7.5\angle 72.5^0$ A or **I = 7.5 A**

And $Pf = \cos 72.5^0 =$ **0.3 (leading)**

13. A current of average value 18.019 A is flowing in a circuit to which a voltage of peak value 141.42 V is applied. Determine (i) the impedance in the polar form, (ii) the power. Assume that the voltage lags the current by 30^0.

Solution:

Given: I_{av} = 18.019 A, V_m = 141.42 V, V lags I by 30^0. Assuming the applied voltage to be sinusoidal, we have

$V_{(rms\ value)} = V_m / \sqrt{2} = 141.42 / \sqrt{2} = 100$ V

And $I_{(rms)} = K_f I_{av} = 1.11 \times 18.019 = 20$ A

Thus, we can write $I = 20\angle 0^0$ A and $V = 100\angle -30^0$ V

(i) $Z = V/I = 100\angle -30^0 / 20\angle 0^0 = \mathbf{5\angle -30^0\ \Omega}$

(ii) $P = VI \cos \phi = 100 \times 20 \times \cos 30^0 =$ **1732 W**

14. Parallel circuits comprise a resistor of 20 ohms in series with an inductive reactance of 15 ohms in one branch and a resistor of 30 ohms in series with a capacitive reactance of 20 ohms in the other branch. Determine the current and power dissipated in each branch if the total current drawn by the parallel circuit is $10\angle -30^0$ A.

Solution:

Given: $I_{(total)} = 10\angle -30^0$ A. For the two parallel branches, we have

$Z_1 = (20 + j15)\ \Omega$ and $Z_2 = (30 - j20)\ \Omega$

Using current division concept,

$$I_1 = I \times Z_2 / (Z_1 + Z_2) = 10\angle -30^0 \times \frac{(30 - j20)}{(20 + j15) + (30 - j20)}$$

$$= \mathbf{7.175 \angle -57.98^0\ A}$$

And

$$I_2 = I \times Z_1 / (Z_1 + Z_2) = 10\angle -30^0 \times \frac{(20 + j15)}{(20 + j15) + (30 - j20)}$$

$$= \mathbf{4.975 \angle -12.58^0\ A}$$

$P_1 = I_1^2 R_1 = (7.175)^2 \times 20 =$ **1029.6 W** and

$P_2 = I_2^2\, R_2 = (4.975)^2 \times 30 =$ **742.5 W**

15. Two circuits A and B are connected in parallel across 200 V, 50 Hz supply. Circuit A consists 10 ohm resistance and 0.12 H inductance in series while circuit B consists of 20 ohm resistance and 40 μF capacitance. Calculate (i) current in each branch, (ii) the supply current, and (iii) total power factor. Draw the phasor diagram.

Solution:

(i) $Z_A = R + j\omega L = 10 + j(2\pi \times 50) \times 0.12 = (10 + j37.7)\Omega$

$Z_B = R - j(1/\omega C) = 20 - j(1/(2\pi \times 50 \times 40 \times 10^{-6})$

$= (20 - j79.6)\ \Omega$

Taking the applied voltage to be reference phasor,

$I_A = V/Z_A = 200\angle 0^0 / (10 + j37.7) = (1.3147 - j4.96)\ A = 5.13\angle -75.144^0$

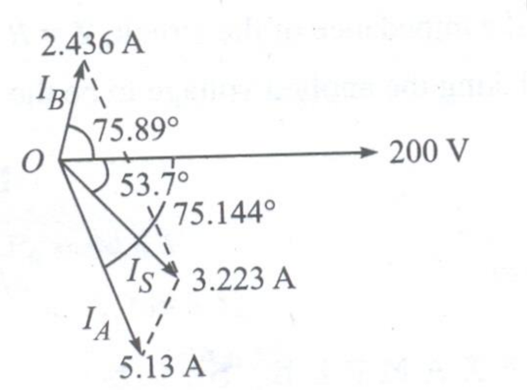
$I_B = V/Z_B = 200\angle 0^0 / (20 - j79.6) = (0.594 + j2.363)\ A = 2.436\angle 75.89^0$

(ii) $I_S = I_A + I_B = (1.3147 - j4.96) + (0.594 + j2.363)$

$= (1.9087 - j2.597)\ A = 3.223\angle -53.7^0$

(iii) Total power factor, pf = $\cos 53.7^0 = 0.592$ (lagging)

The phasor diagram is given in figure.



16. A coil of power factor 0.6 is in series with a 100μF capacitor. When connected to a 50 Hz supply, the pd across the coil is equal to the pd across the capacitor. Find the resistance and inductance of the coil.

Solution:

$X_C = 1/\omega C = 1 / 2\pi fC = 1 / (2\pi \times 50 \times 100 \times 10^{-6}) = 31.8\ \Omega$

Let the impedance of the coil be $Z = r + jX_L$, and let the current in the series circuit be I. Since the pf of the coil is 0.6 the phase angle ϕ of the coil is given as

$\phi = \cos^{-1}(0.6) = 53.13^0$

Also, we have

$X_L/r = \tan\phi \quad \rightarrow \quad X_L = (\tan 53.130)\, r = 1.333r$ ------- (i)

We are given

$V_{coil} = V_C \quad \rightarrow \quad IZ = IX_c$

Or $\sqrt{(r^2 + X_L)} = X_C \quad \rightarrow \quad r^2 + (1.333)^2 r^2 = 31.8^2 \quad \rightarrow \quad r = \mathbf{19\ \Omega}$

From eq. (i),

$X_L = 1.333r = 1.333 \times 19 = 25.33\ \Omega \quad \rightarrow \quad L = X_L / 2\pi f = 25.33 / 2\pi \times 50$

$= \mathbf{40\ .3\ mH}$

DOMESTIC WIRING:

1. 3-way control of a lamp.

The domestic lighting circuits are quite simple and they are usually controlled from one point. But in certain cases it might be necessary to control a single lamp from more than one point (Two or Three different points).

For example: staircases, long corridors, large halls etc.

Three- way Control of lamp:

In case of very long corridors it may be necessary to control the lamp from 3 different points. In such cases, the circuit connection requires two; two-way switches $\mathbf{S_1}$and $\mathbf{S_2}$ and an intermediate switch $\mathbf{S_3}$. An intermediate switch is a combination of two, two way switches coupled together. It has 4 terminals ABCD. It can be connected in two ways

a) Straight connection

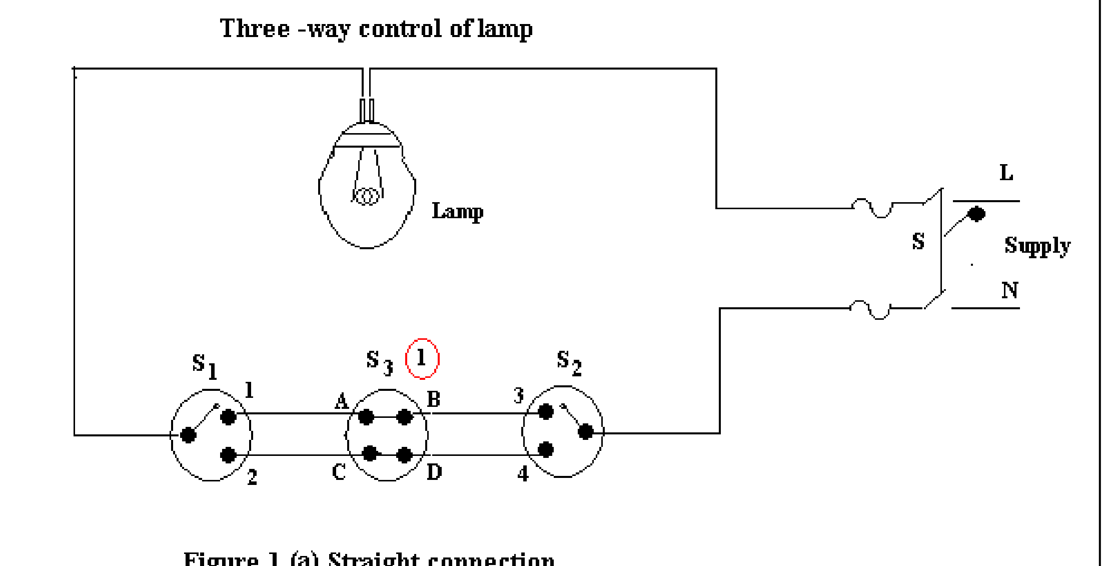


Figure 1 (a) Straight connection

b) Cross connection

In case of straight connection, the terminals or points AB and CD are connected as shown in figure (a) while in case of cross connection, the terminals AB and C D is connected as shown in figure (b). As explained in two –way control the lamp is ON if the circuit is complete and is OFF if the circuit does not form a closed loop.

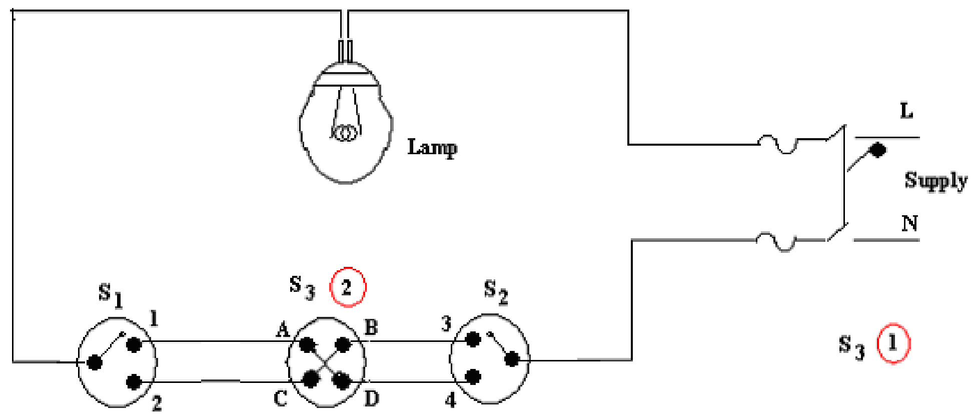


Figure 1 (b) Cross connection

The condition of the lamp is given in the table depending on the positions of the switches **S_1**, **S_2** and **S_3**.

Position of S3	Position of S1	Position of S2	Condition of the lamp
1 Straight connection	1	3	**ON**
	1	4	**OFF**
	2	3	**OFF**
	2	4	**ON**
2 **Cross connection**	1	3	**OFF**
	1	4	**ON**
	2	3	**ON**
	2	4	**OFF**

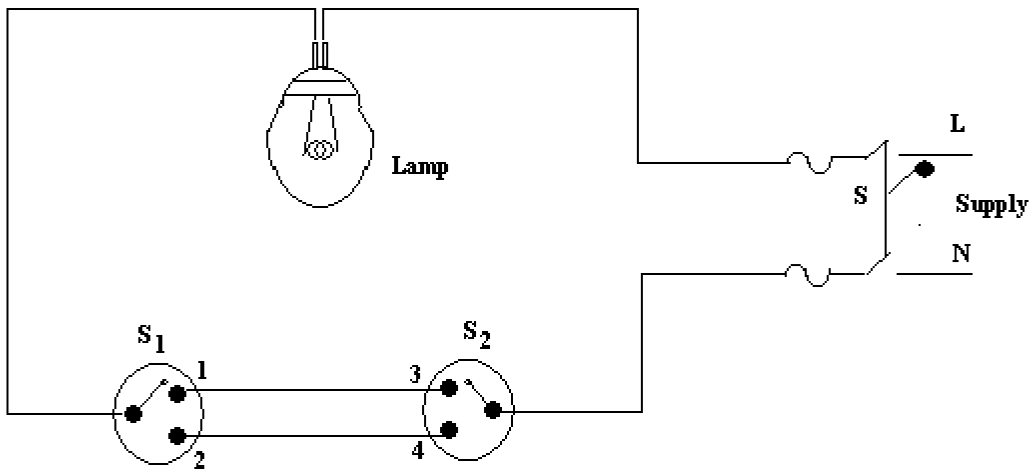
2. two-way control of lamps.

The domestic lighting circuits are quite simple and they are usually controlled from one point. But in certain cases it might be necessary to control a single lamp from more than one point (Two or Three different points).

For example: staircases, long corridors, large halls etc.

Two-way Control of lamp:

Two-way control is usually used for staircase lighting. The lamp can be controlled from two different points: one at the top and the other at the bottom - using two- way switches which strap wires interconnect. They are also used in bedrooms, big halls and large corridors. The circuit is shown in the following figure.



Two -way control of lamp

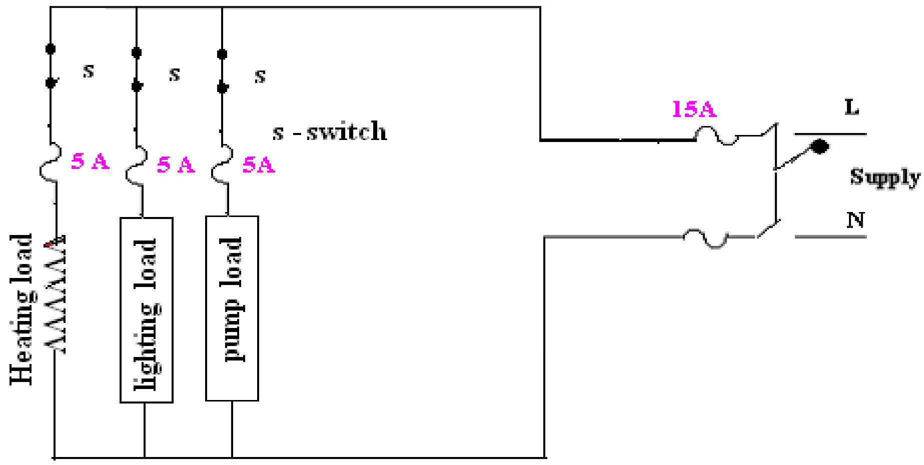
Switches S_1 and S_2 are two-way switches with a pair of terminals 1&2, and 3&4 respectively. When the switch S_1 is in position **1** and switch S_2 is in position **4**, the circuit does not form a closed loop and there is no path for the current to flow and hence the lamp will be **OFF.** When S_1 is changed to position **2** the circuit gets completed and hence the lamp glows or is **ON**. Now if S_2 is changed to position **3** with S_1 at position **2** the circuit continuity is broken and the lamp is off. Thus the lamp can be controlled from two different points.

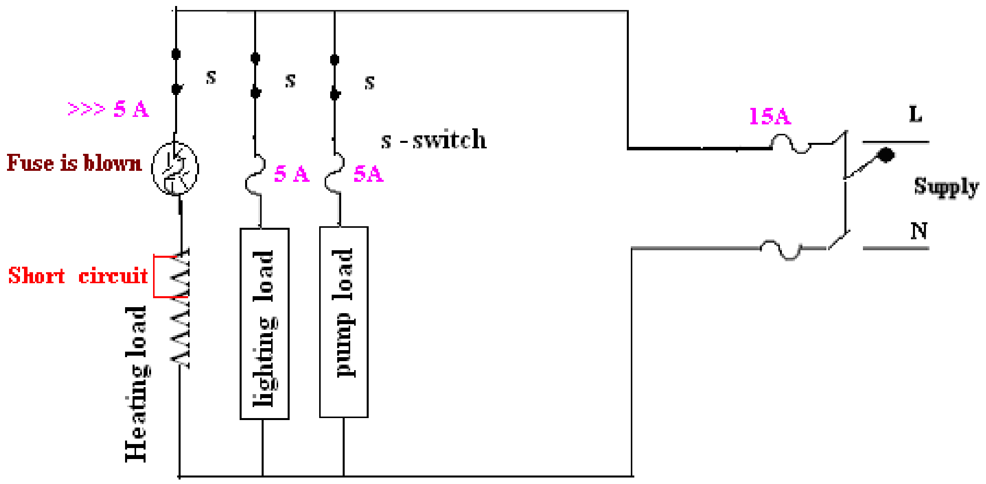
Position of S1	Position of S2	Condition of lamp
1	3	ON
1	4	OFF
2	3	OFF
2	4	ON

3. fuse &requirements of good fuse

A fuse is the simplest device used in an electrical circuit to protect against overloading or fire hazards due to short-circuits.

The electrical equipments are designed to carry a particular rated value of current under normal circumstances. Under abnormal conditions such as short circuit, overload or any fault the current raises above this value, damaging the equipment and sometimes resulting in fire hazard. Fuses are pressed into operation under such situations. Fuse is a safety device used in any electrical installation, which forms the weakest link between the supply and the load. It is a short length of wire made of lead / tin /alloy of lead and tin/ zinc having a low melting point and low ohmic losses. Under normal operating conditions it is designed to carry the full load current. If the current increases beyond this designed value due any of the reasons mentioned above, the fuse melts (said to be blown) isolating the power supply from the load as shown in the following figures.





CHARACTERISTICS OF FUSE MATERIAL:

The material used for fuse wires must have the following characteristics

1. Low melting point
2. Low ohmic losses
3. High conductivity
4. Lower rate of deterioration

4. fuse: (i) rated current, (ii) fusing current and (iii) fusing factor.

Rated current: It is the maximum current, which a fuse can carry without undue heating or melting. It depends on the following factors:

1. Permissible temperature rise of the contacts of the fuse holder and the fuse material
2. Degree of deterioration due to oxidation

Fusing current: The minimum current at which the fuse melts is known as the fusing current. It depends on the material characteristics, length, diameter, cross-sectional area of the fuse element and the type of enclosure used.

Fusing Factor: It is the ratio of the minimum fusing current to the rated current. It is always greater than unity.

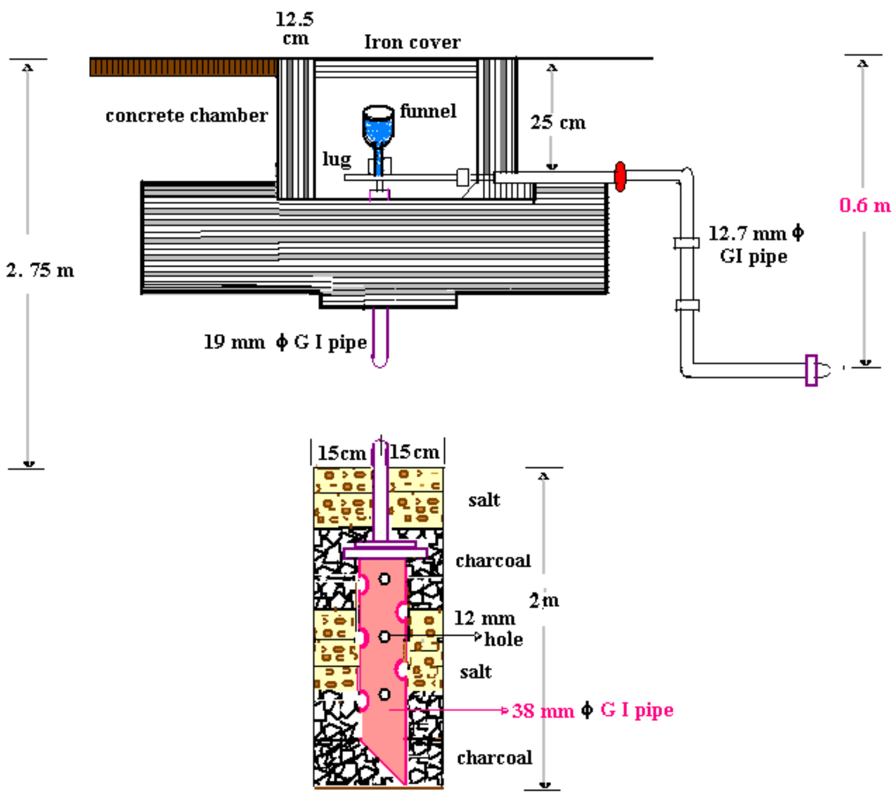
5. necessity of earthing. & pipe earthing

Necessity of Earthing:

1. To protect the operating personnel from danger of shock in case they come in contact with the charged frame due to defective insulation.
2. To maintain the line voltage constant under unbalanced load condition.
3. Protection of the equipments
4. Protection of large buildings and all machines fed from overhead lines against lightning.

Pipe Earthing:

Earth electrode made of a GI (galvanized) iron pipe of 38mm in diameter and length of 2m (depending on the current) with 12mm holes on the surface is placed upright at a depth of 4.75m in a permanently wet ground. To keep the value of the earth resistance at the desired level, the area (15 cms) surrounding the GI pipe is filled with a mixture of salt and coal.. The efficiency of the earthing system is improved by pouring water through the funnel periodically. The GI earth wires of sufficient cross- sectional area are run through a 12.7mm diameter pipe (at 60cms below) from the 19mm diameter pipe and secured tightly at the top as shown in the following figure.



PIPE EARTHING

When compared to the plate earth system the pipe earth system can carry larger leakage currents as a much larger surface area is in contact with the soil for a given electrode size. The system also enables easy maintenance as the earth wire connection is housed at the ground level.

6. earthing of electrical apparatus

The main objective of earthing is to provide safety of operation. In case, the insulation of windings placed inside the machine ever becomes weak, a part of the operating current gets diverted to the surface. When a person touches such a machine, the surface current finds a path through his body to earth. If this “leakage current” is high, the person gets shock which mat even cause death. By earthing the machine, the shock hazard is avoided as the leakage current gets an outlet to earth.

Another objective of earthing, though not widely used now-a days, is to save conducting material. The earth itself provides the return path for the current. This technique of providing return path for the current through earth in case of automobiles and electronic instruments, not so much for saving the conductor but for avoiding complications in laying the return wire.

Earthing also helps in protecting high-rise buildings from atmospheric lightning, A froked metal rod or thick wire, called lightning conductor, sticks out from the top of the building, chimney, tower, etc. Its other end is buried deep into the ground. Whenever lightning occurs, the electricity passes directly from the top of lightning conductor to the earth, thereby protecting the building from any damage.

7. safety precautions working with electricity.

a. Make sure that all metallic parts of the electrical equipments are effectively earthed.
b. Broken switches, plugs, etc., should be replaced immediately.
c. Before replacing a broken switch, plug or blown fuse, always switch off the main supply.
d. Never use equipments and appliances with damaged or frayed lead wires.
e. Never insert bare wires in the holes of a socket, for taking a connection. Always use a proper plug.
f. Always use well insulated tools.
g. Use correct rating of fuse wire.
h. Never try to connect machines or equipments to a voltage supply other than the rated one.
i. While working on an electric pole or tower, use safety-belt and a rubber padded ladder.
j. Strictly follow all the precautions and instructions given on the 'name plate' of the machine you are working.
k. Be careful that your body does not touch the wall or any other metallic frame having contact with earth.

8. Plate earthing

In this method a copper plate of 60cm x 60cm x 3.18cm or a GI plate of the size 60cm x 60cm x 6.35cm is used for earthing. The plate is placed vertically down inside the ground at a depth of 3m and is embedded in alternate layers of coal and salt for a thickness of 15 cm. In addition, water is poured for keeping the earth electrode resistance value well below a maximum of 5 ohms. The earth wire is securely bolted to the earth plate. A cement masonry chamber is built with a cast iron cover for easy regular maintenance.

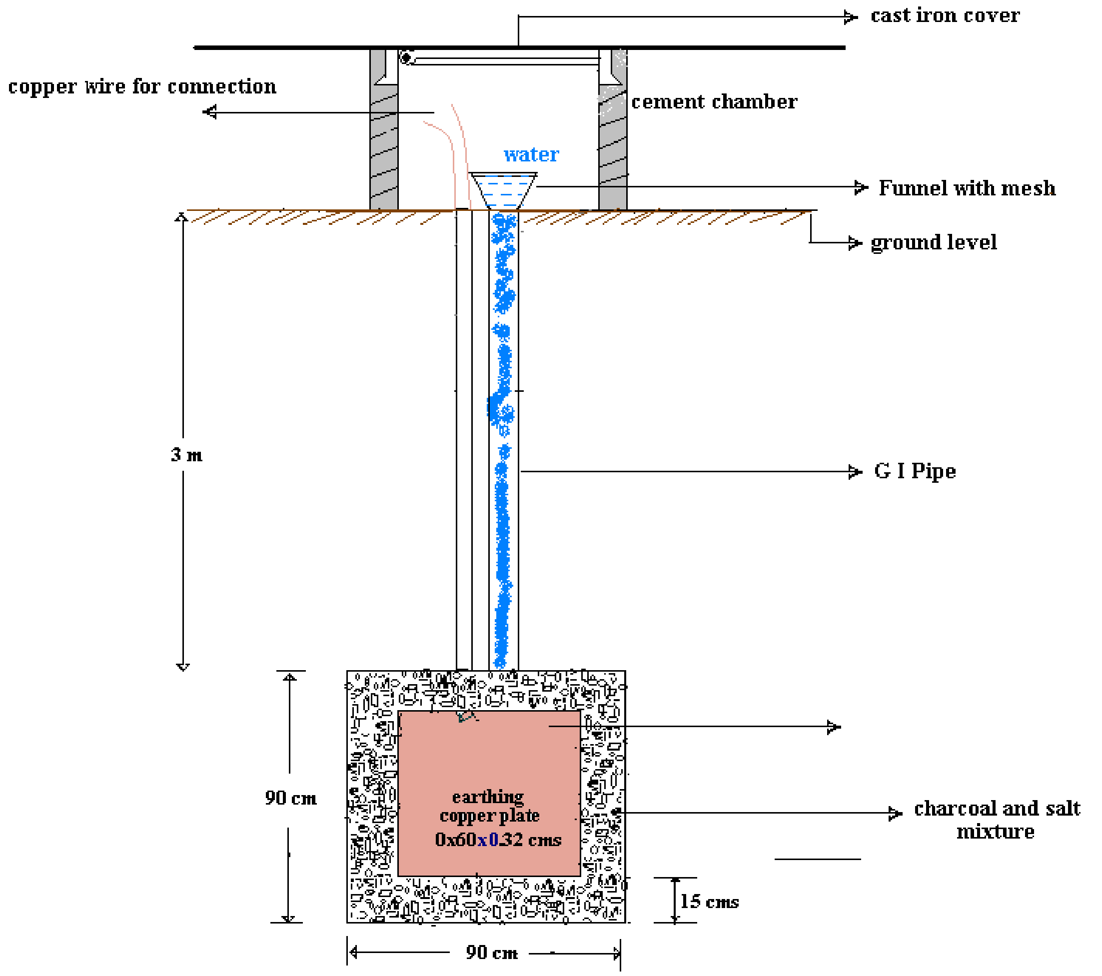


PLATE EARTHING

Module– 4

THREE PHASE CIRCUITS:

1. relationship between the line voltages and the phase voltages in a balanced 3 ϕ supply system.

Solution:

When a balanced generating supply, where the three phase voltages are equal, and the phase difference is 120^0 between one another, supplies balanced equipment load, where the impedances of the three phases or three circuit loads are equal, then the current flowing through these phases will also be equal in magnitude, and will also have a phase difference of 120^0 with one another. Such an arrangement is called a balanced load.

Relationship between Line and Phase values for balanced star connection:

Here three similar ends of the three phase coils are joined together to form a common point. Such a point is called the star point or the neutral point. The free ends of the three phase coils will be operating at specific potential with respect to the potential at the star.

Notations Defined:

E_R, E_Y, E_B : Phase voltages of R,Y and B phases.

I_R, I_Y, I_B : Phase currents

V_{RY}, V_{YB}, V_{BR} : Line voltages

I_{L1}, I_{L2}, I_{L3} : Line currents

In a balanced system,

$E_R = E_Y = E_B = E_P$ $\quad V_{RY} = V_{YB} = V_{BR} = V_L$

$I_R = I_Y = I_B = I_P$ $\quad I_{L1} = I_{L2} = I_{L3} = I_L$

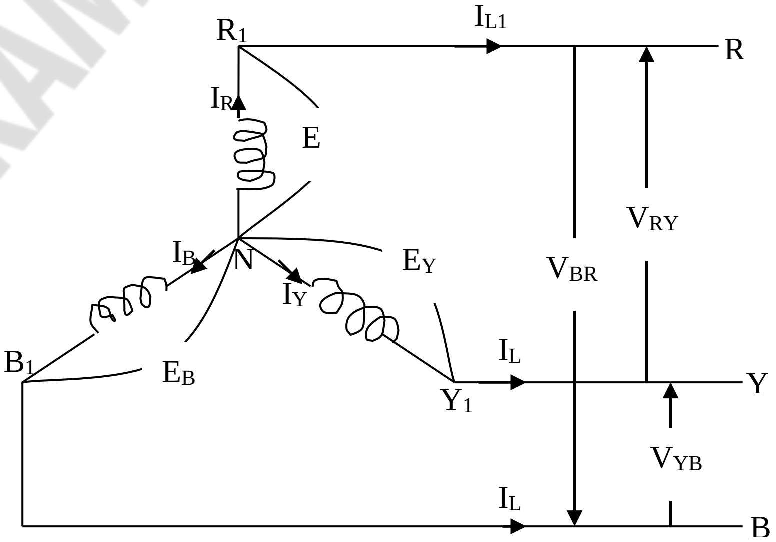


FIGURE: (a)

Current Relationship:

Applying Kirchoff's current law at nodes R_1, Y_1, B_1 we get

$I_R = I_{L1}$; $I_Y = I_{L2}$; $I_B = I_{L3}$.

This means that in a balanced star connected system, phase current equal the line current.

$I_P = I_L$

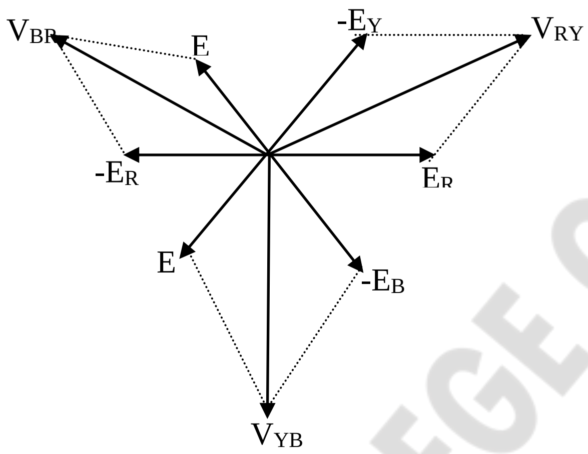


FIGURE: (b)

Voltage Relationship:

Let us apply Kirchoff's voltage law to the loop consisting of voltages E_R, V_{RY} and E_y. We have

$E_R - E_Y = V_{RY}$

Using law of parallelogram,

$V_{RY} = \sqrt{(E_R^2 + E_Y^2 + 2\, E_R E_Y \cos 60^0)}$

Similarly,

$E_Y - E_B = V_{YB}$ and $E_B - E_R = V_{BR}$

Therefore, $V_{YB} = E_P\sqrt{3}$ and $V_{BR} = E_P\sqrt{3}$

Thus, $V_L = \sqrt{3}\quad E_P$

Line voltage = √3 phase voltage

2. power factor on wattmeter reading in a two wattmeter method of measuring power of a 3 ϕ circuit.

Solution:

Case I: Lagging Power Factor

We know that, In the two-wattmeter method,

$W_1 = E_L I_L \cos(30^0 - \Phi)$ and $W_2 = E_L I_L \cos(30^0 + \Phi)$

$W_1 + W_2 = E_L I_L \cos(30^0 - \Phi) + E_L I_L \cos(30^0 + \Phi)$

$= \sqrt{3}\, E_L I_L \cos\Phi$ -------- (i)

Similarly, $W_1 - W_2 = E_L I_L \cos(30^0 - \Phi) - E_L I_L \cos(30^0 + \Phi)$

$= E_L I_L\, (2 \times \sin\Phi \times ½)$

$= E_L I_L \sin\Phi$ ---------- (ii)

Dividing equation (ii) by (i), we get

$$\tan\Phi = \sqrt{3}\, [(W_1 - W_2) / (W_1 + W_2)]$$

Case II: Leading Power factor

For leading power factor,

$W_1 = E_L I_L \cos(30^0 + \Phi)$ and $W_2 = E_L I_L \cos(30^0 - \Phi)$

$W_1 + W_2 = E_L I_L \cos(30^0 + \Phi) + E_L I_L \cos(30^0 - \Phi)$

$= \sqrt{3}\, E_L I_L \cos\Phi$

$W_1 - W_2 = - E_L I_L \sin\Phi$

Therefore, $\tan\Phi = -\sqrt{3}\, [(W_1 - W_2) / (W_1 + W_2)]$

3. advantages of three phase system

Necessity of Three Phase system:

The earliest application of ac current was for heating the filament of an electric lamp. For this purpose, the single-phase system was quite satisfactory. Some years later, ac motors were developed. It was found that single-phase ac supply was not very satisfactory for this application. For instance, the single-phase induction motor – the type most commonly used – was not self-starting unless it was fitted with an auxiliary winding. It was found that by using two separate windings with currents differing in phase by 90^0 or three windings with currents differing in phase by 120^0, the induction motor becomes self-starting, had better efficiency and power factor.

The system utilizing two windings is referred to as a two-phase system and that utilizing three windings is referred to as a three-phase system.

Almost all the electrical power used in the country is generated and distributed in the form of three-phase ac supply. The single-phase ac supply used in houses, offices, factories, etc., originates as a part of 3-phase system.

Advantages of Three-Phase system:

1. Three-phase transmission lines require much less conductor material. Since sum of currents in all the phases is zero, there is substantial saving by eliminating the return conductor or replacing it by a single neutral conductor of comparatively small size.
2. For a given frame size, a three-phase machine gives a higher output than a single-phase machine.
3. The power in a single-phase pulsates at twice the line frequency. However, the sum of powers in the three phases in a three-phase system remains constant. Therefore, a three-phase motor develops a uniform torque, whereas a single-phase motor develops pulsating torque.

4. Since the three-phase supply can generate a rotating field, the three-phase induction motors are self-starting.
5. The three-phase system can be used to supply domestic as well as industrial (or commercial) power.
6. The voltage regulation in three-phase system is better than that in single-phase supply.

4. two wattmeter are sufficient to measure power in 3 ϕ balanced, star-connected circuit

Measurement of power in a 3-phase circuit by Two Wattmeter method:

This method is normally used for measuring power, in 3-phase, 3-wire balanced load circuits. In this we analyze the measurement of power when the load is star connected. The following assumptions are made:

(i) The three-phase supply to which the load is connected, is balanced.

(ii) The phase sequence is R, Y, B

(iii) The load is balanced

(iv) The load is R – L in nature.

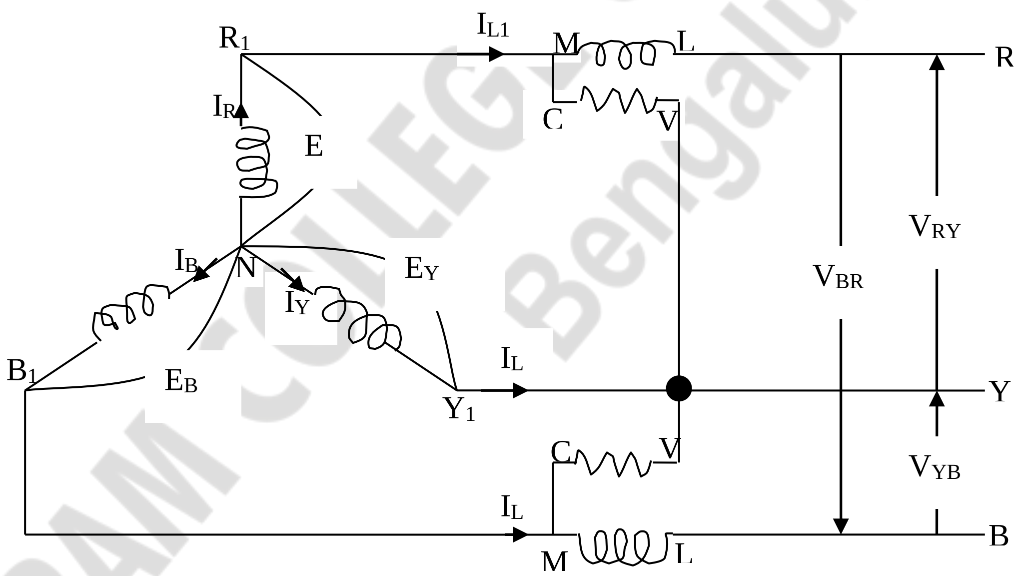


FIGURE: (a)

For Wattmeter 1:

Current measured = $I_{L1} = I_R$

Voltage measured = V_{RY}

Phase angle between them = $30^0 + \Phi$

Power measured $= P_1 = V_{RY}\, I_R \cos(30^0 + \Phi)$

$= V_L\, I_L \cos(30^0 + \Phi)$

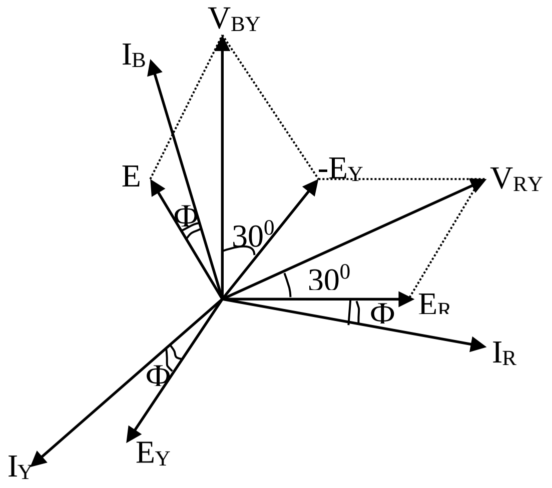


Figure: (b)

For Wattmeter 2:

Current measured = $I_{L3} = I_B$

Voltage measured = V_{BY}

Phase angle between them = $30^0 – \Phi$

Power measured = $P_2 = V_{RY}\, I_R \cos (30^0 - \Phi)$

$= V_L\, I_L \cos (30^0 - \Phi)$

Now, $P_1 + P_2 = V_L\, I_L \cos (30^0 + \Phi) + V_L\, I_L \cos (30^0 - \Phi)$

$= V_L\, I_L\, [\cos 30^0 \cos \Phi – \sin 30^0 \sin \Phi + \cos 30^0 \cos \Phi – \sin 30^0 \sin \Phi]$

$= V_L I_L\, 2. \sqrt{3} / 2 . \cos \Phi$

$= \sqrt{3}\, V_L I_L \cos \Phi$ = Total power in a 3-phase circuit

Thus, two wattmeters connected appropriately in a 3-phase circuit can measure the total power consumed in the circuit.

5. relationship between the phase and line values of voltages and current in a balanced, 3 ϕ delta-connected systems.

Measurement of power in a 3-phase circuit by Two Wattmeter method:

This method is normally used for measuring power, in 3-phase, 3-wire balanced load circuits. In this we analyze the measurement of power when the load is delta connected. The following assumptions are made:

(i) The three-phase supply to which the load is connected, is balanced.

(ii) The phase sequence is R, Y, B

(iii) The load is balanced

(iv) The load is R – L in nature.

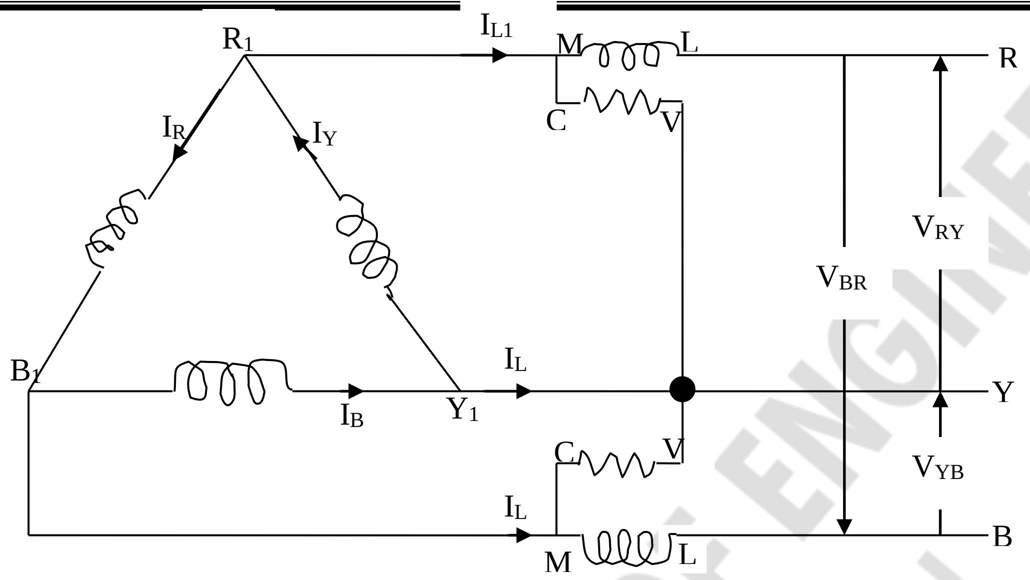


FIGURE: (a)

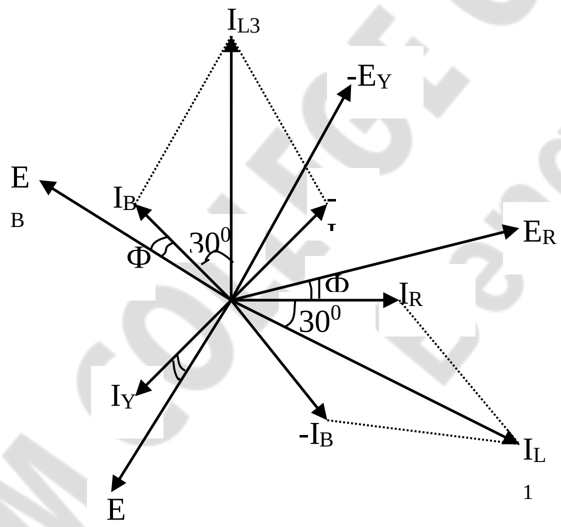


Figure: (b)

For Wattmeter 1:

Current measured = $I_{L1} = I_R - I_B$

Voltage measured = $V_{RY} = E_R$

Phase angle between them = $30^0 + \Phi$

Power measured = $P_1 = V_{RY}\, I_{L1} \cos(30^0 + \Phi)$

For Wattmeter 2:

Current measured = $I_{L3} = I_B - I_Y$

Voltage measured = $V_{BY} = -E_Y$

Phase angle between them = $30^0 - \Phi$

Power measured = $P_2 = E_B\, I_{L3} \cos(30^0 - \Phi)$

$= V_L I_L \cos(30^0 - \Phi)$

Now, $P_1 + P_2 = V_L I_L \cos(30^0 + \Phi) + V_L I_L \cos(30^0 - \Phi)$

$= V_L I_L [\cos 30^0 \cos \Phi – \sin 30^0 \sin \Phi + \cos 30^0 \cos \Phi – \sin 30^0 \sin \Phi]$

$= V_L I_L \, 2. \sqrt{3} / 2 . \cos \Phi$

$= \sqrt{3}\, V_L I_L \cos \Phi$ = Total power in a 3-phase circuit

Thus, two wattmeters connected appropriately in a 3-phase circuit can measure the total power consumed in the circuit.

6. The power flowing in a 3 ϕ, 3-wire balanced load system is measured by two-wattmeter method. The reading in wattmeter A is 750 W and wattmeter B is 1500 W, What is the power factor of the system.

Solution:

The readings of both the wattmeters are positive. Either of them can be taken as W_1 or W_2. Taking $W_1 = 1500$ W and $W_2 = 750$ W. the phase angle is given by

$\tan\phi = \sqrt{3}\,[(W_1 – W_2) / (W_1 + W_2)] = \sqrt{3}\,[(1500 – 750) / (1500 +750)]$

$= 0.577 \quad \rightarrow \quad \phi = \tan^{-1} 0.577 = 30^0$

Therefore, the power factor is pf = $\cos 30^0$ = **0.866**

7. A three phase load consisting of the three equal impedances connected in a delta across a balanced 400 ϕ supply takes a line current of 10 A and a power of o.7 lagging. Calculate from the first principles (i) the phase current, (ii) the total power, and (iii) the tota; reactive KVA. If the three loads were connected in star, what would be the phase current and total power?

Solution:

(a) For delta-connected load, $V_L = 400$ V, $I_L = 10$ A

(i) The phase current, $I_{ph} = I_L / \sqrt{3} = 10 / \sqrt{3} =$ **5.77 A**

(ii) The total power, $P = \sqrt{3}\, V_L I_L \cos \phi = \sqrt{3} \times 400 \times 10 \times 0.7 =$ **4850 W**

(iii) Pf = $\cos \phi = 0.7 \quad \rightarrow \quad \sin \phi = \sqrt{(1 – \cos^2 \phi)} = 0.714$

The total reactive kVA = $\sqrt{3}\, V_L I_L \sin \phi = \sqrt{3} \times 400 \times 10 \times 0.714$ VA

= **4.947 kVA**

(b) For star connected load, $V_L = 400 \text{ V} \rightarrow V_{ph} = V_L / \sqrt{3} = 400/\sqrt{3} = 231$ V

The line current I_L will no longer remain the same as 10 A. To calculate the new value of I_L, we first find the Z_{ph} from the data given above for the delta-connected circuit,

$Z_{ph} = V_{ph} / I_{ph} = 400/5.77 = 69.3\ \Omega$

(i) Whether the circuit is connected in delta or star, the impedance Z_{ph} remains the same. Therefore, for the star-connected load,

$I_{ph} = V_{ph}/I_{ph} = 231/69.3 =$ **3.33 A** $\rightarrow \quad I_L = I_{ph} = 3.33$ A

(ii) The total Power , $P = \sqrt{3}\, V_L I_L \cos\phi = \sqrt{3} \times 400 \times 3.33 \times 0.7$

$= \mathbf{1617\ W}$

8. Calculate the active and reactive components of each phase of Y-connected 10 kV, 3-phase alternator supplying 5 MW at 0.8 pf. If total current remains the same, when load pf is raised to 0.9, calculate the new output and its active and reactive components per phase.

Solution:

(i) Given: P = 5 MW, $pf_1 = \cos\phi_1 = 0.8$, $V_L = 10$ kV, star-connected.

$\sin\phi_1 = \sqrt{(1-\cos^2\phi_1)} = \sqrt{(1 - 0.8^2)} = 0.6$

Since $P = \sqrt{3}\, V_L I_L \cos\phi_1 \rightarrow I_L = P / (\sqrt{3}\, V_L \cos\phi_1)$

$= 5 \times 10^6 / (\sqrt{3} \times 10 \times 10^3 \times 0.8)$

$= 360.8\ A = I_{ph}$

$V_{ph} = V_L / \sqrt{3} = 10kV / \sqrt{3} = 5.77\ kV$

Active component of each phase

$= V_{ph} I_{ph} \cos\phi_1 = 5.77 \times 360.8 \times 0.8 = 1665\ kW = \mathbf{1.665\ MW}$

Reactive component of each phase

$= V_{ph} I_{ph} \sin\phi_1 = 5.77 \times 360.8 \times 0.6 = 1249\ kVAR = \mathbf{1.249\ MVAR}$

(ii) Next, total current remaining the same, the pf is raised to 0.9. Thus,

$Pf_2 = \cos\phi_2 = 0.9 \quad \rightarrow \quad \sin\phi_2 = \sqrt{(1-\cos^2\phi_2)} = 0.436$

Therefore, $P = \sqrt{3}\, V_L I_L \cos\phi_1 = \sqrt{3} \times 10 \times 10^3 \times 360.8 \times 0.9 = \mathbf{5.624\ MW}$

Active component of each phase

$= V_{ph} I_{ph} \cos\phi_1 = 5.77 \times 360.8 \times 0.9 = 1874\ kW = \mathbf{1.874\ MW}$

Reactive component of each phase

$= V_{ph} I_{ph} \sin\phi_1 = 5.77 \times 360.8 \times 0.436 = 907.7\ kVAR = \mathbf{0.9077\ MVAR}$

9. Three similar coils each having resistance of 10 ohms and reactance of 8 ohms are connected in star across a 400 V, 3-phase supply. Determine (i) the line current, and (ii) the reading of each of the two wattmeter connected to measure the power.

Solution:

Given: $R = 10\Omega$, $X_L = 8\ \Omega$, $V_L = 400$ V, star connected load.

$Z_{ph} = (10 + j8)\ \Omega = 12.8\angle 38.6^0\ \Omega$; $V_{ph} = V_L / \sqrt{3} = 400/\sqrt{3} = 231$ V

Therefore, $I_{ph} = V_{ph} / Z_{ph} = 231/12.8 = 18$ A

(i) The line current, $I_L = I_{ph} = \mathbf{18\ A}$

(ii) The total power, $P = \sqrt{3}\, V_L I_L \cos\phi = \sqrt{3} \times 400 \times 18 \times \cos 38.6^0 = \mathbf{9746\ W}$

(iii) The readings of the two wattmeters,

$W_1 = V_L I_L \cos(30^0 - \phi) = 400 \times 18 \times \cos(30^0 - 38.6^0) = \mathbf{7119\ W}$

$$W_2 = V_L I_L \cos(30^0 + \phi) = 400 \times 18 \times \cos(30^0 + 38.6^0) = \mathbf{2627\ W}$$

10. A balanced three-phase, star connected load draws power from a 440 V supply. The two wattmeters connected indicated W_1 = 5 kW and W_2 = 1.2 kW. Calculate the power, power factor and current in the circuit.

Solution:

Given: V_L = 440 V, star connected, load, W_1 = 5 kW, W_2 = 1.2 kW.

The power, $P = W_1 + W_2 = 5 + 1.2 =$ **6.2 kW**

The load phase angle ϕ is given by

$$\tan\Phi = \sqrt{3}\,[(W_1 - W_2) / (W_1 + W_2)] = \sqrt{3}\,[(5-1.2) / (5+1.2) = 1.062$$

$$\Phi = \tan^{-1} 1.062 = 46.7^0$$

Therefore, $pf = \cos\Phi = \cos 46.7^0 =$ **0.686**

$V_{ph} = V_L / \sqrt{3} = 440/\sqrt{3} = 254$ V and

$P_{ph} = V_{ph} I_{ph} \cos\Phi$

Therefore, line current, $I_L = I_{ph} = P_{ph} / V_{ph} \cos\Phi$

$$= (2.067 \times 10^3) / (2.54 \times 0.686) = \mathbf{11.86\ A}$$

11. Three similar coils are connected in delta across a 3-phase supply. The two wattmeters connected to measure the input power indicate 12kW and 7 kW. Calculate (i)the power input (ii) the power factor of the load.

Solution:

Given: W_1 = 12 kW and W_2 = 7 kW

(i) The power input , $P = W_1 + W_2 = 12 + 7 = 19$ kW

(ii) The load phase angle Φ is given by

$$\tan\Phi = \sqrt{3}\,[(W_1 - W_2) / (W_1 + W_2)] = \sqrt{3}\,[(12-7) / (12+7) = 0.456$$

$$\Phi = \tan^{-1} 0.456 = 24.5^0$$

Therefore, $pf = \cos\Phi = \cos 24.5^0 =$ **0.91**

12. The power output to a 2000 V, 50 Hz, 3-phase motor running on full load at an efficiency of 90% is measured by two wattmeters which indicate 300kW and 100kW respectively. Calculate (i) the input, (ii) the power factor, (iii)the line current and (iv) H.P. Output.

Solution:

Given: W_1 = 300 kW , W_2 = 100 kW, E_L = 2000 V , f = 50 Hz, full load efficiency = 90%

(i) Power input to the motor = $W_1 + W_2 = 300 + 100 =$ **400 kW**

(ii) Now, $\tan\Phi = \sqrt{3}\,[(W_1 - W_2) / (W_1 + W_2)] = \sqrt{3}\,[(300-100) / (300+100) = 0.866$

Therefore, $\Phi = \tan^{-1} 0.866 = 40.9^0$

Therefore, Power factor, $\cos\Phi =$ **0.7559**

(iii) 3-Phase power $P = \sqrt{3}\, V_L\, I_L \cos\phi$

$$I_L = 400 \times 10^3 / (\sqrt{3} \times 2000 \times 0.7559) = \mathbf{152.76\ A}$$

(iii) Output of the motor = Input x efficiency

= 400 x 0.9 kW

= 400 x 0.9 / 0.7355 HP

= **489.46 HP**

13. A 440 V, 3-phase a.c motor has an output of 80 HP with an efficiency of 90% and power factor 0.866. Calculate (i) the current in each phase of the motor, if the motor is delta-connected, (ii) the readings of two wattmeters connected in the lines to measure the input power.

Solution:

Given: E_L = 440 V, Motor output = 80 HP

Motor efficiency = 90%, P.f = 0.866

(i) Motor output = 80 HP = 80 x 735.5 W

Therefore, Input to the motor = Motor output / efficiency = 80 x 735.5 / 0.9

= 65,377.78 watts

Power input to 3-phase motor is given as

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

Or Line current $I_L = P / (\sqrt{3}\ I_L \cos\phi) = 65377.78 / (\sqrt{3} \times 440 \times 0.866)$

= 99 A

As the motor is delta connected, phase current $I_p = I_l / \sqrt{3} = 99 / \sqrt{3} = 57.2$ A

(ii) If W_1 and W_2 are readings of the wattmeters connected in the lines to measure the input power, we have

Input power = $W_1 + W_2$ = 65,377.78 watts --------(i)

Power factor $\cos\phi = 0.866$

Therefore, $\phi = 30^0$ and $\tan\phi = \tan 30^0 = 0.5774$

Now, $\tan\phi = \sqrt{3}\,[(W_1 - W_2) / (W_1 + W_2)]$

$0.5774 = \sqrt{3}\,[(W_1 - W_2) / (65377.78)]$

Or $W_1 - W_2 = 21{,}794.5$ -------(ii)

Solving eqns. (i) and (ii) we have

W_1 = 43586.14 watts

W_2 = 21,791.64 watts

THREEPHASE SYNCHRONOUS GENERATORS:

Important Questions with Answer

1. Principle &constructional features of a 3ϕ alternator.

Principle:

Whenever a coil is rotated in a magnetic field an EMF will be induced in the coil. This is called the dynamically induced EMF. Alternators are working on the principle of electromagnetic induction. It is an electrical machine, which converts mechanical energy into electrical energy.

Alternators are also called as Synchronous Generators due to the reason that under normal conditions the generator is to be rotated at a definite speed called "**SYNCHRONOUS SPEED**", Ns rpm in order to have a fixed frequency in the output EMF wave.

Ns is related with the frequency as $N_s = 120f / p$, where f is the frequency and

p is the total number of poles.

Construction:

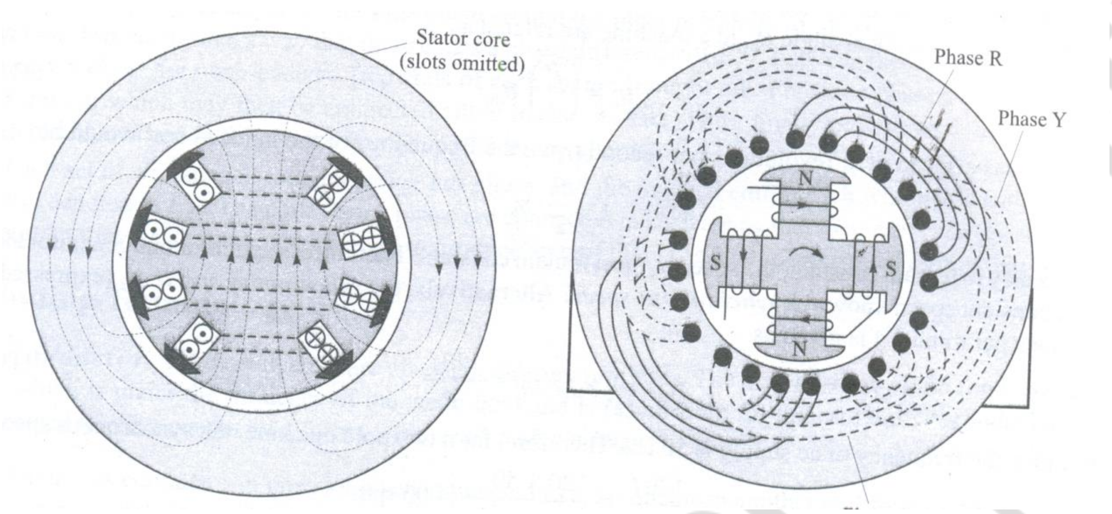
An alternator consists of a three phase armature windings mounted on the stator and field windings mounted on the rotor to provide the required magnetic field.

Stator:

The stator is a cast iron frame that supports the armature core, slotted made of special magnetic iron or steel alloy and laminated to minimize the core loss. In a three-phase alternator, there are three star-connected armature windings. The three ends of the armature windings are brought out and connected to the fixed terminals.

Rotor:

The rotor is the rotating part with N-S poles attached to it. This is supplied with a DC voltage. There are two types of rotors in use: salient or projecting pole rotor and smooth cylindrical or non-salient pole rotor.



b. Salient pole rotor:

This is used in low and medium speed alternators. The rotor core is cylindrical and made up of cast steel. The main poles are of projecting type, rigidly fixed to the rotor core. The series connected field coils are wound on the pole cores. An alternator with such a rotor structure is as shown in fig.. Excitation to field coils is provided via slip rings and brushes. This type of rotor is characterized by a larger diameter and smaller axial length. Hence, the rotor can run only at low speeds.

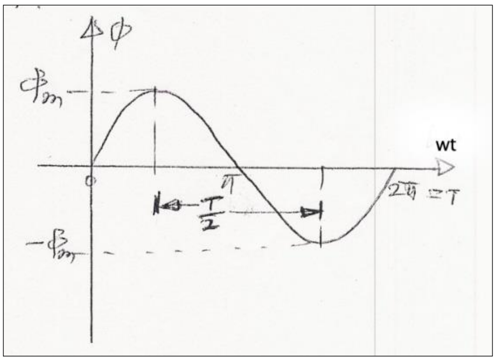
c. Non-salient pole rotor:

This is used in high-speed alternators. The rotor consists of a smooth solid forged-steel cylindrical having a no. of slots, to accommodate field coils. The excitation is supplied to the field coils through brushes and slip rings. The cylindrical rotor is characterized by smaller diameter and larger axial length. This makes the rotor to run at high speeds. An alternator with such a rotor structure is as shown in fig..

2. emf equation of ac generator.

Let,

p	-	number of poles
N	-	speed of rotor in rpm
Z	-	number of conductors in series / ph
Tph	-	number of turns / ph = Zph / 2
f	-	frequency of the induced emf in Hz
Φ	-	flux per pole in wb considered to be sinusoidally distributed
Kd	-	distribution factor
Kp or Kc	-	pitch factor or coil span factor
Kf	-	form factor (1.11 for sinusoidal wave form)



Total flux cut by one conductor in one rotation = $p\,\phi$ wb

Time for one full rotation = 1 / N minutes = 60 / N sec

Rate of change of flux by one conductor = $d\Phi / dt = p\,\phi / (60 / N)$

As we know that the induced emf is due to the rate of change of flux cut by coils, the average induced emf in Z conductors / ph is

$E_{avg} = \Phi Z p N / 60$ volts

As frequency $f = p N / 120$, the average induced emf $= 2 f Z \phi$ volts. $= 2f\ (2 T_{ph})\ \phi$ volts

$$E_{avg} = 4 f \phi T_{ph} \text{ volts}$$

For a sine wave, form factor = 1.11= Erms / Eavg.

Therefore, rms value of induced emf, Erms = 1.11.Eavg.

$E_{rms} = 4.44 f \Phi T_{ph}$ volts per phase. . . . .(1)

If the armature windings are connected in star, the line emf is $E_L = \sqrt{3}$ Eph.

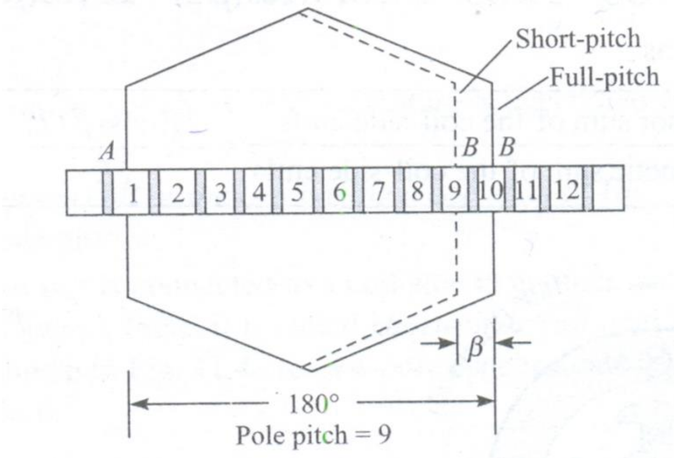
If the armature windings are connected in delta, the line emf is E_L = Eph.

Equation (1) represents the theoretical value of the induced emf in each phase but in practice the Induced emf will be slightly less than the theoretical value due to the following reasons:

(i) The armature windings are distributed throughout the armature in various slots and this is accounted by a factor called the "Distribution factor" Kd and is given by

$K_d = (\sin (m \beta / 2) / m\sin (\beta / 2))$, where m is the number of slots per pole peer phase and β is the slot angle.

$\beta = 180^0$ / no. of slots per pole



(ii) The span of the armature coil is less than a full pitch – This is done deliberately to eliminate some unwanted harmonics in the emf wave, this fact is accounted by a factor called the coil span factor or the pitch factor, Kp and is given by

Kp = Cos (α / 2), where α is the angle by which the coils are short chorded.

The modified Emf equation with these two factors taken into account will be

Eph = 4.44 f Φ Tph .Kp Kd. volts

The product of Kd and Kp is called as the winding factor Kw. which is of value around 0.95.

3. advantages of having stationary armature and rotating field system in an alternator.

The following are the advantages of having the stationary armature:

- Insulation of stationary armature conductors working at high voltage is easier.
- Tapping of electrical energy from a stationary armature is simpler.
- The use of slip rings and brushes are eliminated as the load is directly connected to the alternator terminals.
- The machine can operate at higher speeds enabling a larger output from the alternator.
- Providing ventilation for cooling of the armature conductors is much easier in stator rotor.

4. construction of projected and cylindrical pole alternator.

- **Salient pole rotor:**

This is used in low and medium speed alternators. The rotor core is cylindrical and made up of cast steel. The main poles are of projecting type, rigidly fixed to the rotor core. The series connected field coils are wound on the pole cores. An alternator with such a rotor structure is as shown in fig.. Excitation to field coils is provided via slip rings and brushes. This type of rotor is characterized by a larger diameter and smaller axial length. Hence, the rotor can run only at low speeds.

- **Non-salient pole rotor:**

This is used in high-speed alternators. The rotor consists of a smooth solid forged-steel cylindrical having a no. of slots, to accommodate field coils. The excitation is supplied to the field coils through brushes and slip rings. The cylindrical rotor is characterized by smaller diameter and larger axial length. This makes the rotor to run at high speeds. An alternator with such a rotor structure is as shown in fig..

5. Differentiate between the two types of rotors of synchronous generators.

Cylindrical or Non-Salient pole Type	**Projected or Salient pole Type**
1. Consists of a smooth solid forged-steel cylindrical having a no. of slots.	Main poles are of projecting type, rigidly fixed. Poles are projected out from the surface.
2. Field winding in the slots; unslotted portions act as poles.	Field winding on the projected poles.
3. Characterized by smaller diameter and larger axial length.	Characterized by larger diameter and smaller axial length.
4. Uniform air gap due to smooth cylindrical surface.	Non-uniform air gap.
5. Steam turbines are used as prime movers.	Water turbines are used as prime movers.
6. Works efficiently at high speeds.	Works efficiently at low speeds.
7. Smaller number (2 0r 4) of poles.	Larger number (30 0r 36) of poles.
8. Used in high-speed alternators.	Used in low and medium speed alternators.

6. (i) Pitch Factor (ii) Distribution Factor

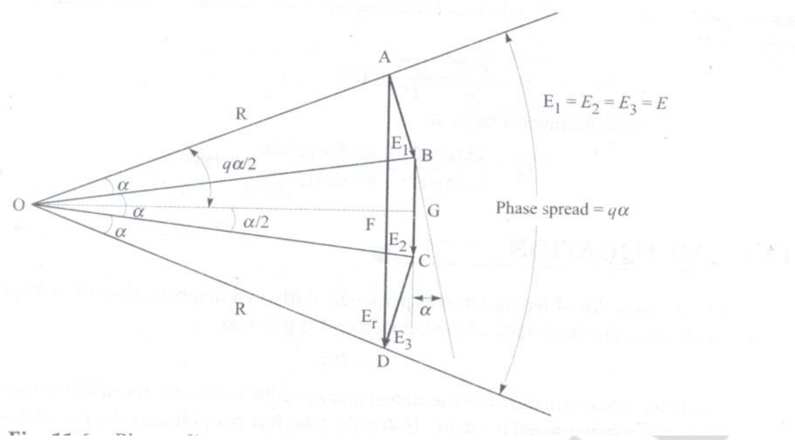
:

- **Pitch factor, Kp:**

Pitch factor or coil span factor is defined as the ratio of vector sum of the induced emfs per coil to the arithmetic sum of the induced emfs per coil (usually < 1).

Kp = Cos (α / 2)

Where α is the short pitch angle



- **Distribution factor, Kd:**

Distribution factor, Kd is defined as the ratio of vector sum of emfs of all coils under each pole to arithmetic sum of emfs, had all coils were concentrated in one slot.

Kd = Sin (m β / 2) / mSin (β / 2)

Where m is the number of slots per pole peer phase and β is the slot angle.

β = 180^0 / no. of slots per pole

7. A 3-phase, 16 pole, star-connected alternator has 144 slots on the armature periphery. Each slot contains 10 conductors. It is driven at 375 rpm. The line value of emf available across the terminals is observed to be 2.657KV. Find the frequency of the induced emf and the flux per pole.
(July 94, July 95, Feb 96, Jan 10; 08 marks)

Solution:

Given: P = 16; Ns = 375 rpm; E_L = 2.657 KV; Slots = 144; Conductors = 10;

Since Ns = 120f / P ⇒ f = PNs / 120 = (16 x 375) / 120 = 50 Hz

Since nothing is mentioned about the pitch of the winding, we assume full pitch, ie., Kp = 1

Now, the number of slots per pole, n = slots / poles = 144 / 16 = 9

The number of slots per pole per phase, m = n / no. of phases = 9 / 3 = 3

The slot angle, α = 180^o / n = 180^o / 9 = 20^o

∴ the distribution factor, Kd = Sin(mβ/2) / m Sin(β/2)

= Sin(3 x 20^o x 2) / 3 Sin(20^o x 2) = 0.9597

Total number of conductors, Z = slots x (conductors / slot) = 144 x 10 = 1440

Conductors per phase, Zph = Z / 3 = 1440 / 3 = 480

Turns per phase, Tph = Zph / 2 = 480 / 2 = 240

For star-connected armature, $E_{ph} = E_L / \sqrt{3}$ = (2.657 x 1000) / √3 = 1.534 KV

Flux per pole, Φ = E_{ph} / (4.44 f Tph Kp Kd)

= (1.534 x 1000) / (4.44 x 50 x 240 x 1 x 0.9597)

Φ = 0.03 Wb = 30 mWb

8. A 3-phase, 50 Hz, 20 pole, salient-pole alternator with star-connected stator windings has 180 slots on the stator. There and the coils are full-pitch are 8 conductors per slot. The flux per pole is 25 mWb. Assuming sinusoidally distributed flux, calculate (a) the speed (b) the generated emf per phase and (c) the line emf.

Solution:

The total number of armature conductors per phase, Zph = 180 x 8 /3 = 480

Therefore, the number of turns per phase, Tph = 480/ 2 = 240

(a) the speed, Ns = 120f / P = (120 x 50) / 20 = **300 rpm**

(b) Since the coils are full-pitch, the pitch factor, Kp = 1.

Number of slots per pole, n = 180 / 20 = 9

Slot angle, α = $180^o / n = 180^o / 9 = 20^o$

Number of slots per pole per phase, m = n / 3 = 3

∴ Kd = Sin(mβ/2) / m Sin(β/2) = $\sin(3 \times 20^o/2) / 3\sin(20^o/2)$ = 0.960

Therefore, the rms value of the generated emf per phase,

Eph = 4.44 f Φ Tph Kp Kd = 4.44 x 50 x 0.025 x 240 x 1 x 0.960 = **1278.7 V**

(c) Since the stator windings is star-connected, the line emf

E_L = √3 Eph = √3 x 1278.7 = **2214.8 V**

9. A 3-phase, 4 pole, star-connected alternator has 24 slots with 12 conductors per slot and the flux per pole of 0.1 Wb. Calculate the line emf generated when the alternator is run at 1500 rpm.

Solution:

The number of conductors in series per phase, Zph = 24 x (12/3) = 96

Number turns per phase, Tph = Zph / 2 = 96/2 = 48

Number of slots per pole, n = 24/4 = 6

Slot angle, α = $180^o/n = 180^o/6 = 30^o$

Number of slots per pole per phase, m = 6/3 = 2

∴ Kd = Sin(mβ/2) / m Sin(β/2) = $\sin(2 \times 30^o/2) / 2\sin(30^o/2)$ = 0.966

Assume full-pitched winding, the pitch factor, Kp = 1.

The frequency of the generated emf, f = PNs / 120 = (4x1500) / 120 = 50 Hz

Generated emf per phase, Eph = 4.44 f Φ Tph Kp Kd

= 4.44 x 50 x 0.1 x 48 x 1 x 0.966 = 1029.36 V

∴ for star-connected winding, the line emf generated is

E_L = √3 Eph = √3 x 1029.36 = **1783 V**

10. A 12 pole, 500 rpm, star-connected alternator has 48 slots with 15 conductors per slot. The flux per pole is 0.02 Wb and is distributed sinusoidally. The winding factor is 0.97. Calculate the line emf. (Jan 09; 04 marks)

Solution:

Conductors per slot = 15

∴ The number of conductors in series per phase, Zph = 48 x 15 / 3 = 240

Number turns per phase, Tph = Zph / 2 = 240/2 = 120

Assume full-pitched winding, the pitch factor, Kp = 1.

The frequency of the generated emf, f = PNs / 120 = (12 x 500) / 120 = 50 Hz

Generated emf per phase, Eph = 4.44 f Φ Tph Kp Kd

= 4.44 x 50 x 0.02 x 120 x 1 x 0.97 = 516.8 V

∴ for star-connected winding, the line emf generated is

E_L = √3 Eph = √3 x 516.8 = **895.1 V**

11. A 2 pole, 3-phase, alternator running at 3000 rpm has 42 slots with 2 conductors per slot. Calculate the flux per pole required to generate line voltage of 2300V.Assuming Kp = 0.956, Kd = 0.952. (July 08; 05 marks, July 10; 06 marks)

Solution:

Conductors per slot = 2

∴ The number of conductors in series per phase, Zph = 42 x 2 / 3 = 28

Number turns per phase, Tph = Zph / 2 = 28/2 = 14

The frequency of the generated emf, f = PNs / 120 = (2 x 3000) / 120 = 50 Hz

Assuming star-connected armature winding, the line emf generated is 2300V

∴ Eph = E_L / √3 = 2300 /√3 = 1327.9V

Generated emf per phase, Eph = 4.44 f Φ Tph Kp Kd

∴ Φ = Eph / 4.44 f Tph Kp Kd = 1327.9 / 4.44 x 50 x 14 x 0.956 x 0.952

= **0.4695 Wb**

12. A 3-phase, star-connected synchronous generator driven at 900 rpm is required to generate line voltage of 460V at 60 Hz on open circuit. The stator has two slots per pole per phase and 4 conductors per slot. Calculate (i) the number of poles and (ii) the useful flux per pole. (Jan 08; 08 marks)

Solution:

(i) The frequency of the generated emf, f = PNs / 120

∴ the number of poles, P = 120f / Ns = (120 x 60) / 900 = **8**

(ii) Number of slots per pole per phase, m = 2

∴ slots per pole, n = m x 3 = 2 x 3 = 6

∴ Total slots = nP = 6 x 8 = 48

Conductors per slot = 4

∴ Total number of conductors in series per phase, Zph = 48 x (4/3) = 64

Number turns per phase, Tph = Zph / 2 = 64/2 = 32

Slot angle, $\alpha = 180^o/n = 180^o/6 = 30^o$

∴ Kd = Sin(mβ/2) / m Sin(β/2) = Sin(2x30^o/2) / 2Sin(30^o/2) = 0.966

Assume full-pitched winding, the pitch factor, Kp = 1.

For star-connected armature winding, the line emf generated is 460V

∴ Eph = $E_L / \sqrt{3}$ = 460 /$\sqrt{3}$ = 265.6 V

Generated emf per phase, Eph = 4.44 f Φ Tph Kp Kd

∴ Φ = Eph / 4.44 f Tph Kp Kd = 1327.9 / 4.44 x 60 x 32 x 1 x 0.966

= **0.03226 Wb = 32.36 mWb**

13. A 3-phase, 50 Hz, 16-pole alternator with star-connected winding has 144 slots with 10 conductors per slot. The flux per pole is 24.8 mWb and is sinusoidally distributed. The coils are full-pitched. Find (i) the speed and (ii) the line emf. Assume the winding factor, Kd = 0.96 (July 09; 08 marks)

Solution:

(i) The frequency of the generated emf, f = PNs / 120

∴ Ns = 120f / P = (120 x 50) / 16 = **375 rpm**

Conductors per slot = 10

∴The number of conductors in series per phase, Zph = 144 x 10 / 3 = 720

Number turns per phase, Tph = Zph / 2 = 720/2 = 240

Assume full-pitched winding, the pitch factor, Kp = 1.

Generated emf per phase, Eph = 4.44 f Φ Tph Kp Kd

= 4.44 x 50 x 24.8 x 10^{-3} x 240 x 1 x 0.96

$= 1268.5$ V

Since the winding is star-connected, the line emf generated is

$E_L = \sqrt{3}$ Eph $= \sqrt{3} \times 1268.5 =$ **2197 V**

14. A 6 pole, 3-phase, star-connected alternator has 90 slots with 8 conductors per slot and rotates at 1000 rpm. The flux per pole is 50 mWb. Find the induced emf across its lines. Take the winding factor of 0.97. (July 07; 09 marks)

Solution:

(i) since Ns = 120f / P

$\therefore$ The frequency of the generated emf, f = PNs / 120

$= (6 \times 1000) / 120 = 50$ Hz

Conductors per slot = 10

$\therefore$ The number of conductors in series per phase, Zph = $90 \times 8 / 3 = 720$

Number turns per phase, Tph = Zph / 2 = 240/2 = 120

Assume full-pitched winding, the pitch factor, Kp = 1.

Generated emf per phase, Eph = $4.44\, f\, \Phi$ Tph Kp Kd

$= 4.44 \times 50 \times 50 \times 10^{-3} \times 120 \times 1 \times 0.97 = 1292$ V

Since the winding is star-connected, the line emf generated is

$E_L = \sqrt{3}$ Eph $= \sqrt{3} \times 1268.5 =$ **2238 V**

Module –5

SINGLE PHASE TRANSFORMERS:

INTRODUCTION:

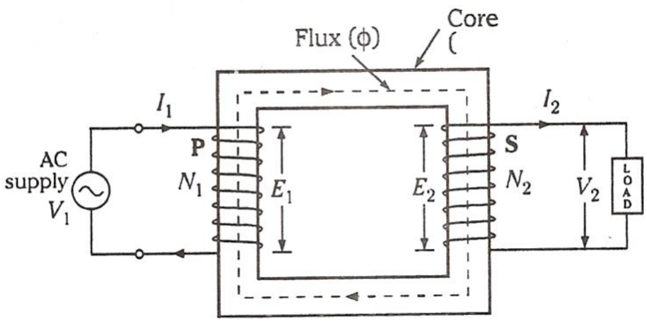
The main advantage of alternating current over direct current is that it can be easily increased or reduced as per requirement during the generation, transmission, distribution and utilization of electric power. This is made possible by means of transformers. For instance, high voltages may be generated and stepped up by means of transformers to still higher voltages for the transmission lines. Other transformers are employed at suitable points to step the voltage down to values suitable for motors, lamps, heaters and other loads, The full-load efficiency of a medium sized transformer is of the order of 97-98 percent, so that the loss at each point of transmission or distribution is small. As the transformer is a static apparatus, there are no moving parts and so the maintenance of a transformer is easy and the amount of supervision is negligible.

Transformers are associated not only with power system applications but with low power applications (such as electronic circuits) as well. However, we shall discuss only the common power-system transformer.

1) **principle of operation of a single phase transformer and e.m.f equation**

A transformer operates on the principle of electromagnetic induction as explained by faraday's law. Mutual induction states that When two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil.

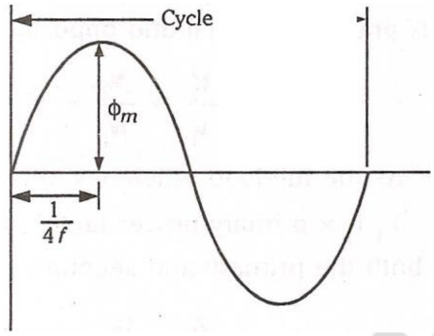
This e.m.f. can drive a current,when a closed path is provided to it. it has magnetically coupled coils .Energy transfer takes place From the primary winding to the secondary winding through the magnetic circuit which couples the two windings. The winding which Receives electrical energy is known as the primary. the winding which delivers electrical energy to the load is known as the secondary. All primary quantities are indicated with subscript 1 and all secondary quantities are indicated with subscript 2. The primary winding Has N1 number of turns while the secondary winding has N2 number of turns as shown in fig.



E.M.F. EQUATION:

When the primary winding is excited by an alternating voltage V1, it circulates alternating current, producing an alternating Flux ϕ. The primary winding has N1 number of turns .The alternating flux ϕ linking with the primary winding itself induces an e.m.f in it denoted as E1.

The flux links with the secondary winding through the common magnetic core. It pproduces induced E.M.F E2 in the secondary winding. This is mutually induced E.M.F. Let us derive the equations for E1 and E2. The primary winding is excited by purely sinusoidal alternating voltage. Hence the flux produced is also sinusoidal in nature having maximum value of ϕm as shown in the Fig 9.2



The various quantities which effect the magnitude of the induced E.M.F are:

Φ = Flux

Φm =Maximum Value Of Flux

N1 = Number of primary Winding turns

N2 =Number of secondary Winding turns

f = Frequency of the supply voltage

E1 = R.M.S value of the primary induced E.M.F

E2 = R.M.S value of the secondary induced E.M.F

From Faraday's law of electromagnetic induction the average e.m.f induced in each turn is proportional to the average rate of change of flux.

Average e.m.f per turn= Average rate of change of flux

Average e.m.f per turn= dϕ/dt

Now dϕ/dt= Change in Flux/Time required for change in flux

Consider the $1/4^{th}$ cycle of the flux as shown in the fig 9.2. Complete cycle gets completed in 1/f seconds. In $1/4^{th}$ time period, the change in flux is from 0 to ϕm.

dϕ/dt = ϕm-0/[1/4f] as dt for $1/4^{th}$ time period is 1/4f seconds

= 4fϕm Wb/sec

Average e.m.f per turn= 4 f ϕm volts

As ϕ is sinusoidal, the induced e.m.f in each turn of both the windings is also sinusoidal in nature. For sinusoidal quantity , Form factor =R.M.S value/Average Value= 1.11

R.M.S value =1.11 * Average Value

R.M.S value for induced e.m.f per turn = 1.11 * 4 f ϕm

= 4.44 f ϕm

There are N1 number of primary turns hence the R.M.S value of induced e.m.f of primary denoted as E_1 is,

E1 = N1 * 4.44 f ϕm volts

While as there are N2 number of secondary turns the R.M.S value of induced e.m.f of secondary denoted E2 is,

E2 = N2 * 4.44 f ϕm Volts

The expressions of E1 and E2 are called e.m.f equations of a transformer.

Thus e.m.f equations are,

E1 = 4.44 f ϕm N1 volts

E2 = 4.44 f ϕm N2 volts.

2. expression for the efficiency of a single phase transformer and obtain the condition for maximum efficiency?

Due to the losses in a transformer, the output power of a transformer is less than the input power supplied.

Power output = power input-Total losses

Power input= power output+Total losses

= power output +Pi+Pcu

The efficiency of any device is defined as the ratio of the power output to the power input. So for a transformer the efficiency can be expressed as,

$$\eta = \frac{\text{power output}}{\text{Power input}}$$

$$\eta = \frac{\text{power output}}{\text{Power output} + P_i + Pcu}$$

Now power output= V2 I2 COSϕ

Where COSϕ= load power factor

The transformer supplies full load of current I2 and with terminal voltage V2.

Pcu = Copper losses on full load = $I^2_2 R_{2e}$

$$\eta = \frac{V_2 I_2 COS\phi_2}{V_2 I_2 COS\phi_2 + P_i + I^2_2 R_{2e}}$$

$V_2 I_2$ = VA rating of a transformer

$$\eta = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + I_2^2 R_{2e}}$$

$$\% \eta_{F.L} = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + I_2^2 R_{2e}} \times 100 \qquad \text{Full load efficiency}$$

$$\% \eta_{F.L} = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + (P_{cu})F.L} \times 100 \qquad \text{Full load efficiency}$$

This is full load percentage efficiency with,

I_2 = Full load secondary current

But if the transformer is subjected to fractional load then using the appropriate values of various quantities, the efficiency can be obtained.

Let n=Fraction by which load is less than full load $= \frac{\text{Actual load}}{\text{Full load}}$

For example if transformer is subjected to half load then,

$$n = \frac{\text{Half Load}}{\text{Full load}} = \frac{(1/2)}{1} = 0.5$$

When load changes ,the load current changes by same proportion.

New $I_2 = n\,(I_2)F.L$

Similarly as copper losses are proportional to the square of current

New $P_{cu} = n^2\,(P_{cu})\,F.L$

So copper losses get reduced by n^2

In general for fractional load the efficiency is given by,

$$\% \eta_{F.L} = \frac{n(\text{VA rating}) \times \cos\phi}{n(\text{VA rating}) \times \cos\phi + P_i + (P_{cu})F.L} \times 100$$

where n= Fraction by which load is less than full load.

Condition for maximum efficiency:

When a transformer works on a constant input voltage and frequency then efficiency varies with the load . as load increases ,the efficiency increases at a certain load current, it achieves a maximum value. If the transformer is loaded further the efficiency starts decreasing. The graph of efficiency against load current I_2.

The load current at which the efficiency attains maximum value is denoted As I_{2m} and maximum efficiency is denoted as $\eta_{max.}$

Let us determine:

1. Condition for maximum efficiency
2. Load current at which η_{max} occurs.
3. KVA supplied at maximum efficiency.

The efficiency is a function of load .load current I_2 assuming $COS\phi_2$ constant.

The secondary terminal voltage V2 is also assumed constant. So for

Maximum Efficiency, $\frac{d\eta}{dI_2} = 0$

$$\eta = \frac{V_2 I_2 COS\phi_2}{V_2 I_2 COS\phi_2 + P_i + I^2_2 R_{2e}}$$

$$,\frac{d\eta}{dI_2} = d/dI_2 \quad \frac{[V_2 I_2 COS\phi_2]}{[V_2 I_2 COS\phi_2 + P_i + I^2_2 R_{2e}]\ dI_2} = 0$$

$$(V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}) \frac{d}{dI_2} (V_2 I_2 \ COS\phi_2) -$$

$$(V_2 I_2 COS\phi_2) . \frac{d}{dI_2} V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e} = 0$$

cancelling (V_2 $COS\phi_2$) from both the terms we get

$$V_2 I_2 COS\phi_2 + P_i + I^2_2 R_{2e} - \quad V_2 I_2 COS\phi_2 - 2 I^2_2 R_{2e} = 0$$

$$P_i - I^2_2 R_{2e} = 0$$

$$P_i = I^2_2 R_{2e} = P_{cu}$$

So condition to achieve maximum efficiency is that,

Copper losses = iron losses = $P_i = P_{cu}$

3) core type and shell type transformers

Construction of Single-Phase Transformer:

The two windings (primary and secondary) of the transformer are insulated from each and from the laminated steel core. The assembled core and the windings are enclosed in a suitable container. Appropriate bushings, either of the porcelain or the capacitor type, are used for insulating and bringing out the terminals of the windings from the enclosure.

The core is invariably constructed of transformer sheet laminations fitted together in such a way as to ensure a continuous magnetic path, with a minimum of air gap. The steel used for these laminations has high silicon content, which is sometimes heat-treated to ensure high permeability and low hysteresis loss at the usual operating flux densities.

Lamination of the core minimizes eddy current loss. These laminations are insulated from each other by a thin coating of a suitable varnish. The thickness of laminations ranges from 0.35 mm for a frequency of 25 Hz to 0.5 mm for a frequency of 50 Hz.

The lamination strips are assembled as shown in Fig. where the joints are staggered to avoid narrow gaps all through the cross-section of the core.

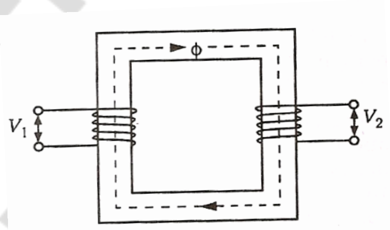


Fig. 7.2

The two main type of transformers are

i) Core-type

ii) Shell-type

(i) Core-type Transformers :

In this type of transformer, a large part of the core is surrounded by the Windings. Fig. 7.2 shows the simplified representation of a core-type transformer, where the primary and secondary windings have been shown wound on the opposite limbs. *However,* in actual practice, half the primary and half *the* secondary windings are *situated side* by *side* on *each limb,* so as to reduce *leakage flux,* as shown in Fig.

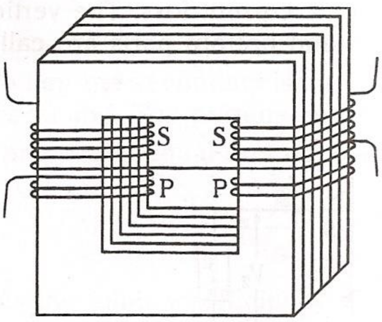


Fig. 7.3

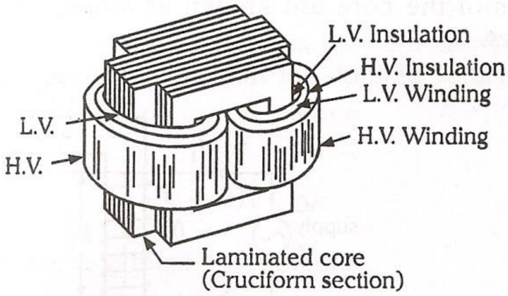


Fig. 7.4

The general form of *the* coils may be circular or oval rectangular. A rectangular core is used with cylindrical coils for small transformers. However, in the case of large-size core-type transformers, round or circular cylindrical coils are wound over a cruciform core section (as shown in Fig. 7.4), offering considerable mechanical strength. These coils are wound in helical layers, each layer being insulated from the other by using paper, cloth or cooling ducts. The net core cross-sectional area is reduced by about 10 % because of paper and other materials.

(ii) Shell-type Transformers

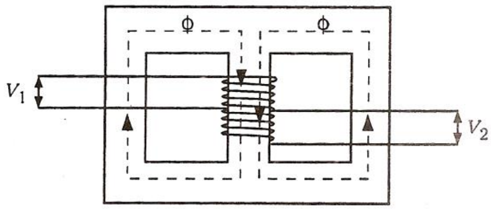


Fig. 7.5

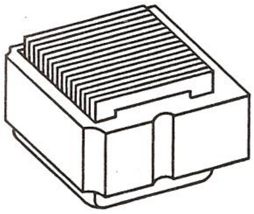


Fig. 7.6

In this type, the windings occupy a smaller portion of the core as shown schematically in Fig. The primary and secondary windings are shown located on the central limb.

The coils are form-wound in this case too; they are multilayer disc type, in the shape of pancakes. Each of these multilayer discs is insulated from the other by using paper. The entire winding comprises stacked discs with insulation spaces between the coils, such spaces forming horizontal cooling and insulating ducts. A commonly used shell-type transformer has a simple rectangular form, as shown in Fig.

4) regulation of a transformer and transformation ratio?

Definition of Voltage Regulation :

Voltage Regulation of a transformer may be defined in various ways, as given below:

Constant Primary Voltage: When a transformer is loaded with a *constant primary voltage* the secondary voltage decreases* because of the ohmic resistances and leakage reactances of the windings,

Let V_{02} = secondary terminal voltage at *no load*

$= E_2 = K E_1 = K V_1$,

because at no load the impedance drop is negligible

V_2 = secondary terminal voltage on *full-load.*

The change in secondary terminal voltage from no-load to full load is = $V_{02} - V_2$

This change divided by V_{02} is called 'regulation down'. Thus,

$$\text{Regulation down} = \frac{V_{02} - V_2}{V_{02}}$$

$$\%\ \text{Regulation down} = \frac{V_{02} - V_2}{V_{02}} \times 100$$

If this change is divided by V_2 *i.e.*, full load secondary terminal voltage, then it is known as 'regulation up'.

* Assuming lagging power factor. It will increase if power factor is leading.

Thus,

Regulation up = $\underline{V_{02} - V_2}$

$$V_2$$

$$\% \text{ Regulation up} = \frac{V_{02} - V_2}{V_2} \times 100$$

Constant Secondary Terminal Voltage V_2: When the transformer is loaded, the secondary terminal voltage falls for lagging power factor or rises for leading power factor loads.

Therefore, to keep the secondary terminal voltage constant, the primary voltage is either increased or decreased depending on the power factor of the load.

Suppose the primary voltage has to be raised from V_1 *to* V_1', then

$$\% \text{ Regulation} = \frac{V'_1 - V_1}{V_1} \times 100$$

Importance of Voltage Regulation :

In the previous Section we have defined voltage regulation under different conditions. The lesser the value of percentage voltage regulation, the better the transformer, because a good transformer should keep its secondary terminal voltage as constant as possible under all conditions of load. Such load could be machinery or equipment which need constant voltage for proper operation. Hence the importance of voltage regulation.

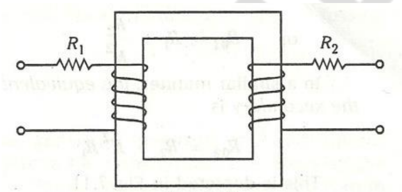


Fig. 7.9

Transfer of Transformer Winding Parameters :In the diagram of a transformer in Fig. 7.9, the resistances of the primary and secondary windings are shown as R_1 and R_2 respectively. We shall now proceed to transfer the resistances of the two windings to anyone winding. This is done to make calculations simple and easy, as we have to ideal with one winding only. The copper loss in the secondary is $1_2^2 R_2$• This loss is supplied by the primary which takes a current of *I).* Thus R_2' is the equivalent resistance in the primary which would have caused the *same* loss as R_2 in the secondary.

$$\therefore R_{01} = R_1 + R_2'$$

or $$\boldsymbol{R_{01} = R_1 + \frac{R_2}{K^2}}$$

In a similar manner, *the equivalent resistance of the transformer as referred to the secondary* is

$$\boldsymbol{R_{02} = R_2 + K^2 R_1}$$

This is depicted in Fig. 7.11.

In a similar way, leakage reactance too can be transferred (Fig. 7.12).

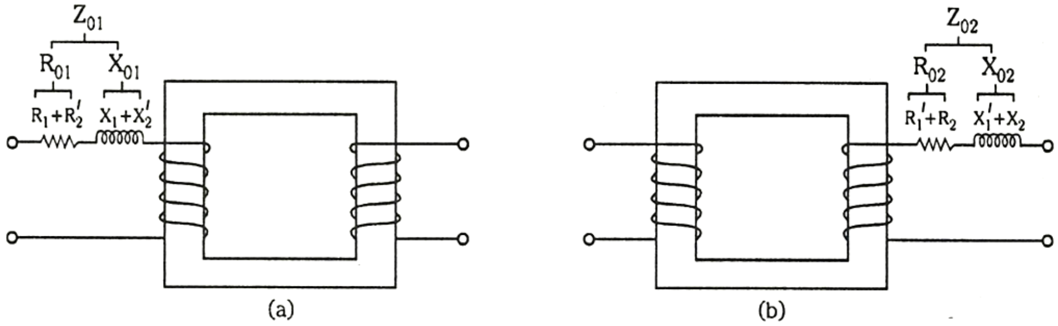


Fig. 7.12

Let X_1' be the primary reactance as referred to the secondary. The voltage drop across it when it is considered to be in the secondary = $I_2\ X_1'$. When it is in the primary, the voltage drop = $I_1\ X_1$. Keeping in mind that the voltages between the two windings are related through K, we have

$$I_2\ X_1' = K\ I_1\ X_1$$

$$\therefore \quad X_1' = K\left(\frac{I_1}{I_2}\right)X_1 = K^2\ X_1$$

Similarly, $X_2' = \dfrac{X_2}{K^2}$

$$\therefore \quad \boldsymbol{X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}}$$

and $$\boldsymbol{X_{02} = X_2 + X_1' = X_2 + K^2\ X_1}$$

Thus $I_1^2 R_2' = I_2^2 R_2$ or $R_2' = \left(\frac{I_2}{I_1}\right)^2 R_2$

We have seen that $\frac{I_2}{I_1'} = \frac{1}{K}$; however, if I_0 is neglected, $I_1' = I_1$.

In that case $\frac{I_2}{I_1} = \frac{1}{K}$

$$\therefore R_2' = \frac{R_2}{K^2}$$

In a like manner, the equivalent primary resistance as referred to the secondary is

$$R_1' = K^2 R_1$$

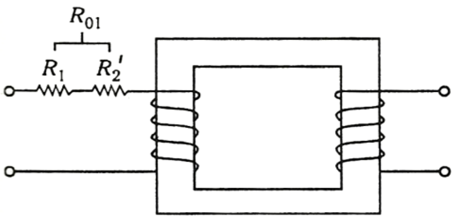


Fig. 7.10

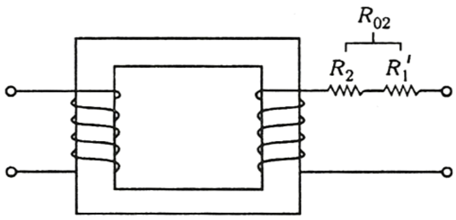


Fig. 7.11

In Fig. 7.10, the secondary resistance has been transferred to the primary. *The resistance $R_1 + R_2' = R_1 + \frac{R_2}{K^2}$ is called the equivalent resistance of the transformer as referred to the primary and is termed R_{01}.*

5) losses in a transformer

Power Losses in a Transformer

Being static, the transformer does not have friction or windage losses.

However, the only losses occurring are

Core or Iron Loss.

Copper Losses.

a) Core or Iron Losses : These losses consist of *hysteresis* and *eddy current losses* and occur due to the alternating flux in the transformer core. Because the core flux remains practically constant for all loads (its variation being }' to 3 % from no - load to full load), the core loss is practically constant at all loads.

Hysteresis Loss : Since the flux in a transformer core is alternating, therefore, power is required for the continuous reversal of the molecular magnets, which comprise the core. This power is dissipaTed in the form of heat and is known as hysteresis loss. It depends on the flux density in the core and the supply frequency.

Hysteresis loss $W_h = P B_{max}$ 1.6 f watt

where *Bmax.:* Maximum Flux Density (Wb/m^2)

f : Frequency (Hz)

P is a constant.

ii) *Eddy - Current Loss:* Due to the alternating flux in the core, eddy currents flow in the core. Power is required to maintain these eddy currents. This power is dissipated in the form of heat and is called *eddy current loss.* In order to ensure that these currents are small, a high resistance path is made out for them. This can be done by making the core of thin laminations, the laminations being separated from each other by varnish. The eddy current loss also depends upon flux density in the core and supply frequency .

. Eddy current loss We = Q $B_{max}{}^{2}$ $f2$ watt Q is a constant.

From our above discussion, it is apparent that core losses (hysteresis and eddy current losses) depend upon flux density in the core and supply frequency. As flux density in the core remains practically constant from no-load to full load, and also supply frequency is constant, it follows that core losses too are constant for a given transformer. These losses are independent of load which is why these are generally termed constant losses.

Core losses can be minimised by using steel of high silicon content for the core and by using very thin laminations.

b) Copper Losses or $I^2 R$ losses :

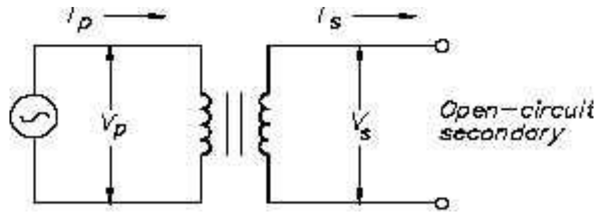
These losses occur due to the ohmic resistance in both the primary and secondary windings. If *R]* and R_2 are the primary and secondary resistances, and *II' 1₂* are the primary and secondary currents respectively.

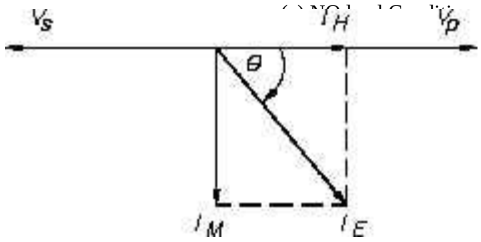
Total *Cu* loss = $1_1^2 R_1 + 1_2^2 R_2 = 1_1^2 R_{01} = I_1 R_{02}$

It is obvious that copper loss is proportional to $(current)^2$ or $(kVA)^2$. In other words, *Cu* loss at half the full-load is one fourth of that at full-load.

6) operation of transformer -no load vector diagram?

Transformer Operation Under No-Load If the secondary of a transformer is left open-circuited (Figure 6), primary current is very low and is called the no-load current. No-load current produces the magnetic flux and supplies the hysteresis and eddy current losses in the core. The no-load current (I_E) consists of two components: the magnetizing current (I_m) and the core loss (I_H). Magnetizing current lags applied voltage by 90°, while core loss is in phase with the applied voltage (Figure 6b). V_P and V_S are shown 180° out of phase. I_H is very small in comparison with I_m, and I_m is nearly equal to I_E. No-load current, I_E, is also referred to as exciting current.





(b) Phasor Diagram

7) working principle of a transformer on load

When the transformer is loaded ,the current I_2 flows through the secondary winding. The magnitude and phase of I_2 is determined by the load. If the load is inductive,I_2 Lags V_2 ,If load is capacitive ,I_2 leads V_2 while for resistive load ,I_2 is in phase with V_2.

A secondary m.m.f. $N_2 I_2$ due to which secondary current sets up its own flux ϕ_2 .This flux opposes the main flux ϕ which is produced in the core due to magnetizing component of no load current. Hence the m.m.f. $N_2 I_2$ is called demagnetizing ampere-turns.

The flux ϕ_2 reduces the main flux ϕ , due to which the primary induced e.m.f. E_1 also reduces .hence the vector difference $V_1 – E_1$ increases due to which primary draws more current from the supply. The additional current drawn by primary is due to the load called load component of primary current denoted as I'_2 as shown .

This current I'_2 is in antiphase with I_2 .The current I'_2 sets up its own flux ϕ_2' , which opposes the flux ϕ_2 . and help the main flux ϕ This flux ϕ_2^1 neutralizes the flux ϕ_2 produced by I_2 . The m.m.f. Ampere turns $N_1 I_2^1$ balances the ampere turns $N_2 I_2$ .The net flux in the core is again maintained at constant level.

As the ampere turns are balanced we can write

$$N_2 I_2 = N_1 I_2^1$$

$$I_2^1 = (N_2 / N_1) \times I_2 \Rightarrow K I_2$$

When transformer is loaded the primary current I_1 has two components.

1. The no load current I_0 which lags V_1 by angle ϕ_0 .It has two components I_m ,I_c
2. The load component I_2^1 which is in antiphase with I_2 ,phase of I_2 is decided by the load.

$$I_1 = I_0 + I_2$$

8. A 200 KVA, 10000 V/400 V, 50 Hz single-phase transformer has 100 turns on the secondary. Calculate :

(i) the primary and secondary currents

(ii) the number of primary turns

(iii) the maximum value of flux.

Solution:

(i) Full-load primary current $= \frac{200 \times 1000}{10000} = 20$ A

and full-load secondary current $= \frac{200 \times 1000}{400} = 500$ A

(ii) No. of primary turns $= \frac{100 \times 10000}{400} = 2500$

(iii) $E_2 = 4.44 \times f N_2 \times \phi_m$

$400 = 4.44 \times 50 \times 100 \times \phi_m$

$\phi_m = 0.018$ Wb

$= 18$mWb

9. Single-phase transformer with 10 : 1 turns ratio and rated at 25 kVA. 1200/120 V, 50 Hz, is used to step down the voltage of a distribution system. The low tension voltage is to be kept constant at 120 V. Find the value of the load impedance on the low tension side so that the transformer is fully loaded. Find also the value of maximum flux, if the low tension side has 25 turns.

Solution:

Full-load current $I_2 = 25000/120 = 208.33$ A

$Z_2 = V_2 / I_2 = 0.576$ ohm

$E_2 = 4.44 \times f \times N_2 \times \phi m$

$120 = 4.44 \times 50 \times 25 \times \phi m$

$\phi m = \frac{120}{4.44 \times 50 \times 25} = 0.021$ Wb

10. Find the number of turns required on the H.T. side of a 415/240 V, 50 Hz single-phase transformer, if the area of cross-section of the core is 25 cm^2 and the maximum flux density is 1.3 Wb/m^2•

Solution:

$E_1 = 4.44 f N_1 \; B_m A$

The HT side e.m.f. $= 415$ V $= E_1$

F = 50 Hz, $B_m = 1.3$ Wb/m^2 A= 25 cm^2 = (25×10^{-4}) m^2

. $E_1 = 4.44\, f\, N_1\; Bm\, A$

$415 = 4.44 \times 50 \times N_1 \times 1.3 \times (25 \times 10^{-4})$

$N_1 = 575$

11. A 125 KVA transformer has a primary voltage of 2000 V at 60HZ .primary turns are 182 and the secondary turns are 40.Neglecting losses, calculate:

- **i) no load secondary e.m.f.**
- **ii) full-load primary and secondary currents.**
- **iii) Flux in the core**

Solution:

$K = N_2 / N_1 = 40 / 182 = 20/91$

Full load current $= I_1 = 125000 / 2000 = 62.5$ A

Full load current $= I_2 = I_1 / K = 62.5 \times 91/20 = 284.37$ A

No load secondary e.m.f., $E_2 = KE_1 = (20/91)*2000 = 439.6$V

$E_1 = 4.44\, f\, N_1\, \phi m$

$2000 = 4.44 \times 60 \times 182 \times \phi m$

$\phi m = 0.0412$Wb

12. A 25KVA, single phase transformer has 500 turns on the primary and 40 turns on the secondary winding. The primary is connected to 3000V, 50Hz supply. Calculate (i)primary and secondary currents on full load.(ii)The secondary e.m.f.(iii)the maximum flux in the core.

Solution:

Given rating=25KVA

Primary applied voltage V_1=3000 Volts

Number of primary turns, N_1=500

Number of secondary turns, N_2=40

i) Full load primary current I_1=(KVA ratingx1000)/(Rated primary voltage, V_1)

$I_1 = (25 \times 1000) / (3000) = 8.33$A

Turns Ratio, $K = N_2/N_1$

$= 40/500 = 0.08$

We have, $I_1/I_2 = N_2/N_1$ [Current ratio=1/K]

Or $I_2 = I_1(N_1/N_2)$

Full load secondary current $I_2 = 8.33(1/0.08)$

$= 104.125$A

ii)Now $E_2/E_1 = N_2/N_1$

Secondary Induced e.m.f. $E_2 = E_1\,(N_2/N_1)$

E_2=3000x0.08=240 Volts

ii) The e.m.f equation of a transformer is E_1=4.44fN_1 ϕm

Substituting the various given values,we get

3000=4.44x50x500x ϕm

ϕm=(3000)/(4.44x50x500)=0.027Wb

Thus, the maximum flux carried in the core=0.027Wb.

13. In a 25KVA,2000/200V transformer, the iron and copper losses are 350 watts and 400 watts respectively . Calculate the efficiency at U.P.F. at half-full load.

Sol:ution:

Power factor = cos ϕ = 1

Output at half full-load = (25/2)x cos ϕ Kw = 12.5 x 1 = 12.5 kW

Cu.loss at half full-load = $(1/2)^2$ x F.L Loss

= ¼ x 400 = 100 kW

Iron loss = 350 W

Total losses = 100 + 350 = 450 W =0.45 kW

Input = output + losses = 12.5 + 0.45 = 12.95 kW.

Efficiency = output/input = (12.5/ 12.95) x 100 = 96.52%

11. In a 25 KVA ,2000/200 V single phase transformer, the iron and full-load copper losses are 350 and 400 W respectively. Calculate the efficiency at unity power factor on

a. **full-load**
b. **Half full – load**

Solution:

(a) Full-load :

Output at full-load = 25 cos ϕ kW

Power factor = cos ϕ = 1

Output at full –load = 25 x 1 =25kW

Iron losses = 350W

F.L copper losses =400W

Total losses = 750 W = 0.75 kW

Input = output + losses

= 25 + 0.75 = 25.75 kW

Efficiency = η_1 = (25/ 25.75) x 100 = 97%

(b) Half full –load :

Output = (25/2) x cos ϕ kW = 12.5 x 1 =12.5 kW

Cu loss at half full –load = $(1/2)^2$ x F.L Loss = ¼ x 400 =100 W

Iron loss =350 W

Total losses =100 +350 =450 W =0.45 kW

Input = Output +losses =12.50 +0.45 = 12.95 kW

Efficiency = η_2 = (12.5/ 12.95) x 100 = 96.52%

12. A 50 KVA transformer has an efficiency of 98% at full –load ,0.8 p.f. and an efficiency of 96.9%. at ¼ full-load ,unity p.f. Determine the iron loss and the full –load copper loss.

Solution:

Full –Load :

Output at full –load = 50 cos ϕ = 50 x 0.8 = 40 kW

Input = Output +losses

= output + Full –Load copper losses +Iron losses

= (40 + Full –Load copper losses +Iron losses)kW

Efficiency = $\eta_1 = \frac{\text{output}}{\text{Input}} = \frac{\text{output}}{40 + \text{FLCL} + \text{I L}}$

0.98 = 40/(40 + FLCL +I L)

40 + FLCL +I L =40.8 __________(i)

Quarter full-load:

Iron loss I L remains unchanged. P.f = 1

Output = (50/4) cos ϕ = 12.5 x 1 = 12.5kW

CU.Loss at quarter load ,= $(1/4)^2$ x Full-Load Copperloss

= 0.0625 FLCL

Efficiency = $\eta_2 = \frac{12.5}{12.5 + 0.0625\text{FLCL} + \text{I L}}$ =

0.969 (12.5+0.0625 x FLCL+I L) =12.5

12.5 + 0.0625 FLCL +I L = 12.9_______________(ii) equating (i) & (ii)

27.5 + 0.9375 FLCL = 27.9

FLCL =0.426kW = 426 watts

Substitute FLCL in eq (i)

40+ 0.426 + I L=40.8

I L = 0.374 kW

= 374 watts.

13. A 600 KVA single phase transformer has an efficiency of 92% both at full-load and half-load at unity power factor .Determine its efficiency at 75% of full-load at 0.9 power factor lag.

Solution:

At full –load:

Output = 600 cos ϕ = 600 x 1 = 600 kW

Input = 600/0.92 = 652.2 kW

Total losses = 652.2- 600 = 52.2 kW

Let x = iron losses

y = Full Load .copper losses

x + y = 52.2

AT Half –load ,

Output = 300kW

Input = 300/0.92 = 326.1kW

Total losses =326.1 – 300 =26.1 kW

Copper loss becomes one-fourth of its full load value,

x + y/4 =26.1kW

x + y = 52.2

y = 34.8 kW , x= 17.4kW

At 75% Full-Load :

Copper losses = 0.75^2 x 34.8 = 19.6 kW

Iron losses = 17.4kW

Total losses = 17.4 + 19.6 = 37kW

Output = 600 cos ϕ x 0.75

= 600 x 0.9 x 0.75

= 405 kW

Efficiency = <u>output</u>

Output + losses

$$= \frac{405}{405+37}$$

= 0.916 = 91.6%

14. Determine the efficiency of a 150 kVA transformer at 50% full-load of 0.8 p.f. lag if the copper loss at full-load is 1600w. and the iron loss 1400w.

Solution:

Power factor = 0.8 =cos ϕ

Copper losses at full-load P_c = 1600w = 1.6 kW

Copper losses at 50% full-load = $(1/2)^2 P_c$

= ¼ x 1.6 = 0.4kW

Total losses =Iron losses + cu losses at 50% F.L

= 1.4 + 0.4 = 1.8 kW

Output power at 50% load = ½ x 150 x cos ϕ

= ½ x 150 x 0.8 = 60kW

Input power = 60 + 1.8 = 61.8 kW

$$\eta = \frac{\text{output power}}{\text{input power}} \times 100$$

$$= \frac{60}{61.8} \times 100 = 97\%$$

18. A 240/ 440 v single phase transformer absorbs 35 watts when its primary winding is connected to a 240v ,50 HZ supply . the secondary being on open circuit.when theprimary is short circuited and a 10v ,50HZ, supply is connected to the secondary winding the power absorbed is 48w ,when the current has the full-load value of 15A.Estimate the efficiency of the transformer at half-load,0.8 p.f. lagging.

Solution:

Input power = iron loss =35 watts

Full –Load secondary current = 15 A

The primary winding is short –circuited and the rated full-load current passes through the secondary winding.

Power absorbed = 48 W =Full-load copper loss

Output = $V_2 I_2 \cos\phi$ = 400 x (1/2 x 15) x 0.8 =2400 Watts

Iron loss =35W

Copper loss at ½ Full-load = $(1/2)^2$ x Full-load copper loss

= ¼ x 48 = 12 watts

Total losses = Iron loss + copper loss at ½ Full –load

= 35 + 12 = 47 watts

Input = output + Total loss

= 2400 + 47 = 2447 W

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}} \times 100$$

$$= \frac{2400}{2447} \times 100 = 98\%$$

THREE PHASE INDUCTION MOTORS

1. advantages & Disadvantages of Induction Motor

ADVANTAGES:

1.Its cost is low

2.It has very simple, very robust and rugged, practically unbreakable construction.

3. It is very reliable

4. It is highly efficient

5. It has a fairly good power factor

6. Its maintenance requires minimum of attention

7. It does not need to be synchronized.

DISADVANTAGES:

1.It is essentially a constant speed motor and the speed cannot be varied easily.

2. Its speed reduces to some extent with increase in load, as in the case of d.c. shunt motor.

3. It has a somewhat lesser starting torque, as compared to a d.c. shunt motor.

❖ **CLASSIFICATION -**

They are basically classified into two types based on the rotor construction

1. Squirrel cage motor
2. Slip ring motor or phase wound motor

2. construction of squirrel-cage and phase wound(slip-ring) induction Motors

A. Three-phase Induction motor essentially consists of the following two parts.

(1) stator

(2) rotor

CONSTRUCTION

➢ **Stator**

It is the stationary part of the motor supporting the entire motor assembly. This outer frame is made up of a single piece of cast iron in case of small machines. In case of larger machines they are fabricated in sections of steel and bolted together. The core is made of thin laminations of silicon steel and flash enameled to reduce eddy current and hysteresis losses. Slots are evenly spaced on the inner periphery of the laminations. Conductors insulated from each other are placed in these slots and are connected to form a balanced 3 - phase star or delta connected stator circuit. Depending on the desired speed the stator winding is wound for the required number of poles. Greater the speed lesser is the number of poles.

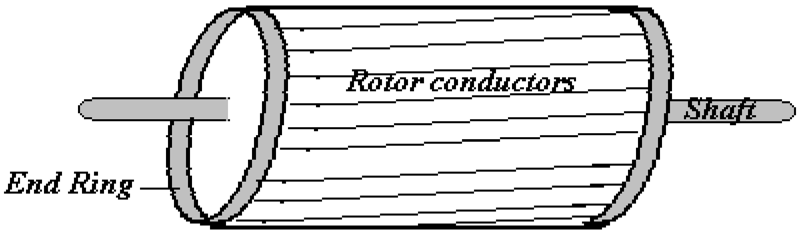
➢ **Rotor**

It is the rotating part of the motor. The following are the two types of rotors employed in 3-phase Induction Motors:

1) Squirrel-cage Rotor: Motors with this type of rotor are known as squirrel-cage Induction motor.
2) Phase-wound or wound rotor: Motors with this type of rotor are known as 'phase-wound' motors, 'wound' motors, or 'slip-ring' motors.

SQUIRREL CAGE ROTOR:

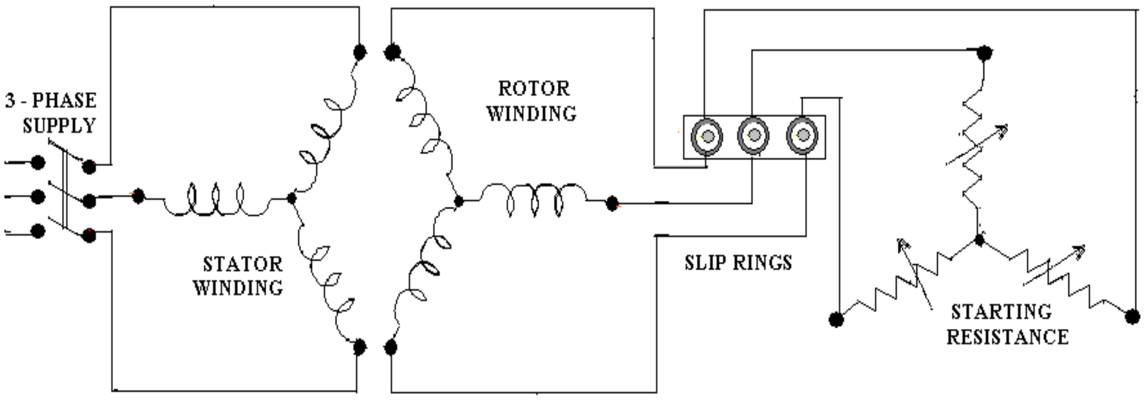
Squirrel cage rotors are widely used because of their ruggedness. The rotor consists of hollow laminated core with parallel slots provided on the outer periphery. The rotor conductors are solid bars of copper, aluminum or their alloys. The bars are inserted from the ends into the semi-enclosed slots and are brazed to the thick short circuited end rings. This sort of construction resembles a squirrel cage hence the name "squirrel cage induction motor". The rotor conductors being permanently short circuited prevent the addition of any external resistance to the rotor circuit to improve the inherent low starting torque. The rotor bars are not placed parallel to each other but are slightly skewed which reduces the magnetic hum and prevents cogging of the rotor and the stator teeth.



Squirrel cage induction rotor

PHASE-WOUND ROTOR: (SLIP-RING ROTOR)

The rotor in case of a phase wound/ slip ring motor has a 3-phase double layer distributed winding made up of coils, similar to that of an alternator. The rotor winding is usually star connected and is wound to the number of stator poles. The terminals are brought out and connected to three slip rings mounted on the rotor shaft with the brushes resting on the slip rings. The brushes are externally connected to the star connected rheostat in case a higher starting torque and modification in the speed torque characteristics are required. Under normal running conditions all the slip rings are automatically short circuited by a metal collar provided on the shaft and the condition is similar to that of a cage rotor. Provision is made to lift the brushes to reduce the frictional losses. The slip ring and the enclosures are made of phosphor bronze.



SLIP RING INDUCTION MOTOR

In both the type of motors the shaft and bearings (ball and roller) are designed for trouble free operation. Fans are provided on the shaft for effective circulation of air. The insulated (mica and varnish) stator and rotor windings are rigidly braced to withstand the short circuit forces and heavy centrifugal forces respectively. Care is taken to maintain a uniform air gap between the stator and the rotor.

Comparison of the squirrel cage and slip ring rotors:

The cage rotor has the following advantages:

1. Rugged in construction and economical.
2. Has a slightly higher efficiency and better power factor than slip ring motor.
3. The absence of slip rings and brushes eliminate the risk of sparking which helps in a totally enclosed fan cooled (TEFC) construction.

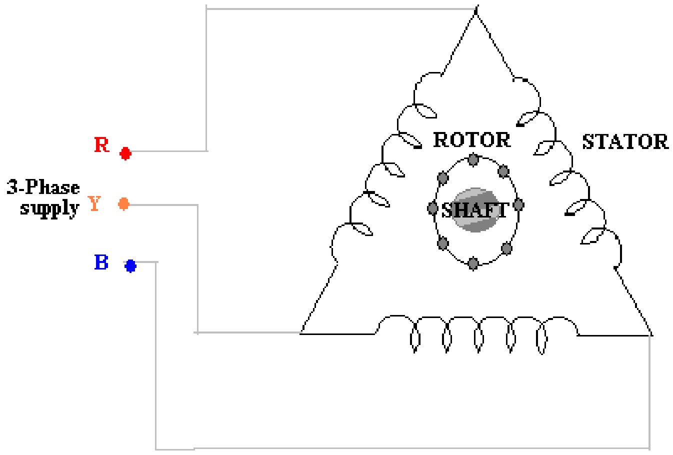
The advantages of the slip ring rotor are:

1. The starting torque is much higher and the starting current much lower when compared to a cage motor with the inclusion of external resistance.
2. The speed can be varied by means of solid state switching

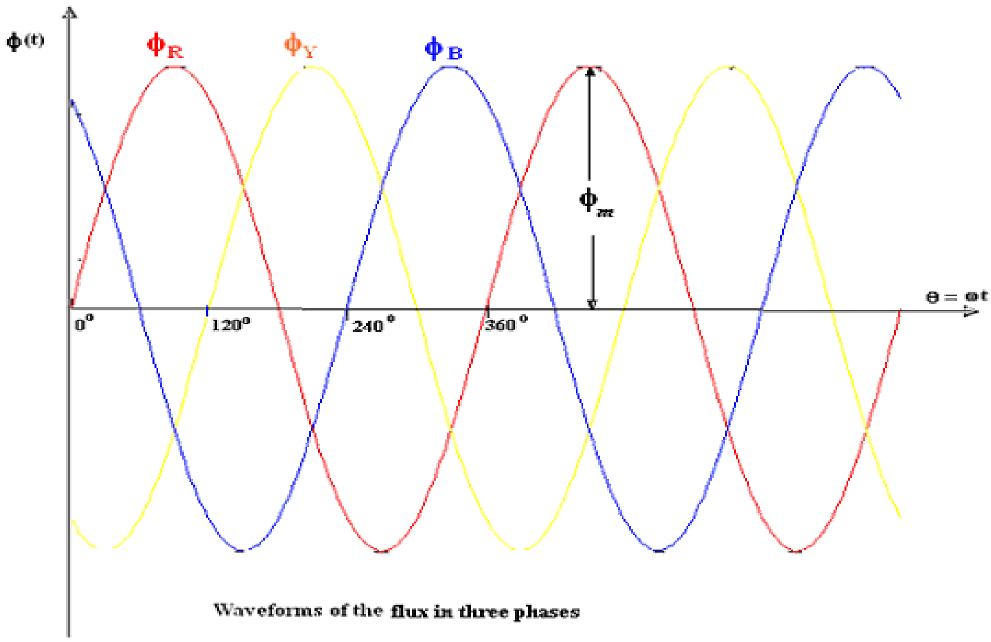
3. Rotating Magnetic Field (RMF)?

A. Production of a rotating magnetic field:

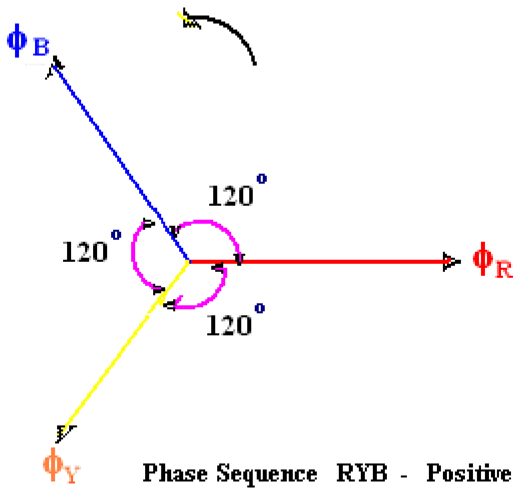
Consider a 3- phase induction motor whose stator windings mutually displaced from each other by 120° are connected in delta and energized by a 3- phase supply.



. The currents flowing in each phase will set up a flux in the respective phases as shown.



Waveforms of the flux in three phases



Phase Sequence RYB - Positive

The corresponding phase fluxes can be represented by the following equations

$\Phi_R = \Phi_m \sin \omega t = \Phi_m \sin \theta$

$\Phi_Y = \Phi_m \sin(\omega t - 120°)$

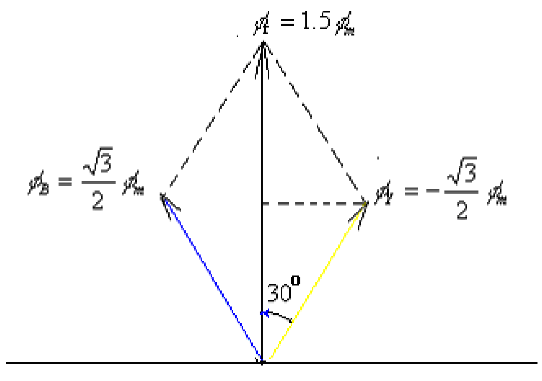
$\Phi_Y = \Phi_m \sin(\theta - 120°)$

$\Phi_B = \Phi_m \sin(\omega t - 240°)$

$\Phi_B = \Phi_m \sin(\theta - 240°)$

The resultant flux at any instant is given by the vector sum of the flux in each of the phases.

(i) When $\theta = 0^\circ$, from the flux waveform diagram ,we have



Resultant flux at $\theta = 0^0$

$\phi_R = 0$

$\phi_Y = \phi_{km} \sin(-120^\circ) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = \phi_m \sin(-240^\circ) = \frac{\sqrt{3}}{2}\phi_m$

The resultant flux ϕ_r is given by,

$\phi_r = 2 * \frac{\sqrt{3}}{2}\phi_m \cos(30^\circ) = 1..5\phi_m$

$\phi_B = \frac{\sqrt{3}}{2}\phi_m$

$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$

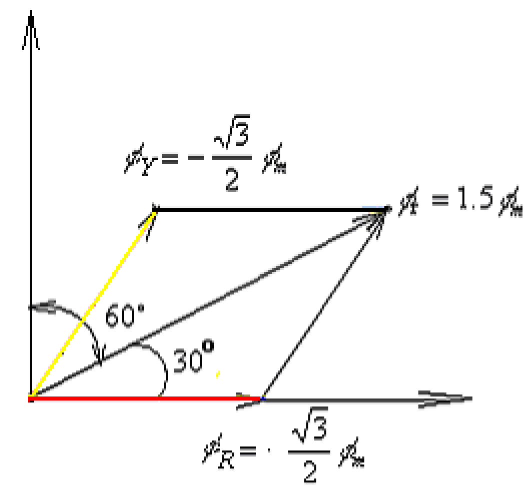
$\phi_r = 1.5\phi_m$

(ii) *When* $\theta = 60^\circ$

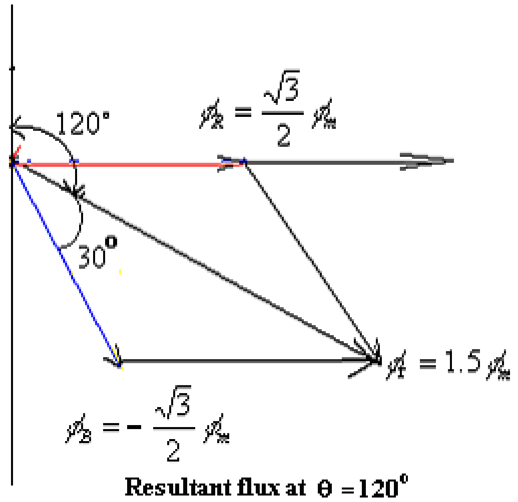
$\phi_R = \frac{\sqrt{3}}{2}\phi_m$

$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = 0$



Resultant flux at $\theta = 60^o$



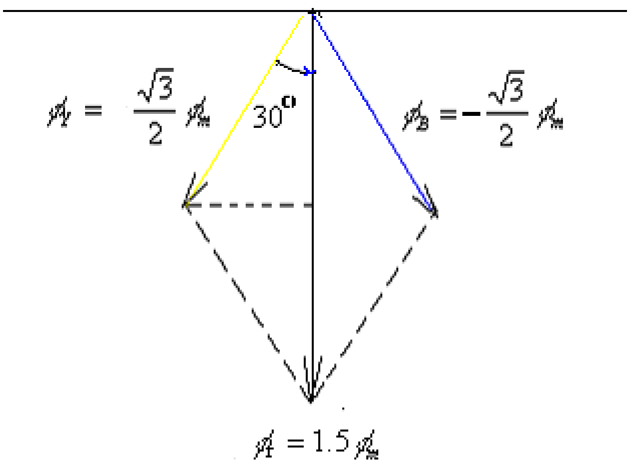
Resultant flux at θ = 120°

(iv) *When* $\theta = 180^\circ$

$\phi_R = 0;$

$$\phi_Y = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi$$



Resultant flux at θ = 180°

From the above discussion it is very clear that when the stator of a 3-phase induction motor is energized, a magnetic field of constant magnitude (1.5 φ_m) rotating at synchronous speed (N_s) with respect to stator winding is produced.

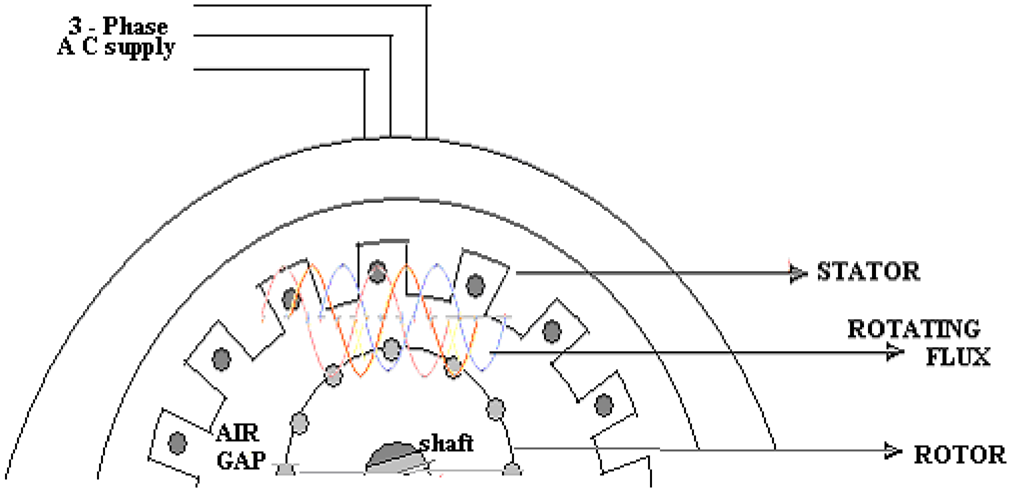
(b) Rotation of the rotor

Consider a 3- phase stator winding energized from a 3 phase supply. As explained earlier a rotating magnetic field is produced running at a synchronous speed N_S

$$N_S = \frac{120\,f}{P}$$

Where f = supply frequency

P = Number of stator poles



As soon as the supply is switched on you can show

- The three phase flux revolving in the air gap
- The flow of current through the rotor conductors
- The rotation of the rotor in the direction of the 3- phase flux but with a difference in speed (trailing behind) between them indicating the slip speed
- When their speeds become equal the rotor should tend to stop rotating indicating zero slip

Consider a portion of 3- phase induction motor as shown in the above figure which is representative in nature. The rotating field crosses the air gap and cuts the initially stationary rotor conductors. Due to the relative speed between the rotating magnetic field and the initially stationary rotor,(change of flux linking with the conductor) an e.m.f. is induced in the rotor conductors, in accordance with the Faraday's laws of electromagnetic induction. Current flows in the rotor conductors as the rotor circuit is short circuited. Now the situation is similar to that of a current carrying conductor placed in a magnetic field. Hence, the rotor conductors experience a mechanical force which eventually leads to production of torque. This torque tends to move the rotor in the same direction as that of the rotating magnetic field.

4)"SLIP" in an induction motor

CONCEPT OF SLIP (*S*)

According to Lenz's law, the direction of rotor current will be such that they tend to oppose the cause producing it. The cause producing the rotor current is the relative speed between the rotating field and the stationary rotor. Hence, to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it. In practice the rotor can never reach the speed of the rotating magnetic field produced by the stator. This is because if rotor speed equals the synchronous speed, then there is no relative speed between the rotating magnetic field and the rotor. This makes the rotor current zero and hence no torque is produced and the rotor will tend to remain stationary. In practice, windage and friction losses cause the rotor to slow down. Hence, the rotor speed (N) is always less than the stator field speed (N_S). Thus the induction motor cannot run with **ZERO SLIP.**

The frequency of the rotor current

$f_r = sf$. The difference between the synchronous speed (N_S) of the rotating stator field and the actual rotor speed (N) is called the **slip speed.**

Slip speed = $N_S - N$ depends upon the load on the motor

If it is apparent that the motor speed is $N = N_s(1-S)$

$$\% \text{ Slip } (s) = \frac{N_S - N}{N_S} * 100$$

Note: In an induction motor the slip value ranges from 2% to 4%

5) the relationship between the frequency of the rotor-induced emf & the frequency of the supply given to the stator.

FREQUENCY OF ROTOR CURRENT or e.m.f.:

When the rotor is at standstill, the frequency of rotor current is the same as the supply frequency.

However, when there is relative speed between the rotor and the stator field, the frequency of the induced voltage, and hence the current, in the rotor varies with the rotor speed i.e. slip. Let at any speed N of the rotor, The frequency of the rotor current be f'.

Then, $N_s - N = \frac{120f'}{P}$ (i)

Also $N_S = \frac{120f}{P}$ (ii)

Dividing i by ii we hav

$$\frac{f'}{f} = \frac{N_S - N}{N_S} = S$$

Hence, the frequency of rotor current may be obtained by multiplying the supply frequency by fractional slip.

6) applications of Squirrel-cage and Slip-ring Motors

Ans.

APPLICATIONS OF INDUCTION MOTORS

Squirrel cage induction motor

Squirrel-cage type of motors having moderate starting torque and constant speed characteristics are widely used Squirrel cage induction motors are simple and rugged in construction, are relatively cheap and require little maintenance. Hence, squirrel cage induction motors are preferred in most of the industrial applications such as in

i) Lathes
ii) Drilling machines
iii) Agricultural and industrial pumps
iv) Industrial drives.
v) Printing machines
vi) Grinders
vii) Driving fans
viii) blowers

Slip ring induction motors

Slip ring induction motors when compared to squirrel cage motors have high starting torque, smooth acceleration under heavy loads, adjustable speed and good running characteristics. They are used in

i) Lifts
ii)Cranes
iii)Conveyors
iv)elevators
v) hoists
vi)compressors.

7) starters

Necessity of starters for 3 phase induction motor

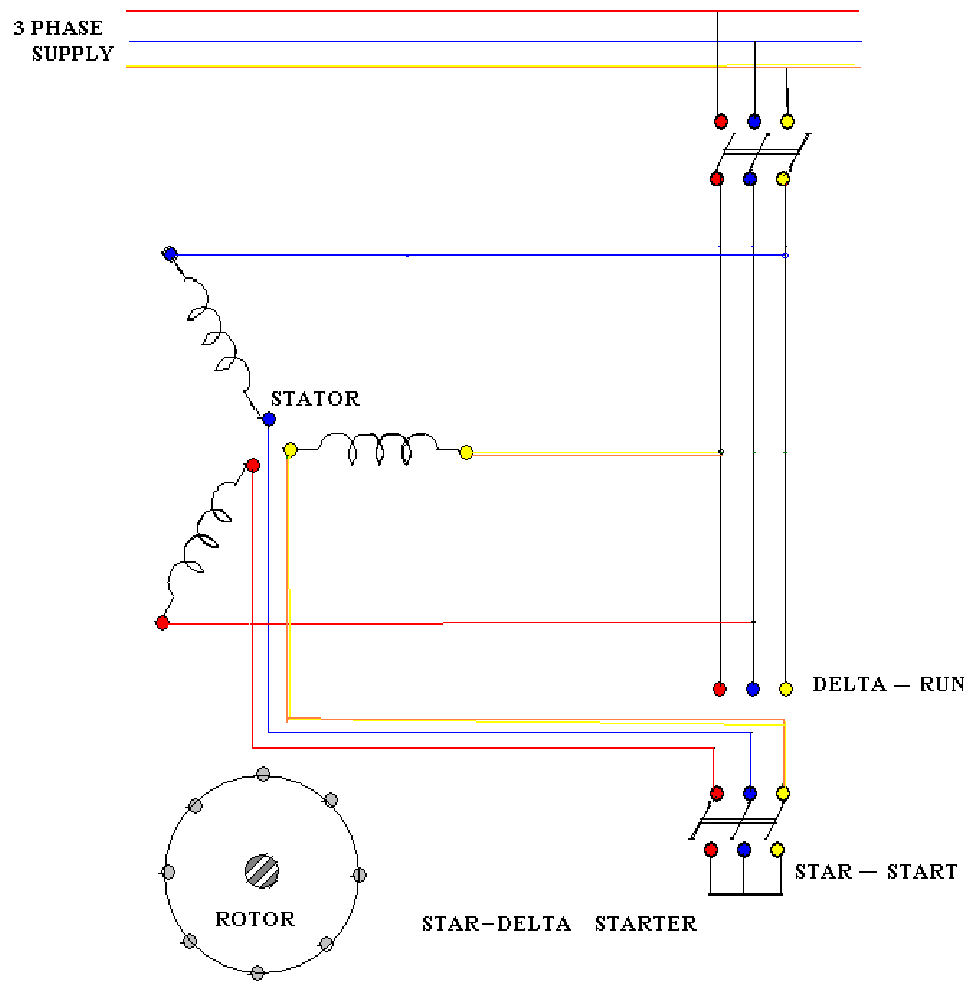
When a 3- phase motor of higher rating is switched on directly from the mains it draws a starting current of about 4 -7 times the full load (depending upon on the design) current. This will cause a drop in the voltage affecting the performance of other loads connected to the mains. Hence starters are used to limit the initial current drawn by the 3 phase induction motors.

The starting current is limited by applying reduced voltage in case of squirrel cage type induction motor and by increasing the impedance of the motor circuit in case of slip ring type induction motor. This can be achieved by the following methods.

1. Star –delta starter
2. Auto transformer starter
3. Soft starter

❖ **Star delta starter**

The star delta starter is used for squirrel cage induction motor whose stator winding is delta connected during normal running conditions. The two ends of each phase of the stator winding are drawn out and connected to the starter terminals as shown in the following figure.



When the switch is closed on the star-start side

(1) The winding is to be shown connected in star

(2) The current I = 1/3 * (I $_{direct\ switching}$)

(3) Reduction in voltage by1/√3

$V = V_{supply} * 1/\sqrt{3}$

When the switch is closed on to delta –run side

(1) the winding to be shown connected in delta

(2) application of normal voltage V_{supply}

(3) normal current I

During staring the starter switch is thrown on to the **STAR - START**. In this position the stator winding is connected in star fashion and the voltage per phase is **1/√3** of the supply voltage. This will limit the current at starting to **1/3** of the value drawn during direct switching. When the motor accelerates the starter switch is thrown on to the **DELTA - RUN** side. In this position the stator winding gets connected in the Δ fashion and the motor draws the normal rated current.

7)A 12 pole, 3 phase alternator is coupled to an engine running at 500 rpm. It supplies an Induction Motor which has a full load speed of 1440 rpm. Find the percentage slop and the number of poles of the motor.

Solution:

N_A = synchronous speed of the alternator

$$F = \frac{PN_A}{120} = \frac{12 \times 500}{120} = 50 \text{ Hz (from alternator data)}$$

When the supply frequency is 50 Hz, the synchronous speed can be 750 rpm, 1500 rpm, 3000rpm etc., since the actual speed is 1440 rpm and the slip is always less than 5% the synchronous speed of the Induction motor is 1500 rpm.

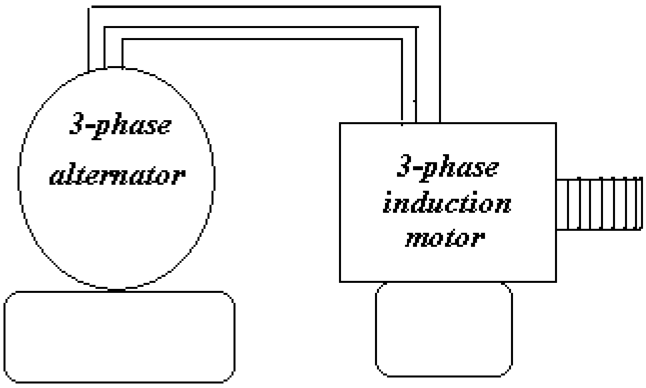
$$s = \frac{N_S - N}{N_S} = \frac{1500 - 1440}{1500} = 0.04 \text{ OR } 4\%$$

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{P} = 1500$$

$\therefore P = 4$

8). A 6 pole induction motor is supplied by a 10 pole alternator, which is driven at 600 rpm. If the induction motor is running at 970 rpm, determine its percentage slip.

Solution:



From alternator date: $f = \frac{P N_A}{120} = \frac{10 \times 600}{120} = 50 \text{ Hz}$

Synchronous speed of the induction motor

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000rpm$$

From I.M. data:

$$\%slip = \frac{N_S - N}{N_S} \times 100 = \frac{1000 - 970}{1000} = 3\%$$

9. A 12 pole, 3 phase alternator is driven by a 440V, 3 phase, 6 pole Induction Motor running at a slip of 3%. Find frequency of the EMF generated by the alternator

Solution:

For induction motor: $N_S = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000rpm$

$N = (1-s)N_S = (1-0.03)1000 = 970rpm$

As the alternator is driven by the Induction motor, the alternator runs at 970 r.p.m.

For alternator: $f = \frac{PN}{120} = \frac{12 \times 970}{120} = 97Hz$

10. A three phase 4 pole, 440 V, 50Hz induction motor runs with a slip of 4%. Find the rotor speed and frequency of the rotor current.

Solution:

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500rpm$$

$$S = \frac{N_S - N}{N_S} i.e. 0.04 = \frac{1500 - N}{1500}, \therefore N = 1440rpm$$

$$f_r = sf = 0.04 \times 50 = 2Hz$$

11.. A 3 phase, 50Hz 6 pole induction motor has a full load percentage slip of 3%.

Find(i) Synchronous speed and (ii) Actual Speed

Solution:

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000rpm$$

$$S = \frac{N_S - N}{N_S} i.e. 0.03 = \frac{100 - N}{1000} \therefore N = 970rpm$$

12. A 3 phase induction motor has 6 poles and runs at 960 RPM on full load. It is supplied from an alternator having 4 poles and running at 1500 RPM. Calculate the full load slip and the frequency of the rotor currents of the induction motor.

Solution:

$$f = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50Hz(\text{from alternator data})$$

forInduction motor

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000rpm$$

$$S = \frac{N_S - N}{N_S} = \frac{1000 - 960}{1000} = 0.04 \text{ or } 4\%$$

$$fr = sf = 0.04 \times 50 = 2Hz$$

13. The frequency of the e.m.f in the stator of a 4-pole induction motor is 50 Hz and that of the rotor is $1\frac{1}{2}Hz$. What is the slip and at what speed is the motor running?

Solution:

Given $P = 4$

$f = 50$Hz

$f_r = 1.5Hz$

(i) To calculate slip (s)

$$f_r = sf$$
$$1.5 = S \times 50$$
We have $$s = \frac{1.5}{50}$$
$$s = 0.03$$
$$s = 3\%$$

ii) To calculate the speed of the motor (*N*)

We have
$$N_s = \frac{120f}{P}$$
$$N_s = \frac{120 \times 50}{4} = 1500rpm$$
We also have
$$N = N_s(1-s)$$
$$N = 1500(1-0.03)$$
$$N = 1455rpm$$

14. A 3-phase, 60Hz induction motor has a slip of 3% at full load. Find the synchronous speed, the full- load speed and the frequency of rotor current at full load.

Solution

Given $P = 6$
$f = 60$Hz
$s = 3\% = 0.03$

- **To find the synchronous speed (N_s)**

We have
$$N_s = \frac{120f}{P} = \frac{120 \times 60}{6}$$
$$N_s = 1200rpm$$

- **To calculate the full load speed (*N*)**

We have
$$N = N_s(1-s) = 1200(1-0.03)$$
$$N = 1164rpm$$

- **To calculate the frequency of the rotor current (f_r)**

We have
$$f_r = sf = 0.03 \times 60$$
$$f_r = 1.8Hz$$

15. A 6-pole alternator running at 600 rpm. supplies a 3-phase, 4-pole induction motor. If the induction motor induced e.m.f makes 2 alternations per second, find the speed of the motor.

Solution :

- **Alternator**

$$P = 6$$
$$N_s = 600$$

We have the frequency of induced e.m.f of an alternator given by

$$f = \frac{PN_s}{120} = \frac{6 \times 600}{120} = 30Hz$$

Hence, induction motor receives the supply at 30Hz frequency

- **Induction motor**

It is given that the rotor induced e.m.f makes two alternations per second i.e. 1.0 cycle per second

$$\therefore f_r = 1.0Hz$$

We have

$$f_r = sf$$
$$s = \frac{f_r}{f} = \frac{1.0}{30}$$
$$s = 0.033$$

The speed of the rotating magnetic field is given by

$$N_s = \frac{120f}{P_m}$$ Where P_m = Number of poles of induction motor

$$N_s = \frac{120 \times 30}{4} = 900rpm$$

The speed of the induction motor (N) is given by

$$N = N_s(1-s) = 900(1-0.033)$$
$$N = 870rpm$$

16. A 10-pole induction motor is supplied by a 6-pole alternator, which is driven at 1200rpm. If the motor runs with a slip of 3, what is the speed of the induction motor?

Solution

- **Alternator**

$$P = 6 \text{ pole}$$
$$N_s = 1200\text{rpm}$$

Therefore, the frequency of the e.m.f generated is given by

$$f = \frac{PN_s}{120} = \frac{6 \times 1200}{120}$$
$$f = 60Hz$$

Hence, the induction motor is supplied at 60Hz frequency.

- **Induction motor**

Supply frequency = f = 60Hz

Slip = S = 3%

Stator poles = P_m =10

Speed of the rotating magnetic field,

$$N_s = \frac{120f}{P_m} = \frac{120\times 60}{10}$$
$$N_s = 720rpm$$

Speed of the motor

$$N = N_s(1-S) = 720(1-0.03)$$
$$N = 698.4rpm$$

17. A 3-phase induction motor has 6-poles and runs at 960r.p.m. on full load. It is supplied from an alternator having 4-poles and running at 1500 r.p.m. calculate the full load slip of the motor.

Solution

- **Alternator**

P = 4 poles

N_s = 1500 rpm

The frequency generated e.m.f is given by

$$f = \frac{PN_s}{120} = \frac{4\times 1500}{120}$$
$$f = 50Hz$$

Hence, the induction motor is supplied at 50 Hz

- **Induction motor**

$$P_m = 6\,poles$$
$$f = 50Hz$$
$$N = 960rpm$$

The speed of the rotating magnetic field is given by

$$N_s = \frac{120f}{P_m} = \frac{120\times 50}{6}$$
$$N_s = 1000rpm$$

We have slip of an induction motor given by

$$S = \frac{N_s - N}{N_s} = \frac{1000-960}{1000} = 0.04$$
$$S = 4\%$$

18. A 4-pole, 30hp, 3-phase 400 volts, 50Hz induction motor operates at an efficiency of 0.85 with a power factor of 0.75(lag). Calculate the current drawn by the induction motor from the mains

Solution Given P = 4

V = 400

ή = 0.85

cos φ = 0.75

Output= 30 hp

= 22.06538 Kw (1metric hp=735.5 watts)

We have,

$$\eta = \frac{Output}{Input}$$

$$Input = \frac{Output}{\eta} = \frac{22.065}{0.85}$$

$$Input = 25.96KW$$

But, for a 3-phase induction motor circuit, the power input is also given by the expression

$$P = \sqrt{3}V_L I_L \cos\Phi$$

$$I_L = \frac{P}{\sqrt{3}V_L \cos\Phi} = \frac{25.96\times1000}{\sqrt{3}\times400\times0.75}$$

$$I_L = 49.94 Amperes$$

19. A 5 hp, 400V, 50Hz, 6-pole, 3-phase induction motor operating on full load draws a line current of 7 amperes at 0.866 power factor with 2%slip. Find the rotor speed.

Solution.

Given P = 6
s = 2%
= 0.02
cos ϕ = 0.866
f = 50 Hz

$$Output = 5hp = 5\times735.5watts$$

$$Output = 3.677KW$$

$$I_L = 7amperes$$

To find the rotor speed:

Speed of the rotor magnetic field is given by

$$N_s = \frac{120f}{P} = \frac{120\times50}{6}$$

$$N_s = 1000rpm$$

Speed of the rotor = $N = N_s(1-s)$
= 1000(1-0.02)
N = 980rpm

20. A 3-phase, 6-pole, 50 Hz induction motor has a slip of 1% at no-load and 3%at full-load. Find:

1. **Synchronous speed,**
2. **No-load speed**
3. **Full-load speed,**
4. **Frequency of rotor current at standstill, and**
5. **Frequency of rotor current at full-load**

Solution. :

Number of poles, p = 6

No- load slip, s_0 = 1%

Full-load slip, s_f = 3%

1. Synchronous speed,

$$N_s = \frac{120f}{p} = \frac{120\times50}{60} = 1000r.p.m.(Ans)$$

2.No-load speed N_0,

We know that

$$s = \frac{N_s - N}{N_s} or N = N_s(1-s)$$

$$N_0 = N_s[1-s_0] = 100\left[1-\frac{1}{100}\right] = 990 r.p.m.(Ans)$$

3.Full – load speed

$$N_f = N_s[1-s_f] = 1000\left[1-\frac{3}{100}\right] = 970 r.p.m.(Ans)$$

4. Frequency of rotor current at standstill, f_r

At standstill,

$$s = 1$$

$$f_r = sf = 1\times 50 = 50 Hz.(Ans)$$

6. Frequency of rotor current at full – load, f_r =?

$$f_r = s\times f = \frac{3}{100}\times 50 = 1.5 Hz.(Ans)$$

21. A 3-phase, 12-pole alternator is coupled to an engine running at 500 rpm. The alternator supplies an induction motor which has a full-load speed of 1455rpm. Find the slip and number of poles of the motor.

Solution.

Number of poles of the alternator, p_a =12

Speed of the engine, N_e = 500rpm

Full-load speed of the induction motor, N_m = 1455rpm

Slip, s =?

Number of poles of the induction motor, P_m =?

Supply frequency,

$$f = \frac{N_a p_a}{120} = \frac{500\times 12}{120} = 50 Hz$$

When the supply frequency is 50Hz, the synchronous speed can be 3000, 1500, 1000, 750 rpm etc. since the full-load speed is 1455rpm and the full-load slip is always less than 4%, the synchronous speed is1500rpm.

Slip,

$$s = \frac{N_s - N}{N_s} = \frac{1500-1455}{1500} = 0.03 or 3\% (Ans)$$

Also,

$$N_s = \frac{120 f}{P_m}$$

$$P_m = \frac{120 f}{N_s} = \frac{120\times 50}{1500} = 4 poles$$

Hence**, number of motor poles = 4. (Ans)**

22. A 4- pole, 50 Hz induction motor at no-load (N_{NL}) has a slip of 2%. When operated at full load the slip increases to 3%. Find the change in speed of the motor from no-load to full load.

Solution:

$$N_s = \frac{120f}{P}$$

$$= \frac{120 \text{ x } 50}{4} = 1500rpm$$

$$no-load \text{ speed } N_{NL} = N_S(1-S_{NL})$$

$$= 1500(1-0.02) = 1470rpm$$

$$full\ load\ speed\ N = N_S(1-S_{FL})$$

$$= 1500(1-0.03)$$

$$= 1455rpm$$

change in speed from no - load to full load

$$\text{N}_{\text{NL}} - N_{FL} = 1470 - 1455 = 15rpm$$