Equally Important for
TU.PU. PoU and KU

A TEXT BOOK ON

ELECTRICAL MACHINE

By
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1st → DC Generator & DC motor.
2nd → Induction Machine
3rd → Transformer

TABLE OF CONTENTS

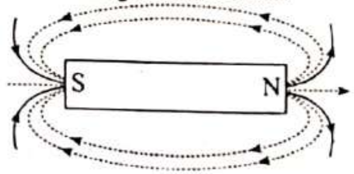
Chapter 7: Fractional Kilowatt Motors **288-338**

CHAPTER 1 Magnetic Circuits & Induction

MAGNETIC FIELD: THEORY REVIEW

Magnetic field:

Magnetic field is the space around a magnet within which the magnet has affect on the magnetic materials.



$$F = \frac{1}{4\pi\mu_0\mu_r}\cdot\frac{m_1 m_2}{d^2}$$

or, $\mu = \mu_0 \cdot \mu_r$

where,

m_1 = magnetic pole strength of the first pole (Wb)

m_2 = magnetic pole strength of the second pole (Wb)

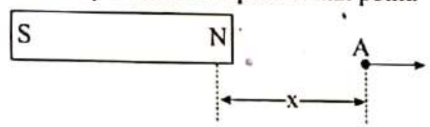
d = Distance between two poles (m)

μ_0 = permeability of free space

μ_r = Relative permeability of the medium on which the two poles are lying.

Magnetic field intensity (H):

Magnetic field intensity at any point of a magnetic field is defined as the force experienced by a unit north pole at that point.



$$H_A = \frac{m}{4\pi d^2}$$

Magnetic flux density (B):

It is defined as the magnetic flux per unit area.

$B = \phi/A$ (Wb/m^2) or Tesla

Work done and its Applications

The unit N-pole in moving around any closed path in a magnetic field is equal to the "Amp-turns" (NI) linked with the closed path.

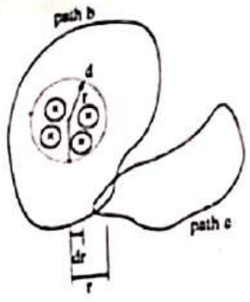
Mathematically,

$$\underbrace{\oint H.dr}_{\text{Work done in a closed path/per unit pole}} = NI$$

Work done in a closed path/per unit pole

Application

1)



For path-d, linking N-conductors, then the work done in moving a unit N-pole around the circular path is path C and is given by,

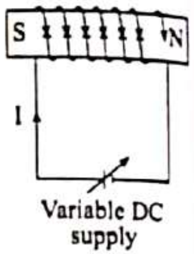
$\oint H.dr = NS$

or, $H\oint dr = NI \Rightarrow H.2\pi r = NI$

$$\Rightarrow \boxed{H = \frac{NI}{2\pi r}}$$

HYSTERESIS CURVE/B-H CURVE/MAGNETIZING CURVE

Consider an electromagnet supplied by a variable DC supply. The magnetizing force inside the core is given by, $H = \frac{NI}{\ell}$, when varying I, H in the material can be varied & accordingly B will also vary.



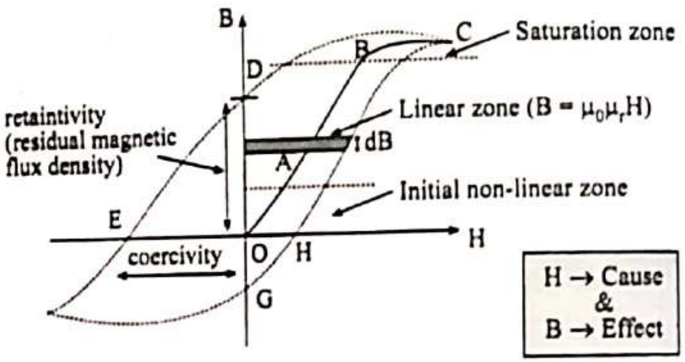


Fig.: Hysteresis loop

There is a loss in the process of magnetization & demagnetization in the form of heat and is called hysteresis loss, due to the property of magnetic material known as retaintivity.

The magnetic flux at any instant is given by,

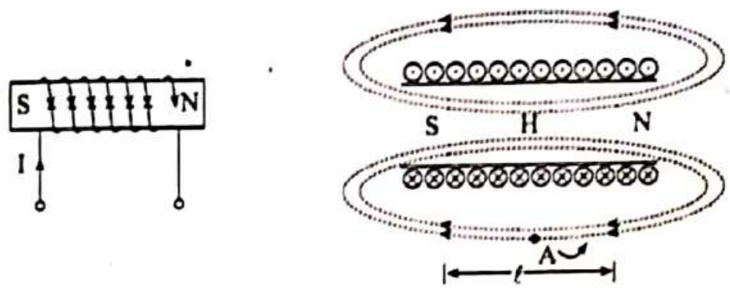
$\phi(t) = B(t).A$

Then emf induced in the coil, according to Faraday's law of electromagnetic induction,

$$e = \frac{Nd\phi}{dt} = N\frac{d(B.A.)}{dt} = NA\frac{dB}{dt}$$

& also magnetizing force is, $H = \frac{NI}{\ell}$

MAGNETIC FIELD DUE TO A SOLENOID (ELECTROMAGNET)



Assume that 'H' remains constant thought 'ℓ' of the solenoid & is negligible outside the solenoid- If a unit N-pole is moved around a closed path in a direction opposite to H, the work done is given by work law as,

$H \times \ell = NI$ $\therefore H = \frac{NI}{\ell}$ magnetizing force inside the solenoid.

(Work done against the magnetizing force.)

m(weber)	= μ.m(Am)
↑	↑
engineering	physics

Hence,

$F = \frac{m_1 m_2}{4\pi\mu d^2}$ $H = F/m = \frac{m}{4\pi\mu d^2}$ (A/m)

$B = \phi/A$ (Wb/m^2) $B = \mu H = \mu\frac{M}{4\pi\mu d^2} = \frac{M}{4\pi d^2}$ (Wb/m^2)

Thus, $P = e.I = N.A.\frac{dB}{dt}.\frac{H.\ell}{N} \Rightarrow P = A.\ell.H\frac{dB}{dt}$

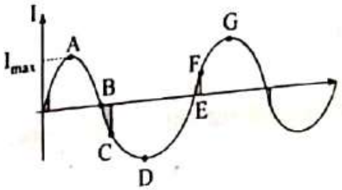
$\therefore$ Energy spent in small time interval, (dw) = P.dt.

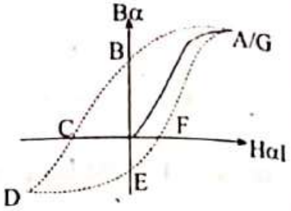
$\therefore$ Energy spent in one cycle of magnetization (i.e. the complete Hysteresis loop) = $\oint GH.dB$ $\Rightarrow$ if H.dB = shaded area

$\therefore$ $\frac{w}{A\ell} = \oint H.dB$ $\oint H.dB$ = complete area of the loop.

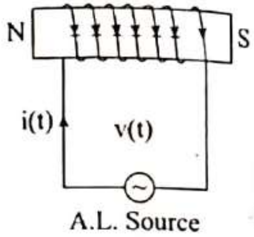
$\therefore$ Energy loss per unit volume = Area of the loop.

Hysteresis loss in ac excitation





With the varying voltage source, the core inside the coil gets magnetized & demagnetized in each cycle causing hysteresis loss.



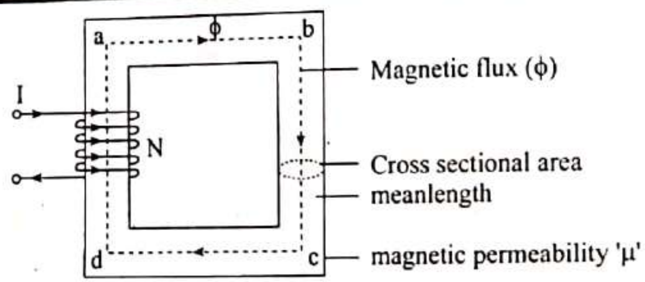
The power loss due to hysteresis.

P_h = η = steinmetz constant
= 502 J/m^3 (sheet steel
= 101 J/m^3 (silicon steel)

addition of silicon reduces 'η', hence reduces hysteresis loss.

$B_m \rightarrow$ max. flux density in the core/v $\rightarrow$ volume of iron core.

MAGNETIC CIRCUIT



⇒ Magnetic flux (ϕ) is analogous to electrical current (I),

⇒ In an electric circuit, the current flows due to an emf source. Similarly, in a magnetic circuit the magnetic flux is produced by a quantity known as mmf (magneto-motive force)

mmf = NI { N = number of turns in the winding; I = current flow through the winding }

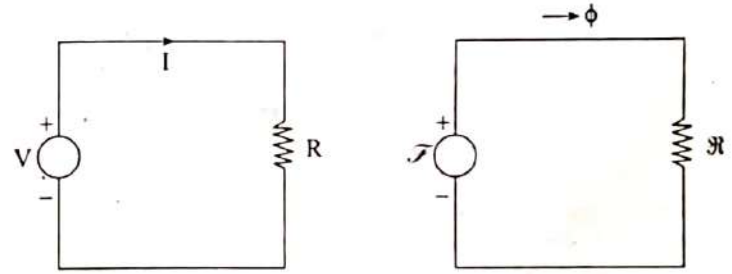
⇒ The current flowing through any electric circuit is opposed by the resistance of the path. Similarly, the magnetic reluctance ($\Re$) nature of the path.

⇒ $\Re = \frac{\ell}{\mu A} = \frac{\ell}{\mu_0 \mu_r A}$, ℓ = mean length of the magnetic path

μ = permeability of the core, A = cross-sectional area of core.

μ_r = relative permeability of the core

OHM'S LAW OF MAGNETIC CIRCUIT



Ohm's law:

V/I = R $\mathcal{F}/\phi = \Re$ $\phi = B \times A$

$\Rightarrow \phi = \mu H \times A$

$\Rightarrow \phi = \frac{\mu NI}{\ell}$

V = IR $\mathcal{F} = \phi\Re$ $\Rightarrow \phi = \frac{NI}{(\ell/\mu A)}$

Fig: Analogy between electric and magnetic circuits.

Hence, Ohm's law in magnetic circuit is,

mmf ($\mathcal{F}$) = $\phi\Re$

Then, the analogy is as:

Electrical	Magnetic circuit
1) current (I)	(1) Magnetic flux (ϕ)
2) emf (E)	(2) mmf ($\mathcal{F}$)
3) Resistance (R)	(3) Reluctance ($\Re$)
(4) I = E/R	(4) ϕ = mmf/$\Re$

SERIES & PARALLEL MAGNETIC CIRCUITS

SERIES MAGNETIC CIRCUIT

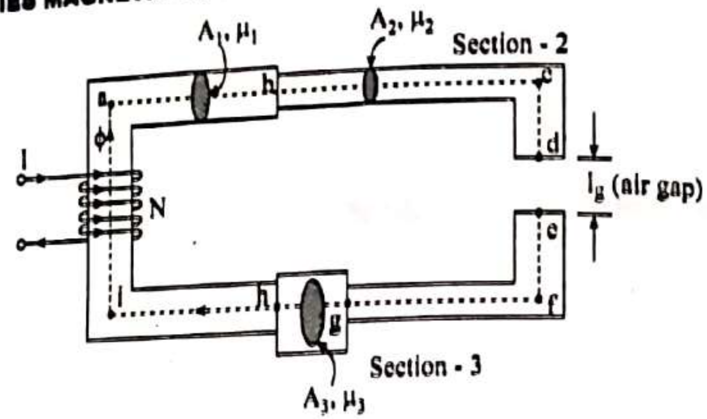


FIG.1: SERIES MAGNETIC CIRCUIT.

Series magnetic circuit is such magnetic circuit where same magnetic flux passes through all section of magnetic circuit as shown in Fig.1.

Here, mmf = NI & the same magnetic flux 'ϕ' flow through each section of the core. Now, reluctance of each part/section can be calculated as:

Section 1:

$\ell_1 = ba + bi + ih$

Area = A_1 and permeability = μ_1

$$\therefore \quad \mathfrak{R}_1 = \frac{\ell_1}{\mu_1 A_1}$$

Section 2:

$\ell_2 = bc + cd + ef + fg$

Area = A_2 and permeability = μ_2

$$\therefore \quad \mathfrak{R}_2 = \frac{\ell_2}{\mu_2 A_2}$$

Section 3:

$\ell_3 = hg$; Area = A_3 and permeability = μ_3

$$\therefore \quad \mathfrak{R}_3 = \frac{\ell_3}{\mu_3 A_3}$$

Air-gap:

length = ℓ_g; Area = A_g & permeability = μ_0

$$\therefore \quad \mathfrak{R}_g = \frac{\ell_g}{\mu_0 A_g}$$

Then, total reluctance in series is given by:

$$\mathfrak{R} = \mathfrak{R}_1 + \mathfrak{R}_2 + \mathfrak{R}_3 + \mathfrak{R}_g$$

$$\therefore \quad \phi = \frac{mmf}{\mathfrak{R}}$$

$$\Rightarrow \quad \boxed{\phi = \frac{NI}{\mathfrak{R}_1 + \mathfrak{R}_2 + \mathfrak{R}_3 + \mathfrak{R}_g}}$$

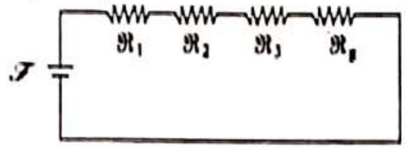


Fig: Electrical energy

Air gap has very high reluctance with compare to iron core. It reduces the magnetic flux in the circuit. It is quite similar to addition of very high resistance in series with low resistance in case of series electric circuit.

PARALLEL MAGNETIC CIRCUIT

If the magnetic flux produced by mmf, divides into two or more parallel paths in some sections of the magnetic circuit in a core, then those section are said to be in parallel as shown in figure.

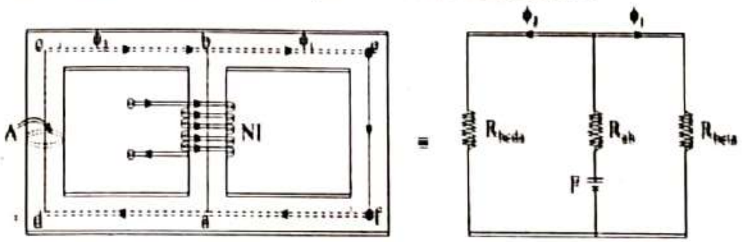


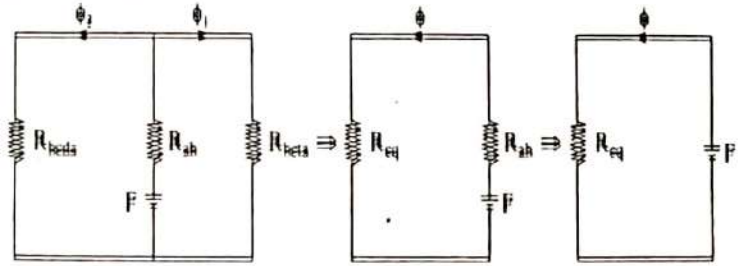
Fig: Electrical arology

Thus, in this case

$$R_{ah} = \frac{\ell_{ah}}{\mu A}; \; R_{beda} = \frac{\ell_{beda}}{\mu A}$$

$$R_{beta} = \frac{\ell_{beta}}{\mu A}$$

Thus, as in electrical circuit, the magnetic equivalent reluctance can be calculated as:



$$R_{eq} = \frac{R_{beda} \cdot R_{beta}}{R_{beda} + R_{beta}} \qquad R = R_{eq} + R_{ah}$$

$$\phi_{net} = \phi = F/R$$

$$\therefore \quad \phi = \frac{mmf}{R_{ab} + \frac{R_{bcda} * R_{beta}}{R_{bcda} + R_{beta}}}$$

$$\Rightarrow \quad \boxed{\phi = \frac{NI}{R_{ab} + \frac{R_{bcdc} * R_{beta}}{R_{bcda} + R_{beta}}}}$$

B-H RELATIONSHIP (MAGNETIZATION CHARACTERISTICS)

$B = \mu H$; $H = NI/\ell \Rightarrow H \propto I$

$B = \phi/A \Rightarrow B \propto \phi$

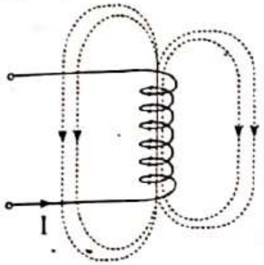


Fig: Coil without core

In the free space, the magnetic flux density (B) is directly proportion to the magnetizing force (H)

or, $B \propto H$

or, $B = \mu_0 H$, where μ_0 = permeability of free space

$= 4\pi \times 10^{-7}$ H/m

Here, the relationship between B & H is linear one

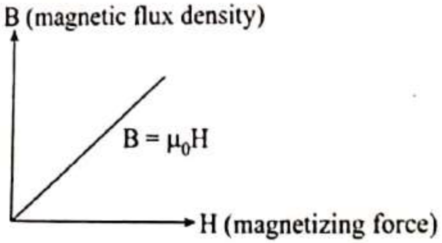


Fig: B-H characteristic curve without core, in free space.

The relationship between B and H in the case where magnetic materials are used as a core is strictly non-linear. For example, in the case of electric motors and transformers. A typical B-H curve for a magnetic material is shown below:

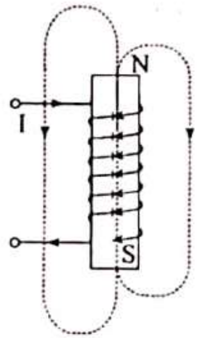


Fig: B-H characteristic curve with iron core (ferromagnetic material)

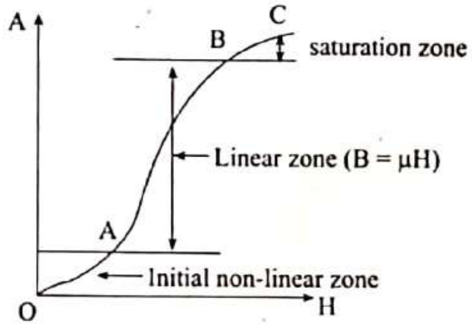


Fig. Typical BH curve of magnetic material

EDDY CURRENT LOSS

According to Faraday's law of electromagnetic induction the time varying flux in the core induces emf in the coils. Since the core itself is a conductor emf will also be induced in the core resulting circulating currents in the core. These currents are known as eddy currents and have a power loss (I^2R) associated with it. This loss is known as eddy currents loss.

This loss depends upon the
- → Resistivity of the material
- → Mean length of the path of the circulating current for a given cross-sectional area.

The eddy current loss in the core is given by:

$$\boxed{P_e = kB_m^2 f^2 t^2 V} \text{ (watt)}$$

Where,

B_M = maximum value of flux density in the core.

f = frequency of exciting current

V = volume of iron core.

t = thickness of each lamination.

k = constant, depending upon the nature of the core.

In practical applications, the eddy current loss can be reduced by:

(i) Adding silicon to steel which will give a high resistivity of the material.

(ii) By dividing up the solid core into laminations while making sure that each lamination is insulated form each other.

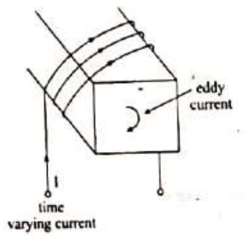


Fig. Solid core

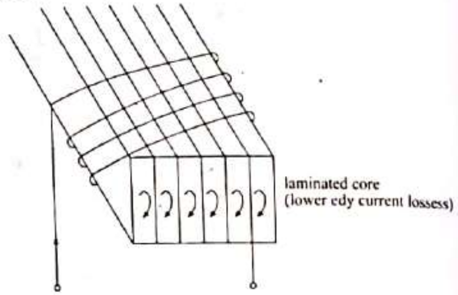


Fig. Laminated core

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION, STATICALLY & DYNAMICALLY INDUCED EMF.

A Gentlemen named Michael Faraday invented the relationship between Electricity & magnetism. He observed that the emf induce in a circuit when magnetic flux linking with the circuit changes momentary with respect to time. After his detail study of this phenomenon, he formulated some laws, which are well known as Faraday's laws of electromagnetic induction.

i) First Law

Whenever the magnetic flux linked with a conductor changes with respect to time, an emf will be induced in it.

(Magnetic flux linkage changes = cuts magnetic flux)

ii) Second law

The magnitude of emf induced is equal to the time rate of change of magnetic flux linkages.

The magnetic flux-linkage could be changed into two different ways:

(a) Statically induced emf
(b) Dynamically induced emf

$$e = N\frac{d\phi}{dt} = N\frac{d(BA)}{dt} = BN\frac{dA}{dt} + NA\frac{dB}{dt}$$

a) Statically induced emf: (Coil stationary field changing)

In this method, there is no physical movement of conductor or coil, only the magnitude of magnetic flux is changed. Hence changing the flux-linkage.

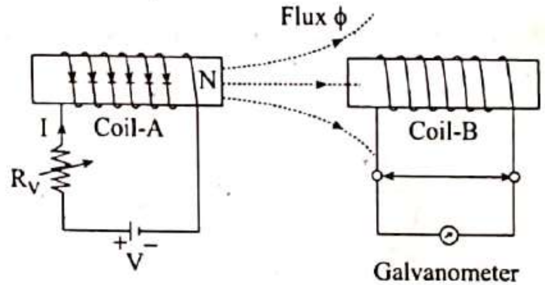


Fig: Illustration of statically induced emf.

→ When I is kept constant; no change in flux-linkage occur in coil-B & then no induced emf in coil-B.

→ When I is increased, change in flux-linkage i.e. increase in it occurs, and the galvanomerter shows a deflection in one direction indicating induced emf causing current flow. When I is decreased, the observation is just opposite.

→ If the magnetic flux in the coil-B changes from ϕ_1 to ϕ_2 in a small time interval from t_1 to t_2, then according to second statement given by Faraday's law of electromagnetic induction, emf induced in a single turn of coil-B is given by.

$$e(\text{per turn}) = \frac{\phi_2 - \phi_1}{t_2 - t_1} = \frac{d\phi}{dt} = \text{Rate of change of flux}$$

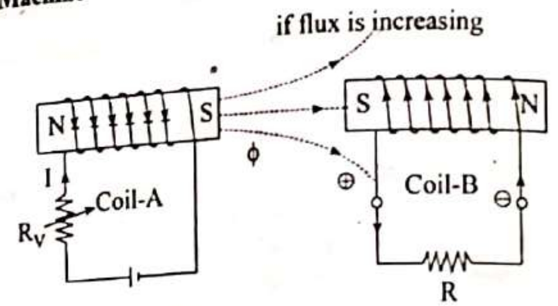
For 'N' number of turns in the coil-B. Total emf induced across the coil is given by

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

According to Lenz's law: Direction of induced current/emf in the conductor will be such that the magnetic field set up by the induced current opposes the cause by which the current/emf was induced.

Mathematically,

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



emf is induced to oppose the cause i.e. to decrease the flux from coil A.

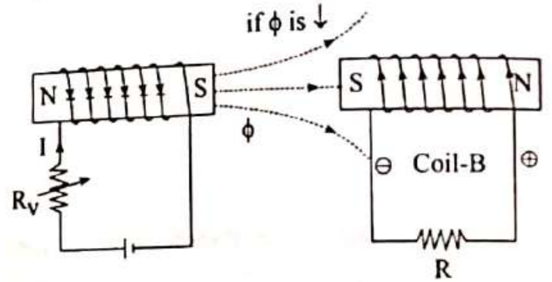


Fig: Lenz's law

b) Dynamically Induced Emf

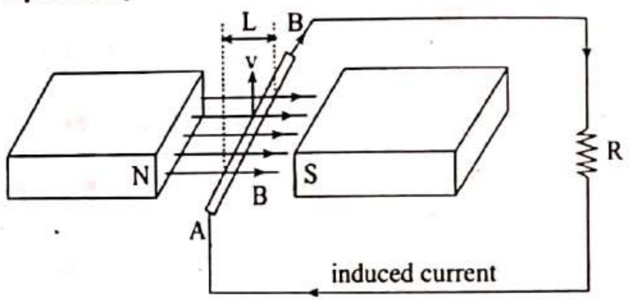


Fig: Dynamically induced emf

In this method, field is stationary & conductor cuts across it which is responsible for the change in flux linkage.

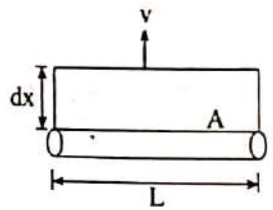


Fig: Area swept by the conductor in time.

As shown in the first figure, the conductor is moving upward in the magnetic field with velocity v. In small time 'dt' the conductor swept a distance dx with velocity 'v' Let, L be the length of conductor inside the electric field.

When the conductor moves in the magnetic field, there is a change in flux-linkage.

Now, the change in flux-linkage will be equal to the change in flux when conductor moves a distance dx, which is given by,

$d\phi = B \times A$; where A = area swept by conductor.

or, $d\phi = B \times dx \times L$

or, $d\phi = B \times L \times v \times dt \left(\because v = \frac{dx}{dt}\right)$

or, $\frac{d\phi}{dt} = BLv$ ...(i)

We know that, induced emf is given by,

$e = \frac{d\phi}{dt}$ ...(ii)

Thus,

e = BLv, Here, e, B & v are vector quantity. The direction of induced emf (or current) can be found out by using Fleming's right hand rule.

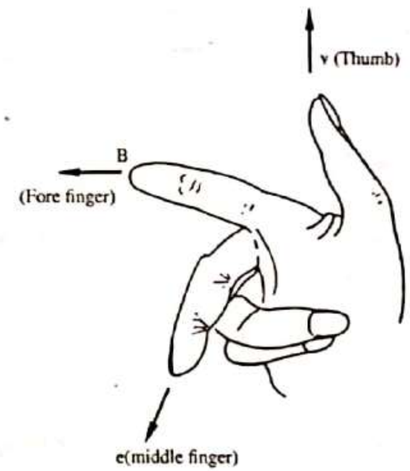
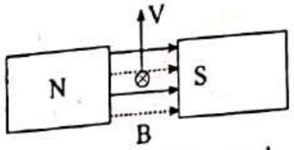
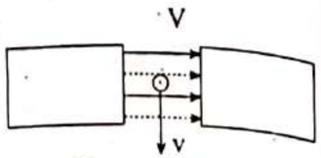


Fig: Fleming's right hand rule.

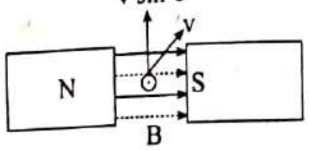


⊗→ Current flow inward the paper



⊙→ Current flow outward

If the direction of motion is inclined to the magnetic flux density as shown below;



Then only the component of velocity perpendicular to field 'B' is taken. Since the component parallel to B has no change in flux linkage. Thus, in general, the induced emf for dynamic case is

$$\boxed{e = BLv\sin\theta}$$

FORCE ON CURRENT CARRYING CONDUCTOR:

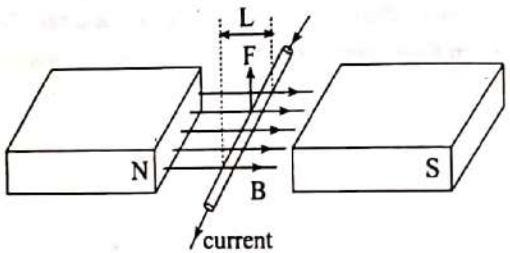


Fig: Force developed on current carrying conductor in a magnetic field.

When a current carrying conductor is placed in a magnetic field, then a force will develop on the conductor, whose magnitude is given by,

F = B.I. L (Newton)

Where,

B = magnetic flux density (Wb/m^2)

I = current passing through the conductor (A)

L = length of conductor lying within the magnetic field (m).

and the direction of force is given by the Fleming's left hand rule.

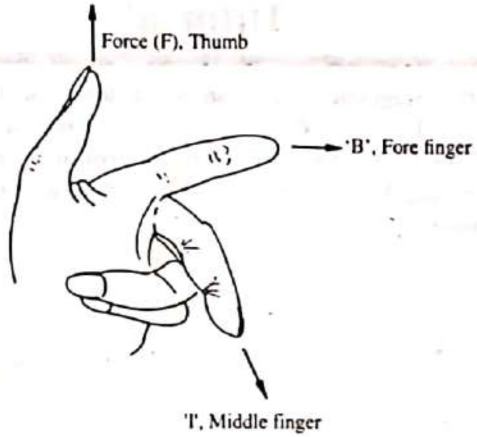


Fig. Flemming's left hand rule

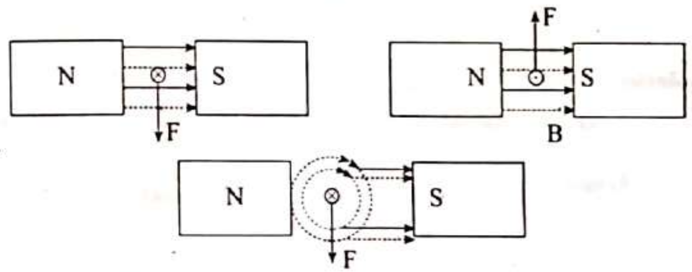
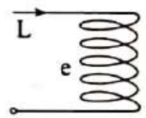


Fig. Application of Flemming's left hand rule

Self-Inductance:

nature to oppose the change in current through it represented by coefficient of inductance (L).



(i) $L\frac{di}{dt} = N\frac{d\phi}{dt} \Rightarrow \frac{Nd\phi}{dt}$

for $\phi \propto i \; \frac{d\phi}{di} = \text{constant} = \frac{\phi \leftarrow \text{rms, avg, peak}}{I \leftarrow \text{rms, avg, peak}}$

$$\Rightarrow \boxed{L = \frac{N\phi}{I}}$$

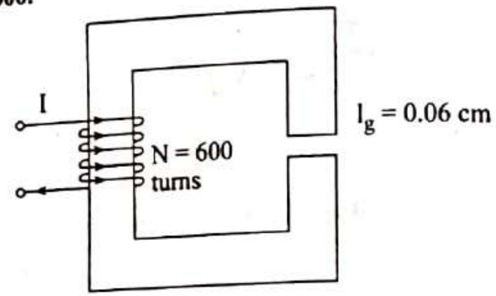
If $\phi \propto i$ is not valid, L may vary

ii) $L = \frac{N\phi}{I} = \frac{N}{I} \times \frac{\text{mmf}}{\text{reluctance}} = \frac{N}{I} \times \frac{NI}{\ell/\mu A} = \frac{N^2 \mu A}{\ell}$

$$\Rightarrow \boxed{L = \frac{N^2 \mu_r^2 \mu_0 A}{\ell}}$$

Tutorial

1. **For the magnetic circuit shown below calculate the value of current 'I' required to produce a magnetic flux density of 1.2 Tesla. Given that cross-sectional area of the core is 16 sq. mm, air gap length (ℓ_g) = 0.60 cm and length of core (ℓ_c) = 40 cm. Take $\mu_r = 6000$.** **[2075]**



Solution:

Total flux required (ϕ) = $B \times A = 1.2 \times 16 \times 10^{-4} = 19.2 \times 10^{-4}$ Weber

Reluctance of core = $\Re_C = \frac{\ell}{\mu A} = \frac{40 \times 10^{-2}}{4\pi \times 10^{-7} \times 6000 \times 16 \times 10^{-4}}$

$= 33157.28$

Reluctance of air gap = $\Re_g = \frac{\ell_g}{\mu A} = \frac{0.60 \times 10^{-2}}{4\pi \times 10^{-7} \times 16 \times 10^{-4}}$

$= 298415.52$

Total reluctance of the circuit ($\Re$) = $\Re_c + \Re_g = 331572.8$

Now,

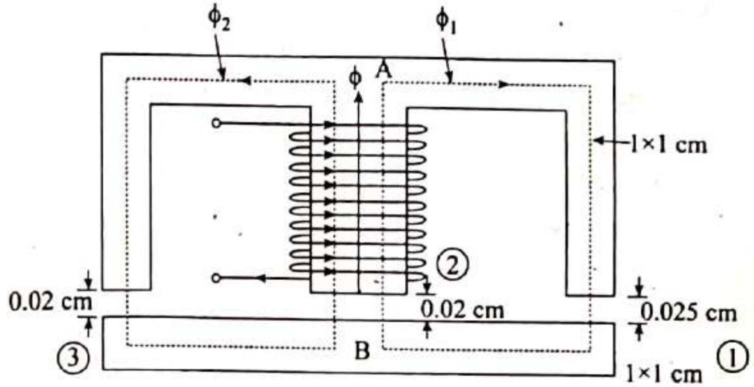
$$\phi = \frac{NI}{\Re}$$

or, $I = \frac{\phi \Re}{N} = \frac{19.2 \times 10^{-4} \times 331572.8}{600} = 1.06$ A

2. **For the given magnetic circuit cast steel core with dimensions as shown:**
   Mean length from A to B through either outer limb = 0.5m
   Mean length from A to B through central outer limn = 0.2m [2074]

Solution:

In the magnetic circuit shown, it is required to establish a flux of 0.75 mWb in the air gap of the central limb. Determine the mmf of the exciting coil for the core material (a) $\mu_g = \infty$ $\mu_r = 5000$



a) $\mu_r = \infty$, i.e. there are no mmf drops in the magnetic core. In this figure, two outer limbs are parallel magnetic circuit.

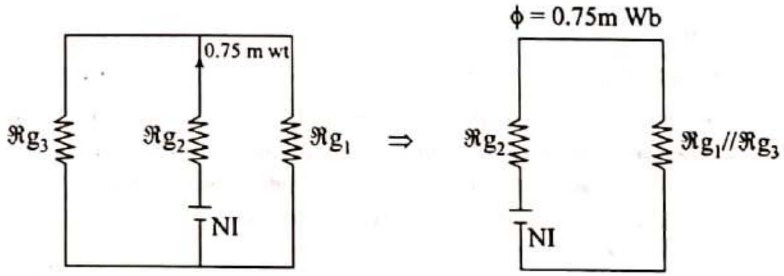
Now, air gap reluctances are:

$\Re_{g_1} = \frac{0.025 \times 10^{-2}}{45c \times 10^{-7} \times 1 \times 10^{-4}} = 1.99 \times 10^6$ AT/Wb

$\Re_{g_2} = \frac{0.02 \times 10^{-2}}{4\bar{x} \times 10^{-7} \times 2 \times 10^{-4}} = 0.796 \times 10^6$

$\Re_{g_3} = \frac{0.02 \times 10^{-2}}{4\bar{x} \times 10^{-7} \times 1 \times 10^{-4}} = 1.592 \times 10^6$

the electrical analog of the magnetic ckt is:



(a) (b)

mmf = $\phi \Re = 0.75 * 10^{-3} (\Re g_1 || \Re g_3 + \Re g_2) = 1230$ AT

b) $\mu_r = 5000$, mmf = 1466 AT

3. **The magnetic circuit as shown in fig: 1 has dimensions: $A_C = 4*4$ cm^2. $L_g = 0.06$ cm, $l_c = 40$ cm, N = 600 turns. Assume the value of $\mu_r = 6000$ for iron core. Find the exciting current for $B_c = 1.2$ T, the corresponding flux and flux linkage.** **[2073, 2071]**

Solution:

Here, Area of core (A_C) = $4 \times 4 = 16\ cm^2 = 16 \times 10^{-4}\ m^2$

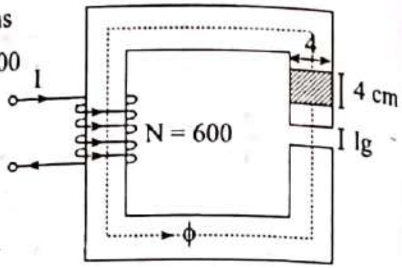
Length of air gap (ℓ_g) = $0.06\ cm = 0.06 \times 10^{-2}\ m$

Length of iron core (ℓ_C) = $40\ cm = 0.4\ m$

Number of turns (N) = 600 turns

Relative permeability (μ_r) = 6000

Flux density (B_C) = 1.2T



Now,

$$\phi = B_c \times A$$
$$= 1.2 \times 16 \times 10^{-4}$$
$$= 1.92 \times 10^{-3}\ Wb$$

Equivalent reluctance ($\Re_{eq}$) $= \Re_c + \Re_g = \dfrac{\ell_C}{\mu_0\mu_r A_c} + \dfrac{\ell_C}{\mu_0 A_g}$

$$= \frac{0.4}{6000 \times 4 \times 10^{-7} \times 16 \times 10^{-4}} + \frac{0.06 \times 10^{-2}}{4\pi \times 10^{-7} \times 16 \times 10^{-4}}$$

$\therefore\ \Re_{eq} = 331572.79$

So, $\phi = \dfrac{NI}{\Re_{eq}} \Rightarrow I = \dfrac{\phi\Re_{eq}}{N}$

$\therefore\ I = \dfrac{1.92 \times 10^{-3} \times 331572.79}{600} = 1.06\ A.$

Flux = $\phi = 1.92 \times 10^{-3}$ Wb

Flux linkage = NBA = Nϕ = $600 \times 1.92 \times 10^{-3} = 1.152$ Wb-turn

4. **A wrought iron bar of 30 cm long and 2 cm diameter is bent into a circular shape as shown in fig:2. It is then wound with 600 turns of wire. Calculate the current required to produce a flux of 0.4 mWb in the magnetic circuit for the following cases:**
   i) With no air gap
   ii) With air gap of 1 mm, μ_r=4000 **[2075]**

Solution:

Here, Area of core (A_C) = $\dfrac{\pi d^2}{4} = \dfrac{\pi}{4} \times 0.02^2 = 3.14 \times 10^{-4}\ m^2$

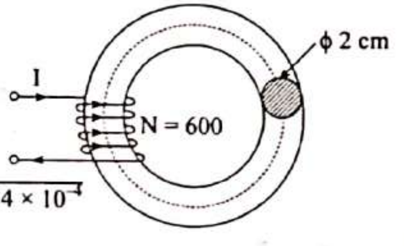
Length of iron core (ℓ_C) = 0.3 m

No. of turns (N) = 600 turns

Flux (ϕ) = 0.4×10^{-3} Wb

Case I:

With No air gap:



$$\Re = \frac{\ell_C}{\mu A_C}$$
$$= \frac{0.3}{4000 \times 4 \times 10^{-7} \times 3.14 \times 10^{-4}}$$

$\therefore\ \Re = 190073.57$

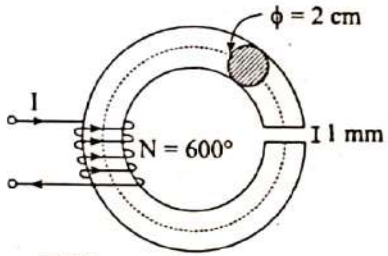
Now,

$$I = \frac{\phi\Re}{N} = \frac{0.4 \times 10^{-3} \times 190073.57}{600}$$

$\therefore\ I = 0.126\ A$

Case II:

Air gap of 1 mm.



Here, $\Re_{eq} = \Re_C + \Re_g$

$$= \frac{\ell_C}{\mu_0\mu_r A_c} + \frac{\ell_g}{\mu_0 A_C}$$
$$= \frac{1}{4\pi \times 10^{-7} \times 3.14 \times 10^{-4}}\left[\frac{0.3}{4000} + 10^{-3}\right]$$
$$= 2724387.959$$

$\therefore\ I = \dfrac{\phi\Re_{eq}}{N} = \dfrac{0.4 \times 10^{-3} \times 2724387.959}{600} = 1.816\ A.$

5. **The magnetic circuit of a cast steel core as shown in fig:3 has a the following dimension:**

   Mean length from A to B through either outer limb = 0.5 m

   Mean length from A to B through central limb = 0.2 m

   In the magnetic circuit, determine the mmf required to establish a flux of 0.75 mWb in the air gap of the central limb of the core. Take μ_r = 5000 **[2070]**

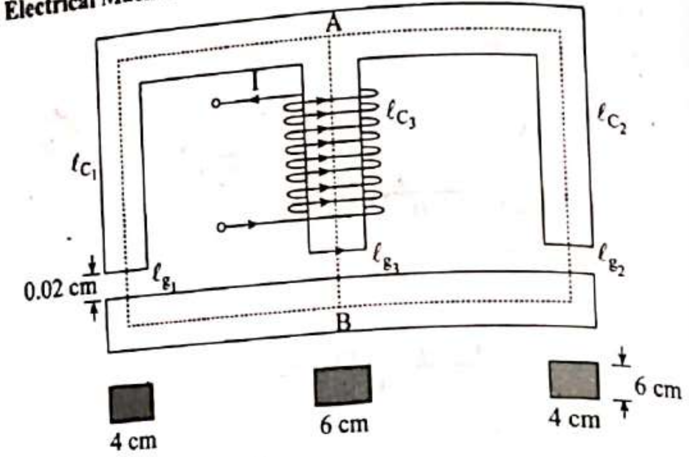
Solution:

Here, $\ell_{C_1} = 0.5\ m = \ell_{C_2}$

$\ell_{C_3} = 0.2\ m$

$\phi = 0.75 \times 10^{-3}$ Wb

$\mu_1 = 5000$



Here, $\Re_{C_1} = \Re_{C_2} = \dfrac{\ell_{C_1}}{\mu_0\mu_r A_{C_1}} = \dfrac{0.5}{5000 \times 4\pi \times 10^{-7} \times 24 \times 10^{-4}} = 33157.27$

$$\Re_{g_1} = \Re_{g_1} = \frac{\ell_{g_1}}{\mu_0 A_{g_1}} = \frac{0.02 \times 10^{-2}}{4 \times 10^{-7} \times 24 \times 10^{-4}} = 66314.56$$

$$\Re_{C_3} = \frac{\ell_{C_1}}{\mu_0 \mu_r A_{C_3}} = \frac{0.2}{5000 \times 4\pi \times 10^{-7} \times 36 \times 10^{-4}} = 8841.94$$

$$\Re_{g_3} = \frac{\ell_{g_3}}{\mu_0 A_{g_3}} = \frac{0.02 \times 10^{-2}}{4\pi \times 10^{-7} \times 36 \times 10^{-4}} = 44209.706$$

Now,

$$\Re_{eq} = \left[\frac{(\Re_{C_1} + \Re_{g_1})}{(\Re_{C_2} + \Re_{g_2})}\right] + (\Re_{C_3} + \Re_{g_3})$$

$$= \left[\frac{(33157.27 + 66314.56)}{(33157.27 + 66314.56)}\right] + (8841.94 + 4209.706)$$

$$= \frac{33157.27 + 66314.56}{2} + 53051.646$$

$$= 102787.561$$

Now,

$$\text{mmf} = NI = \phi\Re_{eq} = 0.75 \times 10^{-3} \times 102787.561$$

$\therefore$ mmf = 77.09 Amp-turn

6. An iron ring of mean length 1.2 m and cross sectional area of 0.005 m^2 is wound with a coil of 900 turns. If a current of 2 A in the coil produces a flux density of 1.2 T in the iron ring, calculate:

i) The mmf

ii) Total flux in the ring

iii) The magnetic field strength

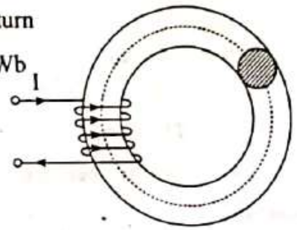
iv) The relative permeability of iron at this flux density [2069]

Solution:

Here, $\ell_C = 1.2$ m, $A_C = 0.005\text{m}^2$

$N = 900$, $I = 2\text{A}$, $B = 1.2$ T

(i) mmf = NI = 900 × 2 = 1800 Amp-turn



(ii) $\phi = BA_C = 1.2 \times 0.005 = 6 \times 10^{-3}$ Wb

(iii) $H = \dfrac{NI}{\ell_C} = \dfrac{1800}{1.2} = 1500$ A/m

(iv) $\phi = \dfrac{NI}{\dfrac{\mu}{\mu A}} = \dfrac{NI\,\mu A_C}{\ell_C}$

$\therefore \quad \mu = \dfrac{\phi \ell_C}{NIA_C}$

or, $\mu_r = \dfrac{\phi \ell_C}{\mu_0 NIA_C} = \dfrac{6 \times 10^{-3} \times 1.2}{4\pi \times 10^{-7} \times 1800 \times 0.005} = 636.619$

7. An iron ring has a mean length of 1.5 m and cross sectional area of 0.01 m^2. It has radial air gap of 4 mm. The ring is uniformly wound with 250 turns. What direct current would be needed in the coil to produce flux of 0.8 mWb in the air gap? Assume relative permeability of iron as 400 and leakage factor as 1.25. [2068]

Solution:

$\ell_C = 1.5$ m, $A_C = 0.01$ m^2

$\ell_g = 0.004$ m, $N = 250$

$\phi_g = 0.08 \times 10^{-3}$Wb, $\mu_r = 400$

Here, leakage factor = 1.25

So, magnetic flux in iron care, $\phi_c = 1.25 \times \phi_g = 1.25 \times 0.8 \times 10^{-3}$

$= 10^{-3}$ Wb

Now,

$$\text{Total mmf} = \phi_C \Re_C + \phi_g \Re_g$$

$$= 10^{-3} \times \frac{1.5}{400 \times 4\pi \times 10^{-7} \times 0.01} + 0.8 \times 10^{-3} \times \frac{0.004}{4\pi \times 10^{-7} \times 0.01}$$

$$= 553.063$$

or, $NI = 553.063$

$\therefore \quad I = \frac{553.0.63}{250} = 2.21$ Amp.

8. **A magnetic circuit has a uniform cross sectional area of 5 cm² and length of 25 cm. a coil of 120 turns is wound uniformly over the magnetic circuit. When the current in the coil is 1.5 A, total flux is 0.3 mWb and when the current is 5 A, the total flux is 0.6 mWb. For each value of the current, calculate:**

   i) **The mmf**

   ii) **Relative permeability of the core** **[2067]**

Solution:

$A_C = 5 \times 10^{-4}\, m^2$, $\ell_C = 25 \times 10^{-2} = 0.25$ m, $N = 120$

Now,

When current through the coil, $I = 1.5$ A, $\phi = 0.3 \times 10^{-3}$

So,

(i) mmf = NI = 120 × 1.5 = 180 Amp-turn

Also,

(ii) $\phi = \frac{NI\,\mu A}{\ell_C} \Rightarrow \mu = \frac{\phi \ell_C}{NIA}$

$\therefore \quad \mu_r = \frac{\phi \ell_C}{\mu_0 NIA} = \frac{0.3 \times 10^{-3} \times 0.25}{4\pi \times 10^{-7} \times 120 \times 1.5 \times 5 \times 10^{-4}}$

$\therefore \quad \mu_r = 663.1455$

When current in the coil is $I = 5$A, $\phi = 0.6 \times 10^{-3}$ Wb.

So,

(i) mmf = NI = 120 × 5 = 600 Amp-turn

(ii) $\mu_r = \frac{\phi \ell_C}{\mu_0 NIA} = \frac{0.6 \times 10^{-3} \times 0.25}{4\pi \times 10^{-7} \times 600 \times 5 \times 10^{-4}}$

$\therefore \quad \mu_r = 397.88$ **Ans.**

9. **A 30 cm long circular iron rod is bent into circular ring and 600 turns of windings are wound on it. The diameter of the rod is 20mm and relative permeability of the iron is 4000. A time varying current $i = 5 \sin 314.16t$ is passed through the winding. Calculate the inductance of the coil and average value of emf induced in the coil. [1.89H, 1890V]** **[2066]**

Solution:

$\ell = 0.3$ m, $N = 600$, $A = \frac{\pi}{4} \times (0.02)^2 = 3.14 \times 10^{-4}\, m^2$, $\mu_r = 4000$,

$i = 5 \sin 314.16\, t$

Now,

Inductance of coil (L) $= \frac{\mu N^2 A}{\ell} = \frac{4000 \times 4\pi \times 10^{-7} \times 3.14 \times 10^{-4} \times 600^2}{0.3}$

$\therefore \quad L = 1.89$H

Instantaneous emf (e) $= L\frac{di}{dt} = 1.89 \times 5 \times 314.16 \cos 315.16\, t$

$\therefore \quad e = 2968.8 \cos 314.16\, t$

$\therefore \quad$ Peak emf $(e_0) = 2.968.812$

Hence, average induced emf $= e_{avg} = \frac{2}{\pi} e_0 = \frac{2}{\pi} \times 2968.812$

$\therefore \quad e_{avg} = 1889.99$ V **Ans.**

10. **A magnetic circuit consists of a circular iron core having mean length of 10cm and cross sectional area of 100 mm². The air gap is 2mm and the core has 600 turns of winding. Calculate the magnitude of current to be passed through the winding to produce air gap flux of 1T(permeability of iron - 4000).** **[2065]**

Solution:

Air-gap Reluctance $(R_g) = \frac{\ell_g}{\mu_0 \times A} = \frac{2 \times 10^{-3}}{\mu_0 \times 100 \times 10^{-6}}$

$= 15915494.31$ At/Wb

Reluctance of core $(R_c) = \frac{\ell_c}{\mu_0\, \mu_r \times A} = \frac{0.1}{\mu_0 \times 4000 \times 100 \times 10^{-6}}$

$= 198943.6789$ AT/Wb

$\therefore \Re_{Total} = \Re_g + \Re_c$

We have,

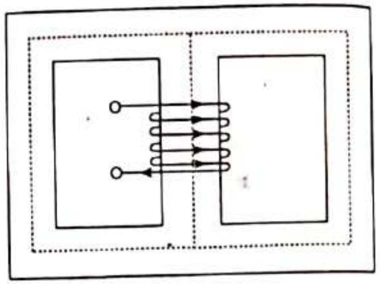
$$\phi = \frac{NI}{R_{total}}$$

or, $(1 \times 100 \times 10^{-6}) = \frac{600 \times I}{16.11 \times 10^6}$

$\therefore$ $I = 2.685$ Amp.

11. For the magnetic circuit shown below, calculate the amp-turn (NI) required to establish a flux of 0.75 Wb in the limb. Given that $\mu_r = 400$ for iron core. [2064]

Solution:



Flux need to be developed (ϕ) = 0.75 Wb; $\mu_r = 4000$, NI = ?

Equivalent electric circuit,

Now,

$$\Re_1 = \frac{\mu}{\mu A_1}$$

$$= \frac{(20 + 20 + 20) \times 10^{-2}}{(\mu_0 \times \mu_r) \times (4 \times 4 \times 10^{-4})}$$

$= 7.46 \times 10^4$ AT/Wb

Similarly,

$\Re_2 = \Re_1$ ($\because$ By Virtue of Symmetricity)

And,

$$\Re_3 = \frac{\ell_3}{\mu_0\mu_r \times A_3} = \frac{0.2}{m_0 \times 4000 \times (6 \times 4 \times 10^{-4})} = 1.66 \times 10^4 \text{ AT/Wb}$$

$\therefore$ $R_{total} = \frac{R_1}{2} + R_3 = 6.39 \times 10^4$ AT/Wb [$\because R_1 // R_2 + R_3 = R_{total}$]

Now,

$$\phi = \frac{NI}{R_{Total}}$$

or, $0.75 = \frac{NI}{5.39 \times 10^4}$

$\therefore$ $NI = 4.04 \times 10^4$ AT

12. An iron ring of mean length of 1.2m and cross-sectional area of 0.05 m^2 is wound with a coil of 900 turns. If a current of 2A in the coil produces a flux density of 2Wb/m^2 in the iron ring. Calculate.

(i) the min$_r$ (ii) total flux in the core

(iii) magnetic field strength

(iv) Relative permeability of the core [2063]

Solution:

(i) mmf = NI = 1800 AT

(ii) Total flux (ϕ) = BA = 0.1 Wb

(iii) Magnetic field strength (H) $= \frac{NI}{\ell} = \frac{900 \times 2}{1.2} = 1500$ A T/meter

(iv) Relative permeability (μ_r) $= \frac{B}{\mu_0 H} = \frac{2}{(\mu_0) \times 1500} = 1061.032$

13. A time varying current (from 2A to 20A) in 50 ms is applied through 2000 number of turns over a core of given dimension. Calculate the emf produced across the coil. [2062]

Solution:

Change in current (di) = (20 – 2) = 18A Change in time (dt) = 50 ms = 50×10^{-35}, N = 2000, $\mu r = 4000$

We have,

$\phi = LI$

or, $NBA = LI$

or, $2000 \times 9 \times 10^{-4} \times B = L \times I$

or, $1.8 \times \frac{N \times I}{A \times R_t} = L \times I$

or, $L = \frac{1.8}{9 \times 10^{-4}} \times \frac{N}{(l_{eff}/\mu_r\mu_0 \times A)}$

$= \frac{1.8}{9 \times 10^{-4}} \times \frac{\mu_r \times \mu_0 \times 9 \times 10^{-4} \times 2000}{2(10 + 15) \times 10^{-2}}$

$\therefore$ $L = 36.1911$ H

$E = L\frac{di}{dt} = 36.1911 \times \frac{18}{50 \times 10^{-3}}$

$\therefore$ $E = 13.028 \times 10^3$ V

14. An iron ring of mean diameter 100 cm and cross-section area 10 cm^2 is wound with 1000 turns and has $\mu r = 2000$. Compute (i) Reluctance (ii) Flux produced when current through the coil is 1A (iii) Flux in ring if a saw cut of 1 mm length is made, the current through the coil remaining the same.

Solution:

(i) Reluctance ($\Re$) $= \frac{l_{eff}}{\mu_0\mu_r A} = \frac{\pi d}{m_0 \times 2000 \times 4x\,(10 \times 10^{-4})}$

$= 1.25 \times 10^6$ AT/Wb

(ii) $\phi = \frac{NI}{R} = 0.0008$ Wb

(iii) $\Re_{air\ gap} = \frac{lg}{\mu_0 \times A} = \frac{1 \times 10^{-3}}{\mu_0 \times 10 \times 10^{-4}} = 795774.71$ AT/Wb

$\Re_t = \Re_{core} + \Re_{air\ gap} = 20.458 \times 10^5$ AT/Wb

Air gap flux $(\phi) = \frac{NI}{\Re t} = \frac{1000 \times 1}{20.458 \times 10^5} = 0.4888$ mWb.

15. A magnetic current consists of a circular iron core having mean diameter of 10 cm and cross-section area of 100 mm^2 and air gap of 2 mm. The core has two turns of winding. Calculate the magnitude of electric current to be passed through the winding to produce air gap flux of 1T. Given $\mu_r = 4000$.

Solution:

Mean diameter of core (d) = 10 cm = 0.1 m

Cross sectional Area (A) = 100×10^{-6} m^2

Length of air gap (lg) = 2×10^{-3} m

No. of turns (N) = 600

Mean Length (l) = πd = 0.314159 m

Magnetic flux density (B) = 1T

Magnetic flux (ϕ) = BA = $1 \times 100 \times 10^{-6} = 100 \times 10^{-6}$ Wb

Relative permeability (μ_r) = 4000

Now, Reluctance of iron core ($\Re_{core}$) = $\frac{l}{\mu_r \mu_0 A}$

[$\because \mu_0 \rightarrow \frac{\text{constant (33)}}{\text{Shift + (7) + (33)}}$ = 625000 AT/Wb.

Reluctance of air gap ($\Re_g$) = $\frac{l_g}{\mu_0 A}$ = 15915494.31 AT/Wb

$\therefore$ The total reluctance of the magnetic flux path is

$\Re_t = \Re_{Core} + \Re_g = 16.54 \times 10^6$ AT/Wb

and, $\phi = \frac{NI}{\Re_t}$ (i.e. ϕ = mmf/$\Re_t$)

or, $100 \times 10^{-6} = \frac{600 \times I}{16.54 \times 10^6}$

$\Rightarrow$ I(dc) = 2.7567 Amp

16. For magnetic circuit shown in figure below, find out the current to be passed through the coil B so that magnetic flux in CD section is 2MWb, Given $\mu_r = 1000$.

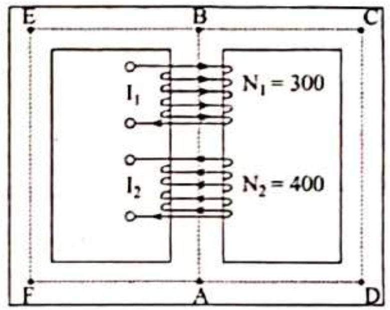
Given,

I_2 = 3A, A_1 = 6cm^2, A_2 = 3 cm^2

AB = CD = EF = 20 cm

BC = AD = BE = AF = 20 cm

Solution:



Equivalent electrical circuit

$R_1 = \frac{l_{eq}}{\mu_0 \mu_r A_2} = \frac{(EF + EB + BC + CD + DA + AF)}{\mu_0 \mu_r \times 3 \times 10^{-4}}$

$= \frac{1.4}{\mu_0 \mu_r \times 3 \times 10^{-4}} = 37.14 \times 10^5$ AT/Wb

$R_2 = \frac{20 \times 10^{-2}}{\mu_0 \times \mu_r \times 6 \times 10^{-4}} = 26.53 \times 10^4$ AT/Wb

Req = $R_1 // R_2 = 24.76 \times 10^4$ AT/Wb

$mmf_1 = N_1 I_1 = 300\ I_1$, $mmf_2 = N_2 I_2 = 1200$ AT

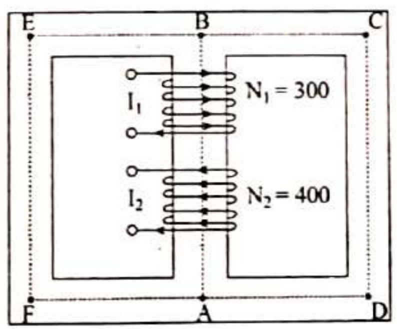
$\phi = \frac{N_1 I_1 - N_2 I_2}{R} \Rightarrow (B_2 A_2 R) = 300I_1 - 1200$

$\Rightarrow 2 \times 10^{-3} \times 3 \times 10^{-4} \times 24.76 \times 10^4 = 300\ I_1 - 1200$

$\therefore$ I_1 = 4 Amp

17. Magnetic circuit shown in figure below, find out the current to be passed through the coil B so that magnetic flux in CD section is 2mWb, Given $\mu_r = 1000$.
Given, I_2 = 3A, A_1 = 6 cm^2, A_2 = 3 cm^2
AB = CD = EF = 20 cm
BC = AD = BE = AF = 20 cm **[2070]**

Solution:



Flux due to coil B (Up ward/clock wise)

$$\phi_B = \frac{\mu_0\mu_r N_1 I_1 A_1}{l_1} = \frac{m_0 \times 1000 \times 300 \times 6 \times 10^4 \times 71}{2(AD + AF + E) + AB}$$

$$\phi_B = 1.6157 \times I_1 \times 10^{-4} \ldots(i)$$

Flux due to coil A(anti-clockwise)

$$\phi_A = \frac{m_0 \times 1000 \times 400 \times 6 \times 10^{-4} \times 3}{1.4} = 6.4627 \times 10^{-4}$$

$$mmf_1 = N_1I_1 = 300\,I_1,\ mmf_2 = 1200 \text{ AT}$$

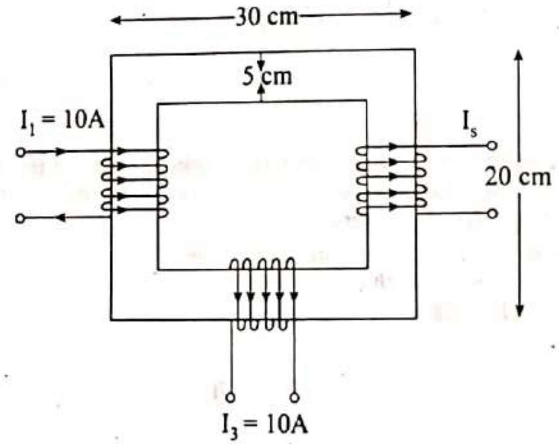
$$\phi = \frac{N_1I_1 - N_2I_2}{R}$$

or, $BA_2R = N_1I_1 - N_2I_2$

$$\Rightarrow \quad I_2 = 300I_1 - 2 \times 10^{-3} \times 3 \times 10^{-4} \times \frac{1.4}{\mu_0\mu_r \times 3 \times 100}$$

18. Calculate the magnetic flux in the core of the following magnetic circuit and show the direction of magnetic flux in the core. Given that cross-sectional area at the core is 25 sq. cm and $\mu_r = 4000$.

Solution:



$B = \mu_4$

$$\phi/A = \mu_0\mu_r\frac{NI}{\ell}$$

$$\phi_1 = \frac{NI\mu_0\mu_pA}{\ell} = \frac{200 \times 10 \times 4\pi \times 10^{-7} \times 4000 \times 25 \times 10^{-4}}{80 \times 10^{-2}}$$

$= 0.031415928$ Wb(↺)

Similarly,

$$\phi_2 = \frac{N_2I_2\mu_0\mu_rA}{l} = \frac{300.15 \times 4\pi \times 10^{-7}}{80 \times 10^{-2}} = 0.07068 \text{ Wb}(\circlearrowright)$$

and
$$\phi_3 = \frac{N_3I_3\,\mu_0\mu_pA}{\ell} = \frac{100 \times 10 \times 4\pi \times 10^{-7} \times 4000 \times 25 \times 10^{-4}}{80 \times 10^{-2}}$$

$= 0.015708$ Wb(↺)

Taking clockwise on positive.

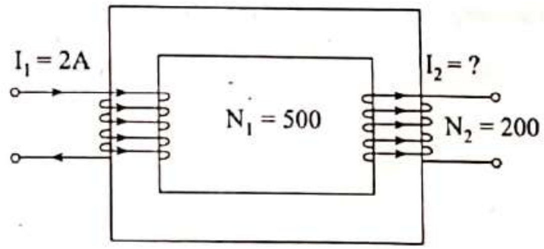
∴ Magnetic flux in the core of the given magnetic circuit

$$= -\phi_1 + \phi_2 - \phi_3 = -0.031416 + 0.07068 - 0.015708$$

$= 0.023556$ Wb(↻)

19. In figure given below, calculate value of I_2 required to establish a magnetic flux density of 1.2 Wb/m² in the core given, $\mu_r = 600$, the mean length of core 40 cm, area of core is 16 sq. cm.

Solution:



Given,

Magnetic flux density (B) = 1.2 Wb/m²

Area of core = 16 cm² = 16×10^{-4} m²

$\mu_r = 600$

Mean length of core (l) = 40 cm = 0.4 m

$$\text{Reluctance of core} = \frac{l}{\mu_0\mu_rA} = \frac{0.4}{m_0 \times 600 \times 0.16 \times 10^{-4}} = 331.57 \times 10^3 \text{ AT/Wb}$$

$mmf_1 = N_1I_1 = 500 \times 2 = 1000$ AT

$mmf_2 = N_2I_2 = 200I_2$ AT

Then, we have,

$$\phi = \frac{N_1I_1 - N_2I_2}{\mathfrak{R}}$$ [along the direction shown in figure (i.e. clockwise)]

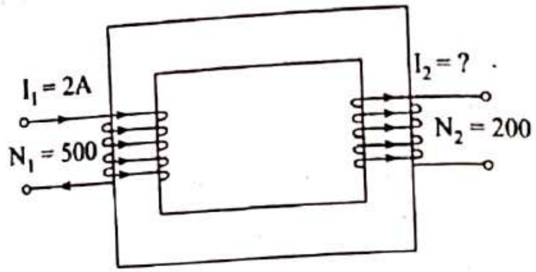
or, $BA\mathfrak{R} = 1000 - 200I_2$

or, $1.2 \times 16 \times 10^{-4} \times 331.57 \times 10^3 = 1000 - 200I_2$

∴ $I_2 = 1.82$ A

20. In figure below, calculate the value of I_2 required to establish a magnetic flux density of 1.2 Wb/m² in the core. Given $\mu_r = 600$, the mean length of core 40 cm, area of core 16 cm².

Solution:



Magnetic flux density (B) = 1.2 Wb/m²

Area of core = 16 cm² = 16×10^{-4} m²

$\mu_r = 600$

Mean length of core (l) = 40 cm = 0.4

Reluctance of core (R_t) $= \dfrac{l}{\mu_0 \mu_r A} = 33.1567X^4$ AT/Wb

$mmf_1 = N_1 I_1 = 500 \times 2 = 1000$ AT

$mmf_2 = N_2 I_2 = 200 \times I_2$

We know,

$$\phi = \frac{N_1 I_1 - N_2 I_2}{R}$$

or, $BA = \dfrac{1000 - 200I_2}{33.157 \times 10^4}$

$\therefore$ $I_2 = 1.8169$ Amp

21. An iron ring has a mean length of 2 m and cross-sectional area of 0.01 m². It has a radial air gap of 4 mm. The ring is ground with 250 turns. What dc current would be needed in the coil to produce a flux of 0.8 Wb in the gap? Assume that $\mu_r = 400$.

Solution:

Reluctance of core ($\Re_C$) $= \dfrac{l_{eff}}{\mu_0 \mu_r A} = \dfrac{2}{\mu_0 \times 400 \times 0.01}$

$= 39.79 \times 10^4$ AT/Wb

Reluctance of Air gap ($\Re_g$) $= \dfrac{l_g}{\mu_0 \times A} = \dfrac{4 \times 10^{-3}}{m_0 \times 0.01} = 31.83 \times 10^4$ AT/Wb

$\therefore$ Total Relucrtance ($\Re_T$) = $\Re_c + \Re_g = 71.62 \times 10^4$ At/Wb

We have,

$$\phi = \frac{NI}{\Re_T}$$

or, $0.8 = \dfrac{NI}{71.62 \times 10^4}$

or, $I = \dfrac{71.62 \times 10^4 \times 0.8}{250}$

$\therefore$ Idc = 2291.84 AS

22. A 30 cm long circular iron rod in bend into circular ring and 600 turns of winding are round on it. The diameter of the rod is 20 mm and relative permeability of the iron is 40.00. A time varying current (i = 5 sin 314.16 t) is passes through the winding. Calculate the inductance of the coil and value of emf induced in the coil.

Solution:

Length of iron rod (l) = 30×10^{-2} m

Number of turns (N) = 600 t, $\mu_r = 4000$

Diameter of the rod (d) = 20×10^{-3}m

Time varying current (i) = 5 sin 314.16 t

Inductance (l) $= \dfrac{N^2 \mu_0 \mu_r \times A}{l} = \dfrac{600^2 \times \mu_0 \times 4000 \times \left(\frac{\pi}{4} \times (20 \times 10^{-3})^2\right)}{30 \times 10^{-2}}$

$\therefore$ L = 1.8949

Now,

I = 5 sin 31416t

$I_{max} = 5$

$\therefore$ $I_{avg} = \dfrac{I_{max}}{\frac{\pi}{2}} = 3.183$

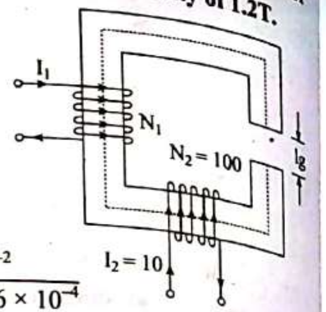
$[wt = 314.16\ t;\ wt = 2\pi ft = 314.16\ t;\ f = \dfrac{314.16}{2\pi} = 50 \text{ Hz}]$

Induction reactance (X_L) $= 2\pi fL = 2\pi \times 50 \times 1.89 = 593.761$

$\therefore$ Average value of emf induced,

$= I_{avg} \times X_L = 3.183 \times 593.761 = 1889.94$ V

23. For the magnetic circuit shown below, calculate the value of current 'I' required to produce a magnetic flux density of 1.2T.



Solution:

Given,

$A = 16\ cm^2$, $lg = 0.06$ cm,

$lc = 40$ cm, $\mu_r = 6000$

$B = 1T$, $\phi = BA = 16 \times 10^{-4}$ Wb

Now,

$$R_{core} = \frac{l_c}{\mu_r \mu_0 \times A} = \frac{40 \times 10^{-2}}{6000 \times \mu_0 \times 16 \times 10^{-4}}$$

$$= 3.316 \times 10^4 \text{ AT/Wb}$$

$$R_g = \frac{l_g}{lbA} = \frac{0.06 \times 10^{-2}}{\mu_0 \times 16 \times 10^{-4}} = 29.841 \times 10^4 \text{ AT/Wb}$$

Applying KVL in the equivalent magnetic circuit

or, $N_2 I_2 - \phi R_g - N_1 I_1 - \phi R_{core} = 0$

or, $1000 - (16 \times 10^{-4}) \times (298415.518) - 6000 I_1 - (16 \times 10^{-4})(33157.299) = 0$

$\therefore$ $I_1 = 0.078$ A

❑❑❑

SPECIAL TYPE OF TRANSFORMER:

INSTRUMENT TRANSFORMERS:

Specially designed transformer with highly accurate transformation ratio. These transformers are used for measurement purpose and in protection scheme.

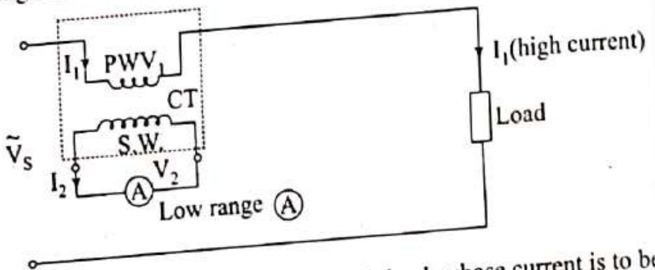
This is of two types

i) Current transformer (CT)

ii) Potential transformer (PT)

i) Current transformer (CT)

It senses high current through primary winding & steps down to a low current in secondary winding CT can be used to measure high current by using a low range ammeter.



PW of CT is connected in series with load, whose current is to be measured.

CT will step down high current I_1 to low current I_2.

A low range ammeter (A) is connected across secondary winding of CT.

From the reading of (A),. we can estimate the value of I_1 from Amp-turn balance.

$$N_1I_1 = N_2 I_2$$

$$\therefore \quad \boxed{I_1 = \frac{N_2}{N_2} * I_2}$$

$$I_1 = kI_2$$

Here, I_2 = Ammeter reading

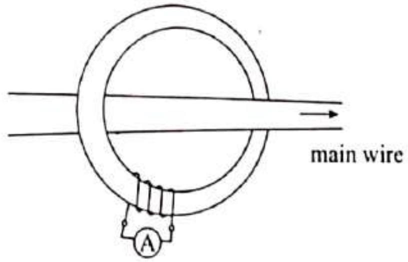
In CT rating plate,

1000 A/5A i.e. $k = I_1/I_2 = 200$

If Ammeter reads 2.Amp

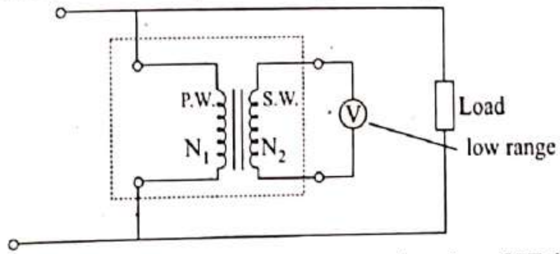
Then, $I_1 = kI_2 = 200*2 = 400$ Amp

The S.W. of a CT shouldn't be left open without Ammeter. If we did so, I_2 will be zero and opposing flux in the iron core will be zero therefore magnetic flux in the core, due to I_1 will be very high hence, high voltage will induce in P.W., as well as secondary winding because of this high voltage, the insulation of P.W. & secondary winding will get damage therefore, if we want to remove the ammeter, the secondary winding must be short circuited by a thick wire.



ii) Potential transformer (PT)

P.T. is used to measure H.V. using a low range voltmeter.



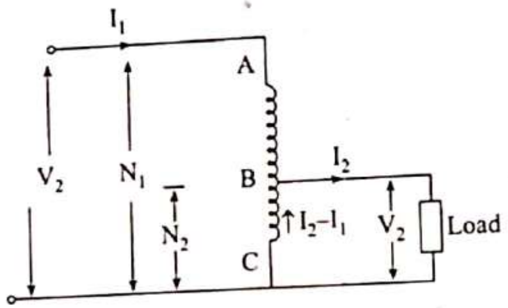
$k = N_2/N_1 = v_2/v_1$ will be given in the rating plate of PT. if v_2 is reading of (v)

In case of CT the p.w. is made of thick wire with few turns because it has to carry full load high current. The secondary winding of CT is made of thin wire with many no. of turns because. S.W. carries low current. But in case of a P.T., P.W. will have many no. of turns & secondary winding will have few turns.

AUTO TRANSFORMER

An auto transformer is a special type of transformer with only one winding. A part of the winding is common to both primary and secondary side.

The figure shows a single phase auto transformer having N_1 turns in the primary and N_2 turns tapped for lower secondary voltage. The winding section BC with N_2 turns is common to both primary & secondary side.



$$\frac{v_2}{v_1} = \frac{N_2}{N_1} = k$$

If I_2 = current drawn by the load

I_1 = current drawn from supply

Current in section BC = $I_2 - I_1$

Cu saving. Weight of Cu $\propto$ NI.

Weight of copper in section AB $\propto (N_1 - N_2) I_1$

Weight of copper in section BC $\propto N_2(I_2 - I_1)$

Total weight of copper used in auto transformer

$(W_{auto}) \propto (N_1 - N_2) I_1 + N_2(I_2 - I_1)$

& $W_{tw} \propto N_1I_1 + N_2I_2$ (normal transformer)

Now,

$$\frac{W_{auto}}{W_{tw}} = \frac{N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1}{N_1I_1 + N_2I_2}$$

or, $$\frac{W_{auto}}{W_{tw}} = 1 - \frac{2N_2I_1}{N_1I_1 + N_2I_2}$$

or, $$\frac{W_{auto}}{W_{tw}} = 1 - \frac{2N_2I_1}{N_1I_1 + N_2I_2} \times \frac{N_1I_1}{N_1I_1}$$

or, $$\frac{W_{auto}}{W_{tw}} = 1 - \frac{2N_2/N_1}{1 + \frac{N_2}{N_1} \cdot I_2/I}$$

or, $$\frac{W_{auto}}{W_{tw}} = 1 - \frac{2k}{1 + k/k} = 1 - \frac{2k}{2} = 1 - k$$

$\Rightarrow$ $$\frac{W_{auto}}{W_{tw}} = 1 - k \Rightarrow \{W_{auto} = (1 - k)\, W_{tw}\}$$

Case I: If $v_1 = 220v$ & $v_2 = 200v$ then

$$k = \frac{200}{220} = 0.909 \approx 1$$

$\therefore$ $W_{auto} = 0.091\, W_{tw}$

$\Rightarrow$ So, the weight of cu required in auto transformer is 9.1% of the normal two winging transformer.

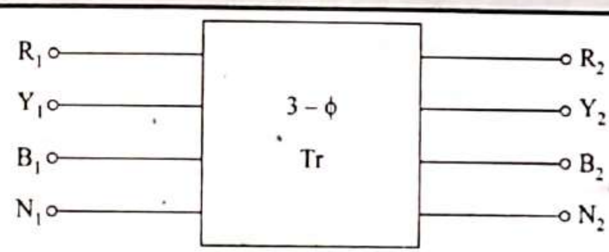
Case II: If $1 = 220v$ & $v_2 = 6v$ then $k = 6/220 = 0.0272$

(very less than 1)

$\therefore$ $W_{auto} = 0.9728\, W_{tw}$

$\Rightarrow$ The weight of the copper required is 97.2% of the normal two winding transformer. Hence, the saving in copper in an auto transformer is only significant when k approaches unity.

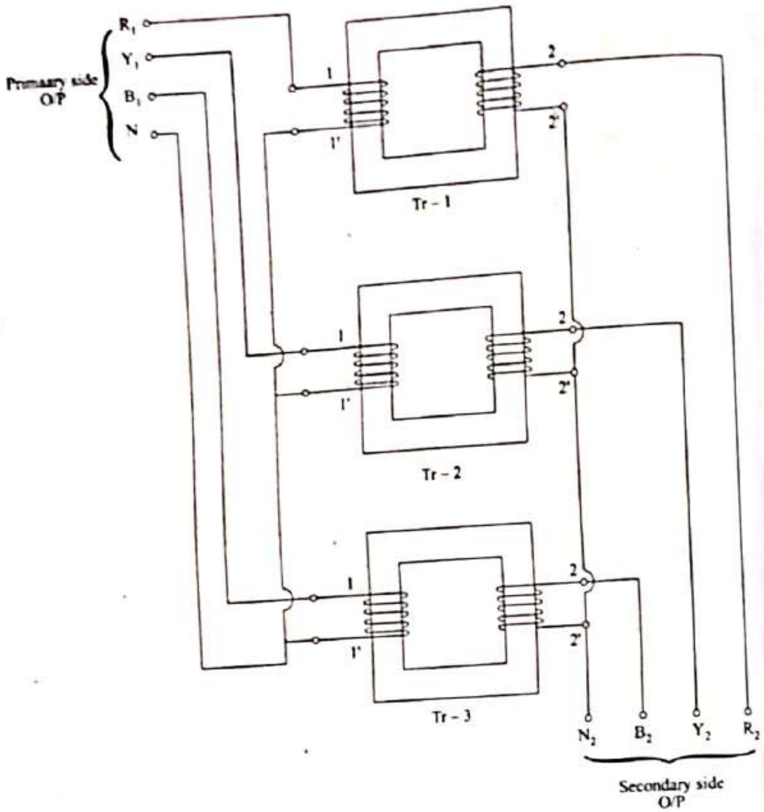
THREE PHASE TRANSFORMER



Step up or step down

3 Nos of 1-ϕ transformer can be used to step up or step down the 3-ϕ a.c. voltage.

Advantage & disadvantage of using the scheme shown above



Advantage

i) Usually a single unit of 3-ϕ transformer is quite large compared to a single phase unit. The transportation becomes easier.

ii) During maintenance only one of the units becomes unavailable so the system becomes more reliable.

Disadvantages:

i) Using 3 separate single phase transformer is more expensive than using a single 3 phase unit.

ii) This kind of scheme is less efficient

iii) It occupies more space.

Evolution of 3-phase Tr.

Let $\phi_R = \phi_m = \sin\omega t$

Then, $\phi_y = \phi_m \sin(\omega t - 120°)$

$\phi_B = \phi_m \sin(\omega t - 240°) = \phi_m \sin(\omega t \ \ 120°)$

As current is also,

$i_R = i_m \sin\omega t$

$i_y = im \sin(\omega t - 120°)$

$i_B = i_m \sin(\omega t - 240°)$

$\phi \alpha i$

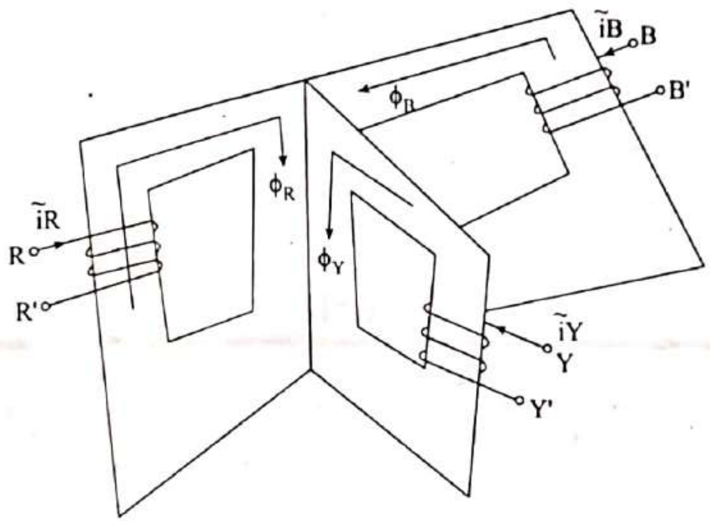


Fig: Three units of single phase Transformer

The total flux to the common limb is,

$\phi_t = \phi_R + \phi_y + \phi_B$ ($\because$ flux vector are in same direction)

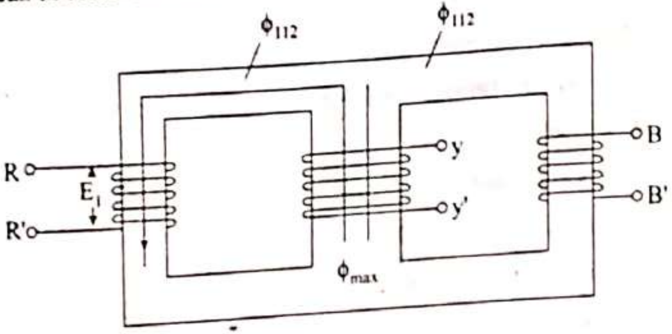
or, $\phi_t = \phi_m \sin\omega t + \phi_m \sin(\omega t - 120°) + \phi_m \sin(\omega t + 120°)$

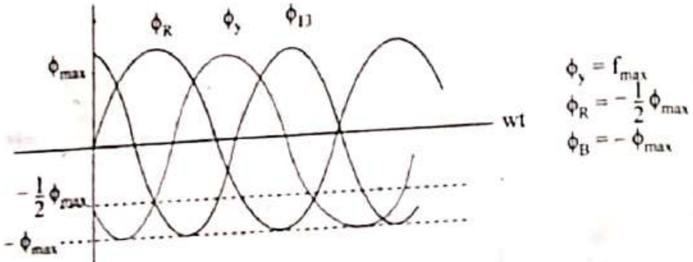
or, $\phi_t = \phi_m \sin\omega t + \phi_m \sin\omega t \cos 120 - \phi_m \cos\omega t \sin 120° + \phi_m \sin\omega t \cos 120° + \phi_m \cos\omega t \sin 120°$

or, $\phi_t = \phi_m \sin\omega t - \phi_m \sin\omega t$

or, $\boxed{\phi_t = 0}$

Hence, no flux flows through the central core therefore central core can be removed and modified design of core can be made as follow:





Tutorial

1. **A 50 kVA, 50 HZ single phase transformer had 500 turns in the primary winding & 100 returns n the secondary winding. the primary winding is supplied by 3000v, 50Hz ac voltage with a full resistive load connected on the secondary size calculate.**
   (i) The emf induced in the secondary winding
   (ii) Primary & the secondary winding current
   (iii) The maximum flux in the core. Assume that it is in ideal transformer. **[2075]**

Solution:

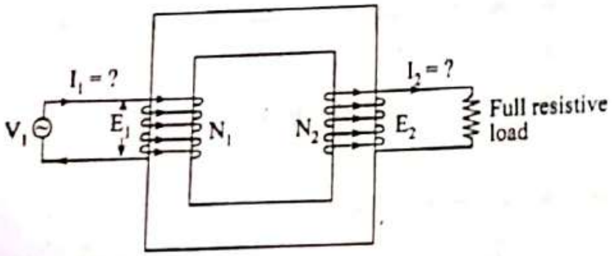


Fig: Ideal transformer

Given, $N_1 = 500$

$N_2 = 100 \quad \Rightarrow K = \frac{N_2}{N_1} = \frac{100}{500} = \frac{1}{5}$

$V_1 = 3000v$, $f = 20$ Hz

Rating, $S = 50$ kVA

(i) We know,

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1}$$

$$\Rightarrow E_2 = \frac{N_2}{N_1} \times E_1 = \frac{100}{500} \times 3000 = 600 \text{ V}$$

(ii) $S = V_1 I_1$

$$\Rightarrow I_1 = \frac{S}{V_1} = \frac{50 \times 1000}{3000} = 16.67 \text{ A}$$

Again,

$$\frac{I_1}{I_2} = k$$

$$\Rightarrow I_2 = \frac{I_1}{K} = \frac{16.67}{\frac{1}{5}} = 83.33 \text{ A.}$$

(iii) $E_1 = 4.44 f\phi_m N_1$

$$\Rightarrow \phi_m = \frac{E_1}{4.44 fN_1} = \frac{3000}{4.44 \times 50 \times 500} = 0.027 \text{ Weber.}$$

2. **A 200 kVA, 2000/440, 50Hz single phase transformer gives the following test results.**

No-load test 440v	1500 W	8A
Short circuit test 30v	2000W	300A

a) **Calculate the equivalent circuit parameter referred to primary side.** **[2074]**

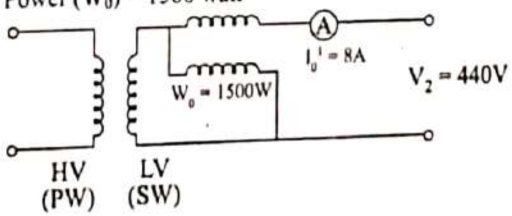
Solution:

From No-load test/open circuit test

Given, voltage (V_2) = 440V

Current (I_0^1) = 8A

Power (W_0) = 1500 watt



2000/440

So, $W_0 = V_2 I_0 \cos\phi_0$

→ $\cos\phi_0 = \frac{W_0}{I_0' V_2} \Rightarrow \cos\phi_0 = \frac{1500}{8\times440} = 0.4261$

→ $\sin\phi_0 = \sqrt{1-\cos^2\phi_0} = 0.9047$

$I_e'(w') = I_0'\cos\phi_0 = 8\times0.4261 = 3.408A$

$I_m'(I_\mu) = I_0'\sin\phi_0 = 8\times0.9047 = 7.24A$

⇒ $R_0' = \frac{V_2}{I_m'} = \frac{440}{3.408} = 129.108\Omega$

$X_0' = \frac{V_2}{I_m'} = \frac{440}{7.24} = 60.77\Omega$

} referred to sec.side

Thus,

$R_0 = \frac{R_0'}{k^2} = \frac{129.108}{(400/2000)^2} = 2667.523\Omega$

$X_0 = \frac{X_0'}{k^2} = \frac{60.77}{(440/2000)^2} = 1255.64\Omega$

From short circuit test:

Given, $V_{sc} = 30v$, $I_{sc} = 300A$

$W_{sc} = 200w$ (copper loss)

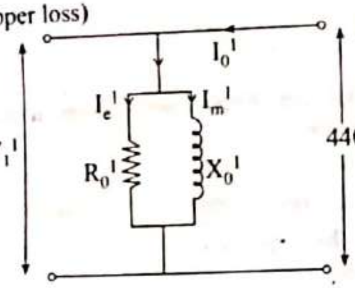
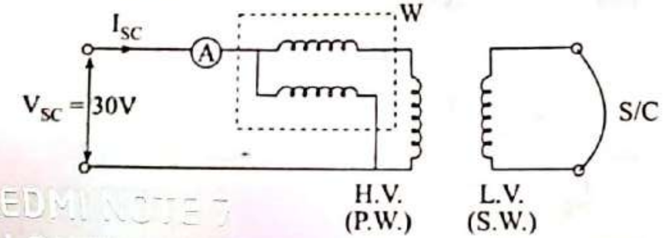


Fig. Equivalent circuit for S.C.T. referred to P. side

From Short circuit test

Given, $V_{SC} = 30$ V, $I_{SC} = 300$ A

$W_{SC} = 2000$ W (copper loss)



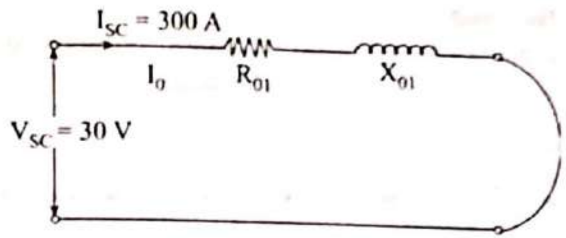


Fig: Equation circuit for S.C.T. referred to P. Side.

Then,

$W_{sc} = I_{sc}^2 R_{01} = W_{cu}$

⇒ $R_{01} = \frac{W_{sc}}{I_{sc}^2} = \frac{2000}{300^2} = 0.022\Omega$

& $Z_{01} = V_{sc}/I_{sc} = \frac{30}{300} = 0.1\Omega$

⇒ $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{0.1^2 - 0.0\text{-}2i^2} = 0.0975\Omega$

3. A 25 kVa, single phase 2200/220v transformer has a primary winding resistance of 1Ω, secondary winding resistance of 0.01 Ω, primary leakage reactance of 1.5Ω. The iron loss of the transfer is 206 watt. Calculate the efficiency of the transformer & the voltage regulation at the flowing condition. **[2073]**

a) half load b) full load c) at 50% overload.

Solution:

Given that,

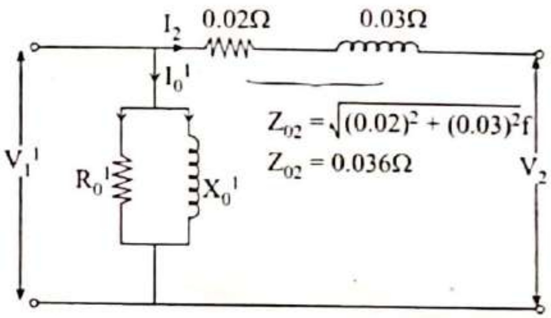
$R_1 = 1\Omega$, $R_2 = 0.01\Omega$ & $k = 220/2200$

$X_1 = 1.5\Omega$, $X_2 = 0.015\Omega$

Let us consider eq. circuit referred to the secondary side.

$R_{02} = R_2 + R_1' = 0.01 + k^2 \bullet 1 = 0.02\Omega$

$X_{02} = x_2 + x_1' = 0.015 + k^2 \bullet 1.5 = 0.03\Omega$



far unity P.f.

a) Half load:

Output kVA = s = (25/2) = 12.5kVA = $v_1 I(_2$(loaded half)

w_i 206 watt → constant with change in load

$$w_{cu} = I_2^2 R_{02} = \left(\frac{12500}{220}\right)^2 \cdot 0.02$$

w = cu = 64.566 watt → copper loss decrease with decrease in load.

$$\eta = \frac{\text{Output pwoer}}{\text{i/P pwoer}} \cdot 100\% = \frac{12500}{(12500 + 206 + 64.566)} \cdot 100 = 97.881\%$$

Alternatively, W_{cu} at any load can be calculated from full load copper loss as:

$$w_{cu}(f) = (I_2(f))^2 R_{02}$$

$$\text{if, } x = \frac{\text{actual load}}{\text{full load}} = \frac{I_2 v_2}{I_2(f) v_2} = \frac{I_2}{I_2(f)} \Rightarrow I_2 = x.I_2(f)$$

then,

$$W_{cu1}(x) = I_2^2 RO_2 = x^2 (I_2(f))^2 RO_2 = x^2.w_{cu}(f)$$

$$\Rightarrow W_{cu}(x) = x^2.\ cu(f)$$

at half load, = 1/2 ⇒ $w_{cu} = \left(\frac{1}{2}\right)^2 w_{cu}(f)$

and voltage regulation

$$V_{reg} = \frac{I_2 R_{02}}{fV_2} = \frac{56.818 * 0.02}{220} = 0.516\%$$

(b) Full load:

Full load output = 25kvA

∴ $v_1 I_2 = 25 * 10^3$

$$\Rightarrow I_2 = \frac{25 * 10^3}{220} = 113.636$$

∴ Copper loss at full load can be calculated as,

$$w_{cu} = I_2^2 R_{02}$$

$$\Rightarrow w_{cu} = (113.636)^2 * 0.02 = 258.264w$$

W_i = 206W → constant doesn't depend on load current

$$\therefore \eta = \frac{P_{output}}{P_{input}} \cdot 100\%$$

$$\frac{25000}{1500 + 258.264 + 206} \times 100\%$$

∴ η = 98.17%

and, V_{regv} (full load) $= \frac{I_2 R_{02}}{fV_2} = \frac{113.636 * 0.02}{220} = 1.033\%$

c) 50% over load:

Now, $cu = \left(1 + \frac{1}{2}\right)^2 w_{cu}(f) = (1.5)^2 \cdot 258.264W = 581.094W$

w_i = 206w

$$\therefore \eta_{50\%}\text{, overload} = \frac{25000}{25000 * 1.5 + 581.094 + 206} = 97.94.4\%$$

and, $V_{red}(50\%\text{ overload}) = \frac{113.636 * 1.5 * 0.02}{220} = 1.549\%$

4. A 200 kVA single phase transformer is in circuit continuous for 8 hrs in a day the load is 160 kw at 0.8 Pf, for 6 hrs, the load is kw at unity power factor & for the remaining period of the day in runs on no load.

Given that the full load copper loss = 3.02 kw and iron loss = 1.6 find the all day efficiency of the transformer. [2070]

Solution:

Given:

Full load O/P = 200 kVA

Full load copper los s= 3.02 kW

Full load iron los s= 1.6 kw

Then,

Output energy = (160 × 8) kwh + (80×b) kwh = (0×10) kwh
= 1760 kwh

iron loss in kwh = 1.6 kw × 24 = 38.4 kwh (unit)

Copper loss for load of 160 kw at 0.8 Pf in 8 hrs

Full load us los s= 3.02 kw @ 200 kvA

Here, actual load = kvA $= \frac{sw}{P.f.} = \frac{160}{0.8} = 200$ kVA

Hence, cu = los s= 3.02 kW

Cu loss in 8 hrs = 3.02 × 8 = 24.16 kwh ⇒ E_{cu18} = 24.16 kwh

Copper loss for load of 80 kw at 1Pf in 6hrs

actual load = kvA $\frac{kw}{P.f.} = \frac{80}{1} = 80$ kVA

$$W_{cu} = \left(\frac{80}{200}\right)^2 \cdot W_{cu}(f) = \frac{4}{25} \times 3.02$$

⇒ W_{cu} = 0.4832 kw

∴ Copper loss in 6 hrs = 0.4832 * 6

$E_{(4.cs)}$ = 2.8992 kwh

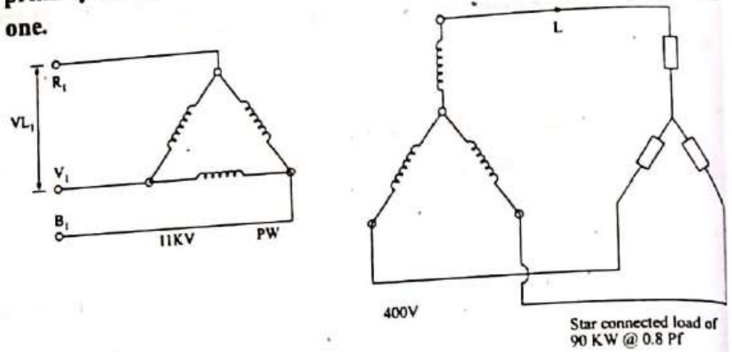
Now,

$$\text{Input energy} = E_{output} + E_i + E_{cu8} + E_{cu6}$$
$$= 1760 \text{ kwh} + 38h + 38.4 \text{ kwh} + 24.16\text{kwh}$$
$$+ 2.8992 \text{ kwh}$$
$$= 1825.4592 \text{ kwh}$$

Thus,

$$\text{All day efficiency, } \eta = \frac{E_{output}}{6_{input}} \times 100\% = \frac{1760}{1825.459} \times 100\% = 96.4\%$$

5. **A 3 phase, 50HZ 11kv/400v Delta/star (Δ-Y) transformer has a balanced star connected load of 90 kW at 0.8 logging p.f. calculate the secondary logging current, primary phase current & the primary line current assuming that the transformer is an ideal one.** **[2072]**



<u>In delta connection</u>

$V_2 - V_{ph}$

$I_2 = \sqrt{3}\, I_P$

$P = \sqrt{3}\, v_2 I_2 \cos\phi$

$P = 3 v_P I_P \cos\phi$

Load = 90- kW (output pwoer)

$P = 90\times10^3 = \sqrt{3}\, v_{L2} I_{L2} \cos\phi$

$= 90\times10^3 = \sqrt{3} *400*I_{L2}*0.8$

$I_2 = 162.38A = I_{P2}$

<u>In star connection</u>

$I_L = I_P$

$v_2 = \sqrt{3}\, v_p$

$P = \sqrt{3}\, v_2 I_2 \cos\phi$

$P = \sqrt{3}\, v_2 I_p \cos\phi$

Ideal transformer ⇒ if P power = O/P power

$\Rightarrow v_{L1}*IP_1 = V_{P2}*I_{P2}$

$\Rightarrow 11*10^3*IP_1 = 400/\sqrt{3} *162.138$

or, $IP_1 = 3.409A$

$\therefore I_{L1} = \sqrt{3}\, IP_1 = \sqrt{3} *4.09$

$= 5.905\text{Amp}$

6. **A single phase 40 kVA transformer has primary voltage of 6600 V, a secondary voltage of 230 V and has 30 turns on the secondary winding. Calculate the number of primary turns. Also calculate the primary and secondary currents.** **[2068]**

Solution:

Capacity of transformer = 40 kVA

$V_1 = 6600$ V, $V_2 = 230$ V, $N_2 = 30$

Now,

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow N_1 = \frac{V_1 N_2}{V_2}$$

or, $$N_1 = \frac{6600 \times 30}{230}$$

$\therefore \quad N_1 = 860.86$

Hence, no. of primary turns = 860.

Now,

$$\text{Primary current } (I_1) = \frac{40 \times 1000}{6600} = 6.06 \text{ A}$$

$$\text{Secondary current } (I_2) = \frac{40 \times 1000}{230} = 173.91 \text{ A}$$

7. **A single-phase 50 Hz transformer has 100 turns on primary and 400 turns on secondary winding. The net cross-section area of the core is 250 cm². If the primary winding is connected to a 230 V, 50 Hz supply, determine (a) the emf induced in the secondary winding and (b) the maximum and rms value of the flux density in the core.**

Solution:

$f = 50$ Hz, $N_1 = 100$, $N_2 = 400$, $A_1 = 250 \times 10^{-4}$ m², $V_1 = 230$ V

(a) Now,

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$\Rightarrow \quad V_2 = \frac{N_1}{N_2} \times V_1 = \frac{400}{100} \times 230 = 920 \text{ V}$$

For an ideal transformer, $E_2 = V_2 = 920$V.

(b) We know, $E_2 = 4.44\, f N_2 B_m A_C$

or, $B_m = \dfrac{E_2}{4.44\, f N_1 A_C} = \dfrac{920}{4.44 \times 50 \times 400 \times 250 \times 10^{-4}}$

$\therefore$ $B_m = 0.414$ Tesla

Also, $B_{rms} = \dfrac{B_m}{\sqrt{2}} = \dfrac{0.414}{\sqrt{2}} = 0.293$ Tesla.

8. **The no-load current of a transformer is 15 A at a p.f. of 0.2 when connected to a 460 V, 50 Hz power supply. If the primary winding has 550 turns, calculate: (a) the magnetizing and working component of no-load current. (b) iron loss (c) maximum and rms value of flux in the core.**

Solution:

$I_0 = 15$ A, $\cos\phi = 0.2$, $V_1 = 460$V, $f_0 = 50$ Hz, $N_1 = 550$.

Now,

(a) Magnetizing component, $I_\mu = I_0 \sin\phi_0 = 15 \sin[\cos^{-1}(0.2)]$

$\therefore$ $I_\mu = 14.69$ A

Working component, $I_w = I_0 \cos\phi_0 = 15 \times 0.2 = 3$A

(b) Iron loss $= V_1 I_0 \cos\phi_0 = 460 \times 3 = 1380$ W

(c) For ideal transformer, $E_1 = V_1 = 460$ V

We know,

$E_1 = 4.44\, f N_1 \phi_m$

$\therefore$ $\phi_m = \dfrac{460}{4.44 \times 50 \times 550} = 3.767$ m Wb

Also, $\phi_{rms} = \dfrac{\phi_m}{\sqrt{2}} = \dfrac{3.767}{\sqrt{2}} = 2.66$ m Wb.

9. ***A 2000V/400V, 50 Hz, single phase transformer draws 2 A at a p.f. of 0.2 lagging when it has no-load. Calculate the primary current and p.f. When secondary current is 200 A at a p.f. of 0.8 lagging. Assume the voltage drop in the winding to be neglected.***

Solution:

$N_1 = 2000$ N, $V_2 = 400$ V, $f = 50$ Hz

$I_0 = 2$A, $\cos\phi_0 = 0.2$ (lag) $\Rightarrow \phi_0 = 78.46°$

$I_2 = 200$ A, $\cos\phi_1 = 0.8$ (lag) $\Rightarrow \phi_0 = 36.87°$

$I_1 = ?$ $\cos\phi_1 = ?$

We know,

$K = \dfrac{V_2}{V_1} = \dfrac{400}{2000} = 0.2$

$\therefore$ $\tilde{I_1} = K\tilde{I_2} = 0.2 \times (200 < -36.87°) = 40 < -36.87°$ A.

Now,

$\tilde{I_1} = \tilde{I_2}' + \tilde{I_0}' = 40 < -36.87° + 2 < -78.46°$

$= 41.51 < -38.702°$ A

Hence, primary current $(I_1) = 41.51$ A.

P.f. $= \cos 38.702° = 0.78$ (lag)

10. **A 100 kVA, 1100/230V, 50 Hz transformer has an HV winding resistance of 0.1Ω and a leakage reactance of 0.4 Ω. The low voltage winding has a resistance of 0.006Ω and a leakage reactance of 0.01 Ω. Find the equivalent winding resistance, reactance and impedance referred to HV and LV sides. [2067]**

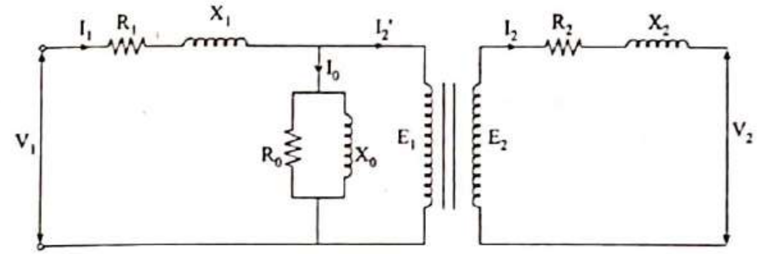
Solution:

Capacity = 100 kVA

$V_1 = 1100$ V, $V_2 = 230$ V, $f = 50$ Hz

HV: $R_1 = 0.1\Omega$, $X_1 = 0.4\Omega$

L.V.: $R_2 = 0.006\ \Omega$, $X_2 = 0.01\ \Omega$



Referred to HV side:

$R_{01} = R_1 + \dfrac{R_2}{K^2} = 0.1 + \dfrac{0.006}{0.2009^2} = 0.237\Omega$

$X_{01} = X_1 + \dfrac{X_2}{K^2} = 0.4 + \dfrac{0.01}{0.209^2} = 0.6289\Omega$

$\therefore$ $Z_{01} = (0.237 + j0.6289)\Omega$

Referred to LV side:

$R_{02} = R_2 + K^2R_1 = 0.006 + 0.209^2 \times 0.1 = 0.0103\Omega$

$X_{02} = X_2 + K^2X_1 = 0.01 + 0.209^2 \times 0.4 = 0.02747\Omega$

$\therefore$ $Z_{02} = (0.0103 + j0.02747)\Omega$

11. **A 50 kVA, 2200/110V transformer when tested gave the following results:**

OC test:	**400 W**	**10 A**	**110 V**
SC test:	**808 W**	**20.5 A**	**90 V**

Compute all the parameters of the equivalent circuit referred to HV and LV sides of the transformer. Draw the equivalent circuits also.

Solution:

Capacity = 50 kVA

$$V_1 = 2200\ V,\ V_2 = 110\ V \Rightarrow K = \frac{110}{2200} = 0.05$$

OC Test:

$$W_i = 400W,\ I_0 = 10A,\ V = 110V$$

$$\therefore\quad I_w = \frac{W_i}{V} = \frac{4.00}{110} = 3.636\ A$$

$$\text{Also, } I_\mu = \sqrt{I_{0_1}^2 - I_m^2} = \sqrt{10^2 - 3.636^2} = 9.315A$$

$$\text{Hence, } R_0 = \frac{V_2}{I_m} = \frac{110}{3.636} = 30.25\Omega$$

$$X_0 = \frac{V_1}{I_\mu} = \frac{110}{9.315} = 11.80\ \Omega$$

SC Test:

$$W_c = 808\ W,\ I_{SC} = 20.5\ A,\ V_{SC} = 90V$$

$$\therefore\quad Z_{01} = \frac{V_{SC}}{I_{SC}} = \frac{90}{20.5} = 4.39\Omega$$

$$\text{Also, } R_{01} = \frac{W_C}{I_{SC}^2} = \frac{808}{20.5^2} = 1.922\ \Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{4.39^2 - 1.922^2} = 3.946\ \Omega$$

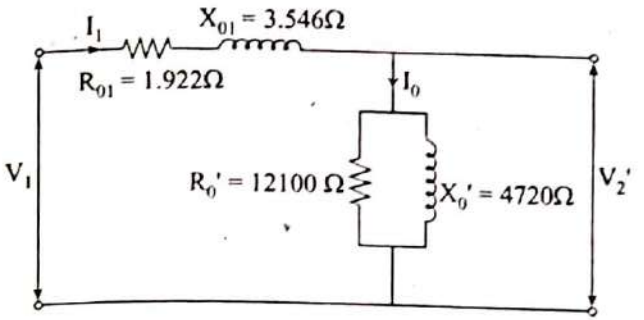
Referred to HV side:

$$R_0' = \frac{R_0}{K^2} = \frac{30.25}{0.05^2} = 12100\Omega$$

$$X_0' = \frac{X_0}{K^2} = \frac{11.80}{0.05^2} = 4720\Omega$$

$$R_{01} = 1.922\Omega$$

$$X_{01} = 3.346\Omega$$



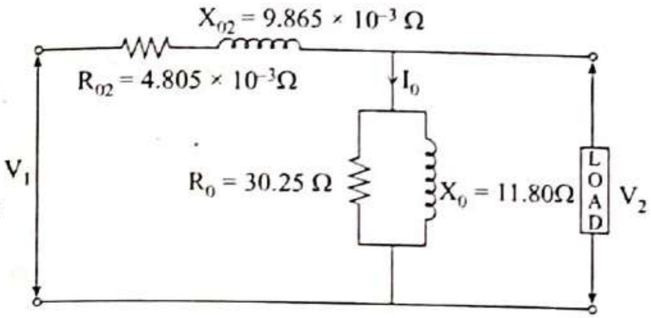
Referred to 1V side:

$$R_0 = 30.25\Omega$$

$$X_0 = 11.80\Omega$$

$$R_{02} = K^2 R_{01} = 0.05^2 \times 1.922 = 4.805 \times 10^{-3}\Omega$$

$$X_{01} = K^2 X_{01} = 0.05^2 \times 3.946 = 9.865 \times 10^{-3}\ \Omega$$



12. **Obtain equivalent circuit parameters and circuit of a 200/400V, 50 Hz, 1- phase transformer from the following test data:**

OC test:	**200 V**	**0.7 A**	**70 W**
SC test:	**15 V**	**10 A**	**85 W**

Calculate (i) the primary current and p.f., (ii) the secondary voltage, when delivering 5 kW at 0.8 p.f. lagging. (iii) Voltage Regulation for 0.8 p.f. leading.

Solution:

OC Test:

$$I_w = \frac{70}{200} = 0.35\ A \Rightarrow \cos\phi_0 = 0.5 \Rightarrow \phi_0 = 60°$$

$$I_\mu = \sqrt{I_0^2 - I_m^2} = \sqrt{0.7^2 - 0.35^2} = 0.606\ A$$

$\therefore \quad R_0 = \frac{V}{I_w} = \frac{200}{0.35} = 571.428\Omega$

$X_0 = \frac{V}{I_\mu} = \frac{200}{0.606} = 330.033\Omega$

SC Test:

$Z_{02} = \frac{15}{10} = 1.5\Omega$

$R_{02} = \frac{85}{10^2} = 0.85\Omega$

$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{1.5^2 - 0.85^2} = 1.235\ \Omega$

Now,

Power delivered $(P_0) = 5kW = 5000\ W$

$\cos\phi_2 = 0.8\ (lag) \Rightarrow \phi_2 = 36.86°$

Now, $P_0 = V_2 I_2 \cos\phi_2$

or, $5000 = 400 \times I_2 \times 0.8$

$\therefore \quad I_2 = 15.625\ A$

So, $I_2' = KI_2 = \frac{400}{200} \times 15.625 = 31.25A < -36.86°$

Now,

i) Primary current, $\tilde{I}_1 = \tilde{I}_2' + \tilde{I}_0 = 31.25 < -36.86° + 0.7 < -60°$

$\therefore \quad \tilde{I}_1 = 31.17 < -35.58°$

ii) Voltage drop in secondary winding $= I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$

$= 15.625\ (0.85 \times 0.8 + 1.235 \times \sin(\cos^{-1} 0.8))$

$= 22.203\ V$

Hence, secondary voltage, $V_2 = 400 - 22.203$

$\therefore \quad V_2 = 377.79\ V$

iii) For P.f. 0.8 leading,

Voltage regulation $= \frac{I_2(R_{02}\cos\phi_2 - X_{02}\sin\phi_2)}{{}_0V_2} \times 100$

$= \frac{15.625\ (0.85 \times 0.8 - 1.235 \times \sin(\cos^{-1}(0.8)))}{400} \times 100$

$= -0.238\%$

13. A 10 kVA, 450/120V, 50 Hz transformer when tested gave the following results:

OC test:	**80 W**	**4.2 A**	**120 V**
SC test:	**120 W**	**22.2 A**	**9.65 V**

Compute (i) the equivalent circuit constants (ii) voltage regulation and efficiency for an 80% lagging p.f. (iii) Secondary Voltage for an 80% lagging p.f. (iv) the efficiency at half full load and 80% lagging p.f.

Solution:

Capacity of transformer (S) = 10 kVA

$K = \frac{120}{450} = 0.267,\ f = 50\ Hz$

i) In hv side,

$Z_{01} = \frac{9.65}{22.2} = 0.434\Omega$

$R_{01} = \frac{120}{22.2^2} = 0.2434\ \Omega$

$\therefore \quad Y_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = 0.359$

Referring to 1V side,

$R_{02}' = K^2 R_{01} = 0.267^2 \times 0.2434 = 0.01735\Omega$

$X_{02} = K^2 X_{01} = 0.267^2 \times 0.359 = 0.02559\Omega$

ii) $\cos\phi_2 = 0.8\ (lag)$

$I_2 = \frac{10 \times 1000}{120} = 83.33\ A$

$\therefore$ Voltage drop in secondary winding $= I_2(R_{02}\cos\phi_2 + X_{02}\sin\phi_2)$

$= 83.33\ (0.01735 \times 0.8 + 0.02559 \times \sin(\cos^{-1} 0.8))$

$= 2.43\ V$

Hence, voltage regulation $= \frac{2.43}{120} \times 100\% = 2.025\%$

Also, Iron loss (from OC test), $W_i = 80W$

Terminal voltage in secondary, $V_2 = 120 - 2.43 = 117.57V$.

Copper loss $= I_2^2 R_{02} = 83.33^2 \times 0.01735 = 120.476W$

Hence,

$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}$

$= \frac{117.57 \times 83.33 \times 0.8}{117.57 \times 83.33 \times 0.8 + 80 + 120.476} \times 100$

$\therefore \quad \eta = 97.5\%$

iii) Secondary voltage = $V_2 = 120 - 2.43 = 117.574$

iv) At half full-load & 80% lagging pf:

$$P = \frac{10}{2} = 5 \text{ kVA}$$

W_i (Iron loss) = 80 W

$$W_c \text{ (Copper loss)} = n^2 \times 120 = \frac{1}{2^2} \times 120 = 30 \text{ W}$$

$$\therefore \quad \eta = \frac{5000 \times 0.8}{5000 \times 0.8 + 80 + 30} \times 100$$

$$\therefore \quad \eta = 97.32\%$$

14. A 5 kVA, 200/400V, 50 Hz, 1-phae transformer gave the following test data:

OC test:	**200 V**	**0.7 A**	**60 W**
SC test:	**22 V**	**16 A**	**120 W**

If the transformer operates on full load, determine the regulation at 0.9 p.f. lagging.

Solution:

Capacity = 5kVA

$$\text{Transformation ratio (K)} = \frac{400}{200} = 2$$

SC Test:

$$Z_{02} = \frac{22}{16} = 1.375\Omega$$

$$R_{02} = \frac{120}{16^2} = 0.46875\Omega \Rightarrow X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = 1.292\Omega$$

Now, full load current in secondary winding,

$$I_2 = \frac{5 \times 1000}{400} = 12.5 \text{ A}$$

$$\therefore \quad \text{Voltage Regulation} = \frac{I_2 (R_{02} \cos \phi_2 + X_{02} \sin \phi_2)}{{}_0V_1} \times 100$$

$$= \frac{12.5(0.46875 \times 0.9 + 1.292 \times \sin(\cos^{-1} 0.9))}{400}$$

$$= 3.078\%$$

15. A 1000/500V 1-phase transformer draws a current of 2.4 A at no-load with a p.f. of 0.35 lagging. With secondary terminals short circuited by a thick wire, the primary winding is supplied by an ac voltage of 80 V, the transformer draws a current of 25 A and consumes 250 W. Calculate the equivalent circuit parameters referred to secondary side and draw the equivalent circuit.

Solution:

$$K = \frac{500}{1000} = 0.5$$

$$I_0 = 2.4\text{A}, \cos \phi_0 = 0.35 \text{ (lag)} \Rightarrow \phi_0 = 69.51°$$

$$V_1 = 1000 \text{ V}, V_2 = 500 \text{ V}$$

Now,

$$R_0' = \frac{V_2}{I_0 \cos \phi_0} = \frac{500}{2.4 \times 0.35} = 595.238\Omega$$

$$X_0' = \frac{V_2}{I_0 \sin \phi_2} = \frac{500}{2.4 \times \sin 69.51°} = 222.4\Omega$$

Also, when secondary terminals are short circuited,

$$Z_{01} = \frac{80}{25} = 3.2\Omega$$

$$R_{01} = \frac{250}{25^2} = 0.4\Omega$$

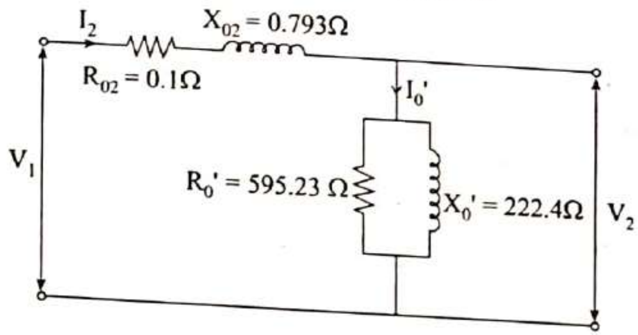
$$\therefore \quad X_{01} = \sqrt{3.2^2 - 0.4^2} = 3.1749\Omega$$

Referring to secondary side,

$$R_0' = 595.238\Omega, X_0' = 222.4\Omega$$

$$R_{02} = K^2 R_{01} = 0.5^2 \times 0.4 = 0.1\Omega$$

$$X_{02} = K^2 X_{01} = 0.5^2 \times 3.1749 = 0.793\ \Omega$$



16. With the secondary short circuited, if 200 V is applied to a 200 kVA, 1-phase, 3300/400 V transformer, the current through primary was the full load value and the input power was 1650 W. Calculate the secondary p. d. and percentage regulation when the secondary load is passing 300 A at 0.707 p.f. lagging with normal primary voltage.

Solution:

Capacity (S) = 200 kVA [3300/400V]

Full load current through primary $(I_1) = \frac{200 \times 1000}{3300} = 60.606$ A

$$Z_{01} = \frac{200}{60.606} = 3.3\Omega$$

$$R_{01} = \frac{1650}{60.606^2} = 0.449\Omega \Rightarrow X_{01} = \sqrt{3.3^2 - 0.449^2} = 3.269\Omega$$

$$\therefore R_{02} = K^2 R_{01} = \left(\frac{400}{3300}\right)^2 \times 0.449 = 6.5968 \times 10^{-3}\,\Omega$$

$$X_{02} = K^2 X_{01} = \left(\frac{400}{3300}\right)^2 \times 3.269 = 0.048\,\Omega$$

Now,

$I_2 = 300$ A, pf $= \cos\phi_2 = 0.707$ (lag)

Voltage drop $= I_2 (R_{02}\cos\phi_2 + X_{02}\sin\phi_2)$

$= 300(6.5968 \times 10^{-3} \times 0.707 + 0.048 \times \sin(\cos^{-1} 0.707))$

$= 11.58$ V

$\therefore$ Secondary P.d. $= 400 - 11.58 = 388.41$V

% Regulation $= \frac{11.58}{400} \times 100 = 2.895\%$

17. A 500 kVA, 50 Hz, 6600V/400V, 1- phase transformer have primary and secondary winding resistances are 0.4 Ω and 0.001 Ω respectively. If the iron loss is 3.0 kW, calculate the efficiency at (a) full load (b) half full load.

Solution:

$$K = \frac{400}{6600} = 0.0606$$

Capacity (S) = 500 kVA

$R = 0.4\Omega$, $R_2 = 0.001\Omega$

Iron loss $(W_i) = 3$kW $= 3000$W

$R_{01} = R_1 + \frac{R_2}{K^2} = 0.6723\,\Omega$

Full load primary current $(I_1) = \frac{500 \times 1000}{6600} = 75.757$A

$\therefore$ Full load Cu loss $(W_{cu}) = I_1^2 \times R_{01} = 75.757^2 \times 0.6723$

$W_{cu} = 3856.749$ W

Now,

(i) Full load:

$$\eta = \frac{500 \times 1000}{500 \times 1000 + 3000 + 3856.749} \times 100 = 98.64\%$$

(ii) Half full load:

$$\text{Cu loss} = \frac{1}{4} \times 3856.749 = 964.187\text{W}$$

$$\text{Capacity} = \frac{1}{2} \times 500\text{ kVA} = 250\text{ kVA}$$

$$\therefore \eta = \frac{250 \times 1000}{250 \times 1000 + 3000 + 964.187} \times 100 = 98.43\%$$

18. A 200 kVA transformer has an efficiency of 98% at full load. If the maximum efficiency occurs at three quarters of full load, calculate the efficiency at half load. Assume p.f. of 0.8 at all loads.

Solution:

$\cos\phi = 0.8$

Capacity (S) = 200 kVA

$\eta_{full} = 98\%$

Let, W_i be iron loss and W_{cu} be copper loss.

So,

$$\eta_{full} = \frac{S}{S + W_i + W_{cu}}$$

$$\text{or,}\quad 0.98 = \frac{200000 \times 0.8}{0.8 \times 200000 + W_i + W_{cu}}$$

or, $W_i + W_{cu} = 3265.306$ ...(i)

Maximum efficiency occurs to $\frac{3}{4}$ of full load. So,

$$W_i = \left(\frac{3}{4}\right)^2 W_{cu}$$

or, $W_i = \frac{9}{16} W_{cu}$ ...(ii)

From (i) and (ii),

$W_i = 1175.51W$

$W_{cu} = 2089.79$ W

Now, for half load,

$$W_{cu,half} = \frac{1}{4} W_{cu} = 521.9475$$

$$\therefore \quad \eta = \frac{\frac{200}{2} \times 1000 \times 0.8}{100 \times 100 \times 0.8 + 1175.51 + 521.9475} \times 100$$

$\therefore \quad \eta = 97.92\%$

19. **An 11000/230V, 150 kVA, 50 Hz, 1-phase transformer has a core loss of 1.4 kW and full load Cu loss of 1.6 kW. Determine (a) the kVA load for maximum efficiency and the maximum efficiency (b) the efficiency at half full load and full load at 0.8 p.f. lagging.**

Solution:

1100/230V, 150 kVA, 50 Hz

$$K = \frac{230}{1100} = 0.209$$

Core loss (W_i) = 1.4 kW = 1400W

Full load Cu loss (W_{cu}) = 1600 W

$$\text{Full load primary current} = \frac{150 \times 1000}{1100} = 136.36 \text{ A}$$

$\therefore$ Full load Cu loss = $136.36^2 \times R_{01}$

or, $1600 = 136.36^2 \times R_{01}$

$\therefore$ $R_{01} = 0.08604\ \Omega$

(a) For maximum efficiency,

$I_1^2 R_{01} = W_i$

or, $I_1^2 \times 0.08604 = 1400$

$\therefore$ $I_1 = 127.556$ A

Hence, required kVA load = V_1I_1 = 1100 × 127.556 = 140.31 kVA.

Also,

$$\eta_{max} = \frac{140.31 \times 1000}{140.31 \times 1000 + 1400 + 1400}$$

$\therefore$ $\eta_{max} = 98.04\%$

(b) $\cos\phi = 0.8$ (lag)

Half-full-load:

$$\eta = \frac{75 \times 1000 \times 0.8}{0.8 \times 75000 + 1400 + \frac{1}{4} \times 1600} \times 100 = 97.087\%$$

Full-load:

$$\eta = \frac{750 \times 1000 \times 0.8}{150 \times 1000 \times 0.8 + 1400 + 1600} \times 100 = 97.56\%$$

20. **A 600 kVA, 1- phase transformer has an efficiency of 92% both at full load and half load at unity p.f. Determine its efficiency at 60% of full load at 0.8 p.f. lagging.**

Solution:

$\cos\phi = 1$

$\eta_{full} = \eta_{half} = 92\% = 0.92$

Now,

$$\eta_{full} = \frac{600 \times 1000 \times 1}{600 \times 1000 \times 1 + W_i + W_{cu}} = 0.92$$

or, $W_i + W_{cu} = 52173.51$ ...(i)

Also,

$$\eta_{half} = 0.92 = \frac{300 \times 1000 \times 1}{300 \times 1000 \times 1 + W_i + \frac{1}{4} W_{cu}}$$

or, $4W_i + W_{cu} = 104347.826$ ...(ii)

From (i) and (ii),

$W_i = 17391.305W$

$W_{cu} = 3478.604W$

Now,

$\cos\phi = 0.8$

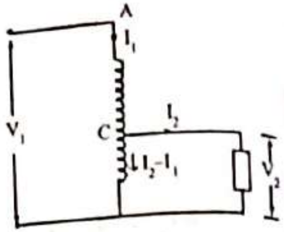
Efficiency at 60% (0.6) of full load:

$$\eta = \frac{0.6 \times 600 \times 1000 \times 0.8}{0.6 \times 600 \times 1000 \times 0.8 + 17391.305 + 0.6^2 \times 34782.604} \times 100$$

$\therefore$ $\eta = 90.59\%$

21. The primary and secondary of an auto-transformer are 230V and 75V respectively. Calculate the currents indifferent parts of the winding when the load current is 200 A. Also calculate the saving in the use of copper.

Solution:



$V_1 = 230V, V_2 = 75V$

$I_2 = 200A.$

$K = \frac{V_2}{V_1} = 0.326$

$\frac{I_1}{I_2} = K \Rightarrow I_1 = KI_1 = 0.326 \times 200$

$\therefore \quad I_1 = 65.2A$

$\therefore$ Current in part AC = 65.2A

Current in part CB = 200 – 65.2 = 134.8A

Now,

$$\text{Saving of Cu} = \left(\frac{W_{two} - W_{auto}}{W_{two}}\right) \times 100\%$$

$$= \left(1 - \frac{W_{auto}}{W_{two}}\right) \times 100\%$$

$$= [1 - (1 - k)] \times 100\%$$

$$= k \times 100\%$$

$$= 0.326 \times 100$$

$$= 32.6\%$$

22. If a three phase star/delta, 33 KV/11KV, 50 Hz, transformer is loaded with a delta-connected load of 100 Ω per phase, calculate the primary line current.

Solution:

$Y/\Delta = 33KV/11KV$

$K = \frac{11}{\frac{33}{\sqrt{3}}} = 0.577$

In secondary (Δ)part:

$V_L = V_{pn} = 11KV = 1100\ V$

Load per phase = 11000 V

Load per phase = 100Ω

$\therefore$ Phase current indelta $(I^s_{ph}) = \frac{1100}{100} = 110\ A$

Now, $\frac{I^p_{pn}}{I^s_{ph}} = K \Rightarrow I^p_{ph} = K \times J^s_{pn} = K \times 110$

$\therefore \quad I^p_{pn} = 63.5A$

For star-connection (Primary side):

Line current $= I^P_L = I^P_{PA} = 63.5A.$

23. A three phase delta/star, 11 KV/400V, 50 Hz, distribution transformer has a star connected balanced load of (4+j6) Ω per phase. Calculate the primary line current.

Solution:

$\Delta/Y = 11KV/400KV$

Here, $K = \frac{\frac{400}{\sqrt{3}}}{11000} = 0.02099$

In secondary (Y) side:

$V^S_L = 400\ V$

$\therefore \quad V^S_{Pn} = \frac{V^S_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94V$

So, $I^S_{Pn} = \frac{V^S_{Pn}}{Z} = \frac{230.94}{4 + j_6} = 32,026 < -56.3°$

Now,

$\frac{I^P_{Pn}}{I^S_{Pn}} = K = 0.02095$

$\therefore \quad I^S_{Pn} = 0.02099 \times 32.0256 = 0.6722\ A$

For primary (Δ) side,

Line current $= I^P_L = \sqrt{3}\, I^P_{Pn} = \sqrt{3} \times 0.6722 = 1.16\ A.$

24. A 300 kVA, 11 KV/400V, Δ/Y, three phase transformer has star connected balanced load of 60 kW at power factor of 0.8 lagging in each phase. Calculate primary line current.

Solution:

$\Delta/Y = 11KV/400KV$ 300 kVA

Here, for each load, W = 60 kW

or, $V^S_{Pn} I^S_{Pn} \cos\phi = 60 \times 1000$

or, $I^S_{Pn} = \dfrac{60000}{\dfrac{400}{\sqrt{3}} \times 0.8} = 324.759$ A

$$K = \frac{\frac{400}{\sqrt{3}}}{11000} = 0.02099$$

$$\frac{I^P_{Pn}}{I^S_{Pn}} = K \Rightarrow I^P_{Pn} = 0.02099 \times 324.759 = 6.816$$

∴ Primary line current $= I^P_L = \sqrt{3}\, I^P_{Pn} = \sqrt{3} \times 6.816 = 11.806$ A.

25. An 11KV/400V delta/star 3-phase transformer has balanced star connected load of 60 kW at p.f. of 80% lagging per phase. Calculate the primary line current. If the transformer has iron loss of 1.0 kW, calculate the approximate efficiency of the transformer. Given that primary winding resistance and leakage reactance are 25Ω per phase and 30Ω per phase respectively. Secondary winding resistance and leakage reactance are 0.01Ω per phase and 0.02Ω per phase respectively.

Solution:

11 KV/400V $\Delta/Y \Rightarrow K = 0.02099$

Here, primary line current, $I^P_L = 11.81$ A

Also,

Iron loss $(W_i) = 1$ kW $= 1000$ W

$R_1 = 25\Omega$/phase, $X_1 = 30\Omega$/phase

$R_2 = 0.01\Omega$/phase, $X_2 = 0.02\Omega$/phase

∴ Primary line current $= I^S_{Pn} = \dfrac{I^P_L}{\sqrt{3}} = \dfrac{11.81}{\sqrt{3}} = 6.818$ A

$$R_{01} = R_1 + \frac{R_2}{K^2} = 25 + \frac{0.01}{0.02099^2} = 47.697\Omega/\text{Phase}.$$

Now,

$$\eta = \frac{3 \times 60 \times 1000 \times 0.8}{3 \times 60 \times 1000 \times 0.8 + 1000 + 3 \times 6.818^2 \times 47.697} \times 100$$

26. A 500 kVA, 33/11 KV, 3-phase, 50 Hz delta/star transformer has resistances of 35 Ω per phase at high voltage side and 876 Ω per phases at low voltage side. Calculate the efficiency at full load and one half of full load respectively (a) at unity p.f. (b) at 0.8 p.f. lagging.

Solution:

Δ/Y, 500 kVA, 33/11 KV

Transformation ratio $= \dfrac{11000}{\sqrt{3} \times 33000} = \dfrac{1}{3\sqrt{3}}$

R_{02} per phase $= 0.876 + \left(\dfrac{1}{3\sqrt{3}}\right)^2 \times 35 = 2.172\Omega$

Secondary phase current $= \dfrac{500 \times 1000}{\sqrt{3} \times 11000} = \dfrac{500}{11\sqrt{3}}$ A

Full load condition:

Full load total Cu loss $= 3 \times \left(\dfrac{500}{11\sqrt{3}}\right)^2 \times 2.172 = 4490$W

Iron loss = 3050W

∴ Total full load losses = 4490 + 3050 = 7540 W

∴ $\eta_{full} = \dfrac{500 \times 1000}{500 \times 1000 + 7540} \times 100 = 98.54\%$

⇒ Output at 0.8 pf = 400 kW

∴ $\eta = \dfrac{400 \times 1000}{400 \times 1000 + 7540} \times 100 = 98.2\%$

Half load condition:

⇒ Output at unity of = 250 kW

Cu loss $= \left(\dfrac{1}{2}\right)^2 \times 4490 = 1222$W

Total loss Q = 3050 + 1222 = 4172 W

$\therefore \quad \eta = \frac{250 \times 1000}{250 \times 1000 + 4172} \times 100 = 98.35\%$

$\Rightarrow$ Output at 0.8 p.f. = 200 kW

$\therefore \quad \eta = \frac{200 \times 1000}{200 \times 1000 + 4172} \times 100 = 98\%$

27. A 20 kVA, 250/2500V, 50 Hz single phase transformer gave the following tst results: no-load tst (on W side): 250v, 1.4A 105W short circuit test on HV side); 120v, 8A, 320w. Calculate the equivalent circuit parameters referred to primary side and draw the equivalent ckt.

Solution:

$S = 20000VA,\ V_1 = 250V,\ V_2 = 2500V,\ k = \frac{V_L}{V_1} = 10$

For open ckt:

$P_0 = 105w(\text{on Lv})$

$I_0 = 1.4A$

$V_1 = 250V$

$\therefore \quad \cos\phi_0 = \frac{P_0}{I_0 V_1} = \frac{105}{1.4 \times 250} \Rightarrow \phi_0 = 72.54$

We have,

$R_0 = \frac{V_1}{I_0 \cos\phi_0} = \frac{250}{1.4 \times \cos(72.54)} = 595.24\Omega$

and

$X_0 = \frac{V_1}{I_0 \sin\phi_0} = \frac{250}{1.4 \times \cos(72.54)} = 87.2\Omega$

For the s.c. test on HV side (i.e. secondary side)

$P_2 = 320w,\ I_2 = 8A,\ V_2 = 120v$

$R_{02} = \frac{W}{I_2^2} = \frac{P_2}{I_2^2} = \frac{320}{8^2} = 5\Omega$

$R_{01} = \frac{R_{02}}{K^2} = \frac{5}{10^2} = 0.52\Omega$ (referred to primary)

And,

$Z_{02} = \frac{V_2}{I_2} = \frac{120}{8} = 15\Omega$

$\therefore \quad X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{15^2 - 5^2} = 14.14\Omega$

(Referred to primary)

$X_{02}' = \frac{X_{02}}{10^2} = 0./1414\Omega$

28. A single phase 50-Hz transformer has 100 turns primary and turns on secondary winding. The net cross-section area of the core is 250 cm². If the primary winding is connected to a 230v, 50 HZ supply, determine (a) emf induced in secondary winding and (b) the maximum and rms value of flux density in the core.

Solution:

$N_1 = 100,\ N_2 = 400,\ A = 250 \times 10^{-4},\ V_1 = 30v,\ f = 50\text{ Hz}$

$v_2 = \frac{N_2}{N_1} \times V_1 = \frac{400}{100} \times 230 = 92\text{-}0V$

$v_2 = 4.44 f N_2 \phi_m = \phi_m = \frac{920}{4.44 \times 50 \times 400} = 0.01036$

$\phi_m = 0.01036$

or, $B_m X_A = 0.01306$

$B_m = \frac{0.01036}{25 \times 10^{-3}} = 0.414\ Wblm^2$

And,

$B_{rms} = \frac{Bm}{\sqrt{2}} = \frac{0.4145}{\sqrt{2}} = 0.293\ Wb/m^2$

29. The no. load current of a transformer is 15A at a Pf of 0.2 when connected to 460v, 50Hz power supply. If the primary winding has 550 turns, calculate:

(a) The magnetizing and working component of no-load current

(b) Iron loss

(c) Maximum and rms values of flux in the core.

Solution:

$I_0 = 15A$

$\cos\phi_0 = 0.2$

$v_1 = 460v$

$f = 50$ HZ

$N_1 = 550$

I_μ = magnetizing component = $I_{09} \sin\phi_0$ = 15 Spn $(\cos^{-1}(0.2))$

I_w = working component = $I_0 \cos\phi_0 = 15 \times 0.2 = 3A$

Iron loss = $V_1 I_0 \cos\phi_0$

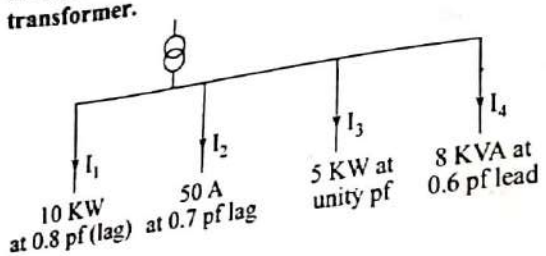
$= 460 \times 15 \times 0.2 = 1380W$

(c) maximum flux $(\phi_m) = \frac{V_1}{4.44 f N_1} = \frac{460}{4.44 \times 50\ 550\ \square}$?? = 3.7 M Wb

$\phi_{rms} = \frac{\phi_m}{\sqrt{2}} = 2.66$ MWb

30. **A small subediting has a single phase 6600/240v transformer supplying four feeders which take the following loads; 1-0 kdw at 0.89Pf lag, 50A at 0.7 Pf lags, 5kw at unity pf. and 8 kVA at 0.6 Pf lead.**

Determine the primary current and power factor which the transformer lakes from the 6600v system. Neglect losses in te transformer. [2072]



Solution:

(a) $P = VI\cos\phi$

or, $10\times10^3 = 240X\ I_1 \times 0.89 \Rightarrow I_f = 52.083A$

$\therefore\ \bar{I_1} = 52.083\angle\text{-}\cos^{-1}(0.8) = 52.083\ \angle\text{-}36.87°$

(b) $\bar{I_2} = 50\angle\text{-}\cos^{-1}(0.7) = 50\ \angle\text{-}45.57°$

(c) $P = VI\cos\phi$

or, $5000 = 240 \times I_3 \times 1$

$\therefore I_3 = 20.83A \Rightarrow \bar{I_3} = 20.83\ \angle 0°$

(d) $s = VI$

or, $8000 = 240 \times I_4$

$\therefore\ I_4 = 33.33A\ \Rightarrow \bar{I_4} = 33.33\ \angle\cos^{-1}(0.6) = 33.33\angle 53.13°$

Now, $\bar{I_s} = \bar{I_1} + \bar{I_2} + \bar{I_3} + \bar{I_4}$

$= 52.08\ \angle\text{-}36.87 + 50\ \angle\text{-}45.57° + 20.83\ \angle 0° + 33.33\ \angle\ 53.13°$

$= 124.203\ \angle\text{-}18.94$

$\therefore\ I_s = 124.204A$

Also,

$$\frac{V_s}{V_i} = \frac{I_p}{I_s}$$

$$\Rightarrow\ I_p = \frac{240}{6600} \times 124.203 = 4.516A$$

And,

From phasor representing of Is

$\phi = -18.94°$

$\therefore\ Pf = \cos\phi = 0.945$ (log)

31. **The primary and secondary winding of a 30kVA, 6000/230v transformer have resistance of 10 and 0.016Ω respectively. The total reactance of the transformer referred to th primary is 282Ω. Calculate the % regulation of the transformer when supplying the full load current at a Pf of 0.8 (lagging).**

Solution:

$V_1 = 6000v$

$V_2 = 230v$

$S = 30000vA$

$R_1 = 10\Omega$

$R_2 = 0.016\Omega$, $\cos\phi = 0.8$ (lag)

$I_1 = \frac{s}{V_1} = \frac{30000}{6000} = 5A$

$X_{01} = X_1 + X_2' = 23\Omega$ (Question)

$R_{01} = R_1 + R_2' = 10 + \frac{R^2}{k^2} = 10 + \frac{0.016}{k^2}$

We have,

$$k = \frac{V_2}{V_1} = \frac{230}{6000} = 0.0383$$

$$R_{01} = 10 + \frac{0.016}{(0.0383)^2} = 20.9\Omega$$

We have,

$$V_{reg} = \frac{I_1R_{01}\cos\phi + I_1X_{01}\sin\phi}{V_1} \times 100\%$$

$$= \frac{5\times20.9 \times 0.8 + 5 \times 23 \times 315}{6000} \times 100\%$$

$= 2.543\%$

32. **A 25 kVA, 6600V/250v. Single phase transformer has the following parameters: $R_1 = 8\Omega$, $X_1 = 15\Omega$, $R_2 = 0.02\Omega$, $X_2 = 0.05\Omega$. Calculate the full voltage regulation of power factor.**

(a) 0.8 log (b) unity (c) 0.8 load

Solution:

$S = 25kVA = 25 \times 1\text{-}0^3VA$, $v_1 = 6600v$, $v_2 = 250v$, $R_1 = 8\Omega$

$R_3 = 0.02\Omega$

$I_c = \frac{S}{V_1} = \frac{25000}{6600} = 3.78A$; $I_2 = \frac{S}{V_2} = \frac{25000}{250} = 100A$

$K = \frac{V_2}{V_1} = \frac{250}{6600} = 0.0378$

$R_{02} = R_2 + R_2' = 0.02 + 8 \times (0.0378)^2 = 0.0314\Omega$ [$\therefore R_2' = R_1 . k^2$]

$X_{02} = X_2 + X_1' = 0.02 + 8 \times (0.0378)^2 = 0.0314\Omega$ [$\therefore R_2' = R_1 . k^2$]

$X_{02} = X_2 + X_1' = 0.05 + 15 \times (0.0378)^2$ [$\therefore X_1' = X_1 k^2$]

$= 0.0714\Omega$

(a) At 0.8 lag

$$V_{reg} = \frac{I_2 R_{02} \cos\phi_2 + I_2 \times X_{02} \times \sin k_2}{V_2} \times 100\%$$

$$= \frac{100 \times 0.0314 \times 0.8 + 100 \times 0.0714 \times (315)}{250} \times 100\% = 2.72\%$$

(b) At unity Pf:

$$V_{reg} = \frac{I_2 R_{02}}{V_2} \times 100\% = \frac{100 \times 0.0314}{250} \times 100\% = 1.256\%$$

(c) At 0.8 Pf lead:

$$V_{reg} = \frac{I_2 R_{02} \cos\phi_2 - I_2 \times X_{02} \times \sin\phi_2}{V_2} \times 100\%$$

$$= \frac{100 \times 0.0314 \times 0.8 - 100 \times 0.0714 \times (3/5)}{250} \times 100\%$$

$= 0.71\%$

33. A 200kVA, 2000/440V, 50Hz single phase transformer gives the following test results.

No-load test 44-0v 1800 8A

Short circuit test 3-0v 32000W 300A

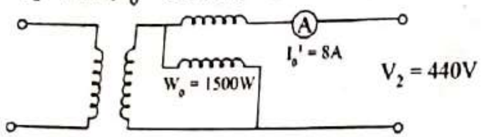
Short circuit test 30v 2000w 300A

Calculate the equivalent circuit parameter referred to secondary side

Solution:

From no-load test/open circuit test

$v_2 - 440v$, $I_0' = 89A$, $W_0 = 1500w$



HV
(PW)
2000/440V

$$w_0 = v_2 I_0' \cos\phi_0 = w_i = I_w^2 r_0'$$

$$\Rightarrow \cos\phi_0 = \frac{w_0}{v_2 I_0'} = \frac{1500}{440 \times 8} = 0.426$$

$$\Rightarrow \sin\phi_0 = \sqrt{1 - \cos\phi_0} = 0.9147$$

$I_c'(I_w) = I_0' \cos\phi_0 = 8 \times 0.4261 = 3.4081A$

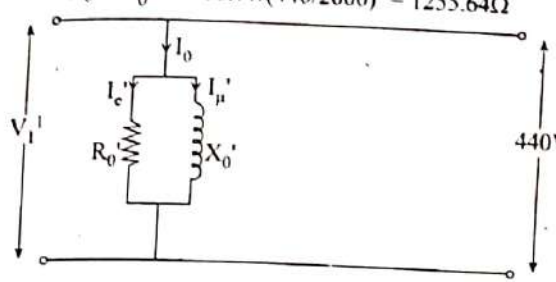
$I_m'(I_\mu) = I_0' \sin\phi_0 = 8 \times 0.9074 = 7.24A$

$$R_0' = \frac{V_2}{I_c} = \frac{440}{8.408} = 129.109\Omega$$

$$X_0' = \frac{V_2}{I_\mu} = \frac{440}{7.24} = 60.77\Omega$$

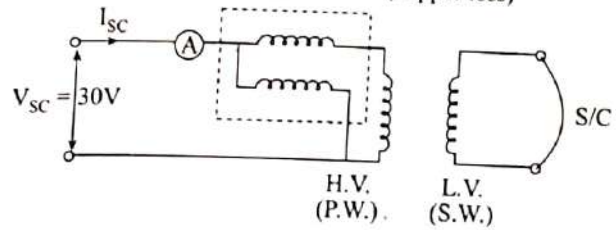
$$\text{Thus, } R_0 = \frac{R_0'}{k^2} = \frac{129.108}{(440/2000)^2} = 2667.528\Omega$$

$X_0 = X_0'/k^2 = 60.77/(440/2000)^2 = 1255.64\Omega$

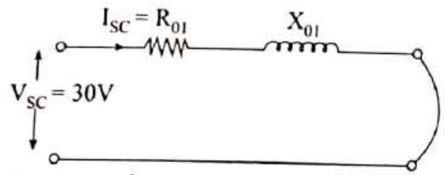


From short circuit test

$V_{sc} = 30v$, $Isc = 300A$, $W_{sc} = 2000w$ (copper loss)



– 300A



(Reffered to primary side.)

So, $W_{sc} = I_{sc}^2$

$R_{01} = w_{cu} = W_{sc}$

$$\Rightarrow R_{01} = \frac{W_{sc}}{I_{sc}^2} = \frac{2000}{300^2} = 0{,}0222$$

$$\Rightarrow Z_{01} = \frac{V_{sc}}{Isc} = \frac{30}{300} = 0.1,\ X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = 0.0975$$

34. A 200 kvA single phase transformer is in circuit continuously for hrs in a day the load is 160kw at 0.8 Pf, for 6hrs, the load is 80 kw at unity P.f for the remaining period of the day it runs on the no load givne that the full load copper loss =3.02 kw & irons loss = 1.6 kW. Find the all day efficiency of the transformer.

Solution:

Full load o/p = 200 kVA

Full load copper loss = 3.02 kw

Full load iron loss = 1.6 kw

then,

Output Energy = (150 × 8) kwh + (80 × 6) kwh + (0×10) kwh

= 1760 kwh

Iron has in kwh = 1.6 kw × 24

= 38.4 unit (kwh)

Copper loss of rload of 160kw at 0.8 pf in 9 hrs

Full load cu loss = 3.02 kw @ 200 kVA

Where,

$$\text{Actual load} = \frac{kW}{P.f} = \frac{160}{0.8} = 200 \text{ kVa}$$

Hence,

cu-loss = 3.02 kW

cu loss in 8 hrs = 3.02 × 8 = 24.16 kwh

Ecu(8) = 24.16 kwh

Copper los sfor load of 80 kw at 1.Pf in 6 hrs.

$$\text{Actual load} = \frac{kw}{P.f} = 80 \text{ kVa}$$

$$W_{cu} = \left(\frac{80}{200}\right)^2 \times \text{wcu (f)} = \frac{4}{25} \times 3.02$$

$\therefore$ $W_{cu} = 0.4832$ kw

Hence, copper loss in 6 hrs = 0.4832 × 6 = 2.8992

E_{cu} (6) = 2.8992 kWh

Now,

Input energy = $E_{output} + E_i + E_{cu(8)} + E_{cu}(6)$

= 1825.46 kwh

Thus,

$$\text{All day efficiency, } \eta = \frac{E_{o/p}}{E_i/p} \times 100\%$$

$$= \frac{1760}{1825.46} \times 100\% = 96.41\%$$

35. A 2000v/400v,m 50Hz single phase transformer drains 2A at a Pf of 0.2 lagging when it has no-load. Calculate the primary current and Pf when secondary current is 200A at a P.f. of 0.89 lagging. Assume the voltage drop in the winding to be neglected.

Solution:

V_1 = 2000V

V_2 = 400V

f = 50Hz

I_0 = 2A, $\cos\phi_0 = 0.2(-1) \Rightarrow \phi_0 = 78.46°$

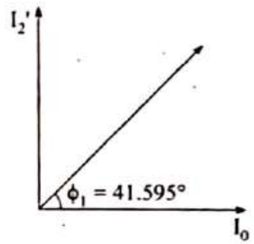
I_1 = ?, I_2 = 200A, $\cos\phi_1$ = ?, $\cos\phi_2 = 0.8(-) \Rightarrow \phi_2 = 36.86°$

$$I_2' = KI_2 = \frac{400}{2000} \times 200 = 40A$$

$\phi_1 = \phi_0 - \phi_2 = 78.46° - 36.86° = 41.593°$

$$I_1 = \sqrt{I_0^2 + (I_2')^2 + 2.I_0I_2' \cos 41.593}$$

= 41.517A



Now, $Pf_1 = \cos\phi_1 = \cos 41.593°$

= 0.7478

36. A 500 kvA transformer has on efficiency at 95% at full load and also at 80% of full load; both at unity P.f.

(a) Separate out the losses of the transformer

(b) Determine thé efficiency of the transformer at 3/4th full load.

Solution:

(a) $$\eta = \frac{500 \times 1}{500 \times 1 + p_i + pc} = 0.95 \ldots(i)$$

Also,

$$\frac{500 \times 0.6}{500 \times 0.6 + P_i + (0.6)^2 P_c} = 0.95 \ldots(ii)$$

From (i) and (ii),m we get

P_i = 9.,87 kw

p_c = 16.45 kw

(b) AT 3/4th full load, we get

$$\eta = \frac{500 \times 0.75}{500 \times 0.75 + 9.87 + (0.85)^2 \times 16.56}$$

$\therefore$ η = 95.14%

37. A 25 kVa, single phase 2200/220V transformer has a primary winding resistance of 1Ω, secondary winding resistance of 0.01Ω, primary leakage reactance of 1.5Ω secondary leakage reactance of 0.015Ω. The iron loss of the transformer is 206W. Calculate the efficiency of the transformer & the voltage regulation at the following condition.

(a) half-load (b) full load (c) at 50% over load

Solution:

$R_1 = 1\Omega$

$R_2 = 0.01\Omega$

$k = \frac{220}{2200} = \frac{1}{100}$

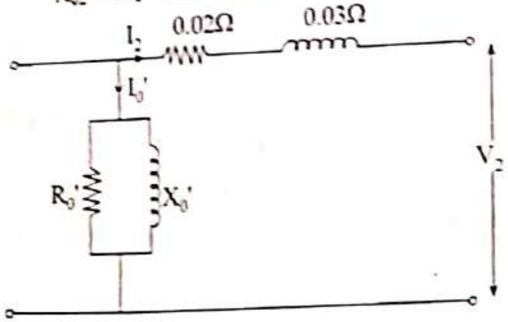
$X_1 = 1.5\Omega$

$X_2 = 0.015\Omega$

Let us consider eq. circuit referred to the secondary side.

$R_{02} = R_2 + R_1' = 0.01 + k^2 \times 1 = 0.02\Omega$

$X_{02} = X_2 + X_1 = 0.2015 + k^2 \times 1.5 = 0.03\Omega$



(a) Half load:

Output kVA = s = 25/2 = 12.5 kVA = $v_2 I_1$ {loaded half}

∴ W_i = 206w (constant with change in load)

$W_{cu} = I_2^2 R_{02} = \left(\frac{2500}{220}\right)^2 \times 0.02$

∴ W_{cu} = 64.566 w

{copper loss decrease with decrease in load}

$\eta = \frac{\text{output power}}{\text{P/p power}} \times 100\%$

$= \frac{12500}{(12500 + 206 + 64.566)} \times 100\%$

= 97.881%

38. A transformer is rated at 100kVA. At full load its copper loss is

(a) the efficiency at full load, unity power factor,

(b) the efficiency at half load, 0.8 power factor,

(c) the efficiency at 75% full load, 0.7 power factor,

(d) the load kVA at which maximum efficiency will occur,

(e) the maximum efficiency at 0.85 power factor, [2071]

Solution:

$S = 100 \text{ kVA} = 100 \times 10^3 \text{ VA}$

$P_{cfl} = 1200 \text{ W}, P_i = 960 \text{ W}$

$\eta = \frac{mS\cos\phi_2}{mS\cos\phi_2 + P_i + m^2 P_{cfl}}$

where $m = \frac{\text{given load}}{\text{full load}}$

(a) At full load m = 1, $\cos\phi_2 = 1$

∴ $\eta = \frac{1 \times 100 \times 10^3 \times 1}{1 \times 100 \times 10^3 \times 1 + 960 + (1)^2 \times 1200}$

= 0.977.88 pu or 97.88%

(b) At half load $m = \frac{1}{2}$, $\cos\phi = 0.8$

$\eta = \frac{\frac{1}{2} \times 100 \times 10^3 \times 0.8}{\frac{1}{2} \times 100 \times 10^3 \times 0.8 \times 960 + \frac{1}{(2)^2} \times 1200}$

= 0.9694 pu = 96.94%

(c) At 75% full load $m = \frac{75}{100} = 0.75$, $\cos\phi_2 = 0.7$

$\eta = \frac{0.75 \times 100 \times 10^3 \times 0.7}{0.75 \times 100 \times 10^3 \times 0.7 + 960 + (0.75)^2 \times 1200}$

(d) $S_M = S_{fl}\sqrt{\frac{P_i}{P_{cfl}}} = 100\sqrt{\frac{960}{1200}} = 89.44 \text{ kVA}$

(e) Maximum efficiency

$\eta_M = \frac{S_M\cos\phi_2}{S_M\cos\phi_2 + 2P_i} = \frac{89.44 \times 10^3 \times 0.85}{89.44 \times 10^3 \times 0.85 + 2 \times 960}$

= 0.9753 pu or 97.53%

□□□

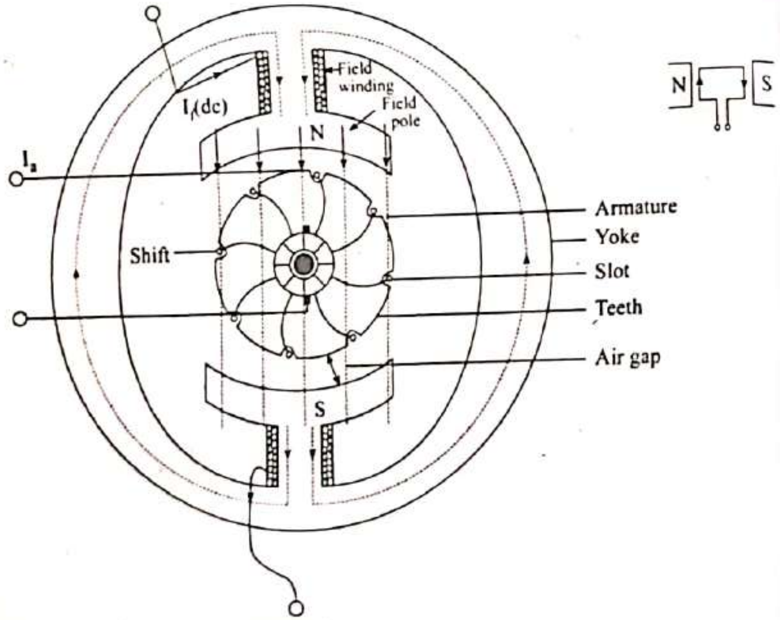
CHAPTER 3

D.C. Generator

A dc generator is an electrical machine which converts mechanical energy into direct current electricity. This energy conversion is based on the principle of production of dynamically induced emf. This article outlines basic construction and working of a DC generator.

CONSTRUCTION OF A DC MACHINE:

Note: A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, a DC generator or a DC motor can be broadly termed as a DC machine. These basic constructional details are also valid for the construction of a DC motor. Hence, let's call this point as construction of a DC machine instead of just 'construction of a dc generator'.



2-poleDC mk

The above figure shows constructional details of a simple 4-pole DC machine. A DC machine consists of two basic parts; stator and rotor. Basic constructional parts of a DC machine are described below.

Yoke: The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.

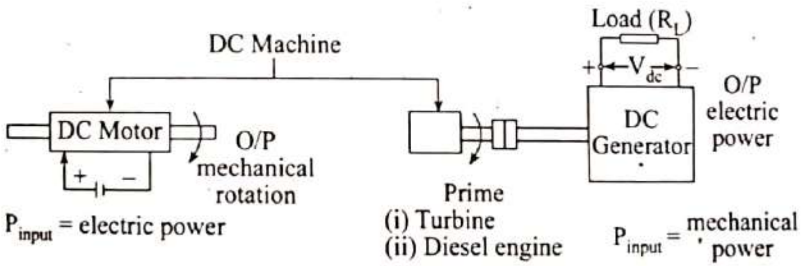
Poles and pole shoes: Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.

Field winding: They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

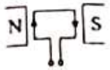
Armature core: Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.

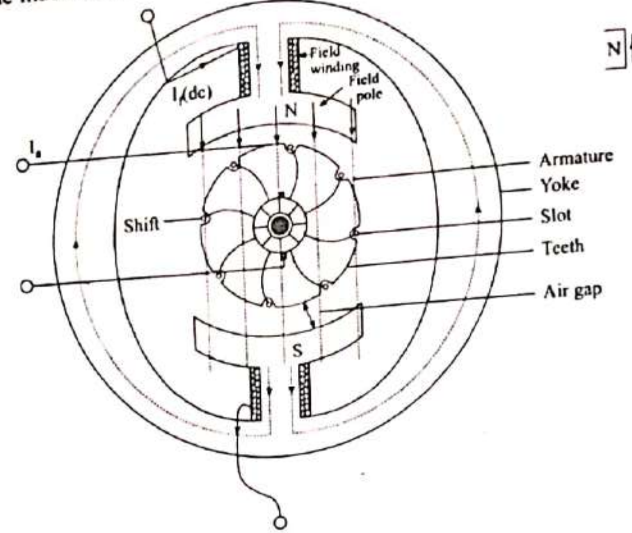
Armature winding: It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

Commutator and brushes: Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.



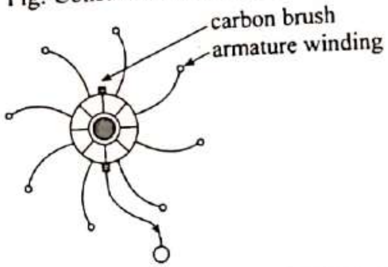
Same machine can be used as motor as well as generator.





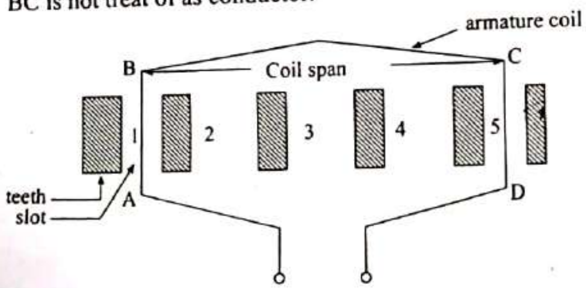
2-poleDC mk

Fig: Construction details of DC m/c



ARMATURE WINDING

i) **Conductor:**
AB & CD are called conductor.
BC is not treat of as conductor.



ii) **Pole pitch.**

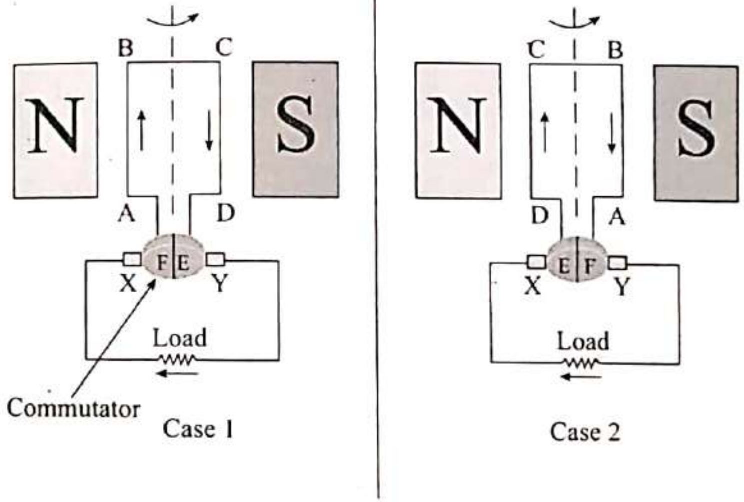
→ Peripheral distance between two poles.

→ finishing end of 1[st] coil (F_1) connected to starting end of 2[nd] coil (s_2) under same pole	→ Finishing end of 1[st] coil, (F_1) connected to starting end of 2[nd] coil (s_3) under. One pole away.
	(ii) A→2, no. of carbon brush = 2
	e.g.

WORKING PRINCIPLE AND COMMUTATOR ACTION

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with a closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of induced current is given by Fleming's right hand rule.

Need of a Split ring commutator:



According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

i) a - a' ⇒ single turn of armature coil

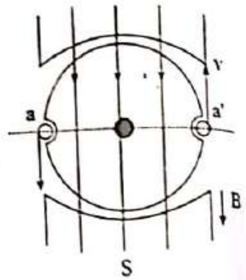
Preference position, $\theta = 0°$

We have,

induced emf

$$e = B\ell V \sin\theta$$

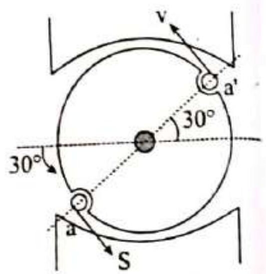
$$e_{aa'} = 0$$



ii) After 30° rotation

$$e_{aa'} = B\ell V \sin\theta$$

$$\Rightarrow e_{aa'} = E_{max}(1/2)$$



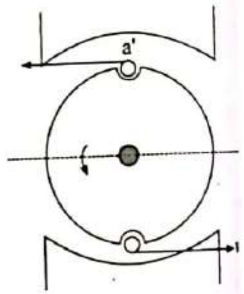
iii) After 90 rotation

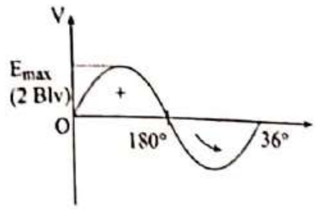
$$e_{aa'} = 2B\ell V\sin 90°$$

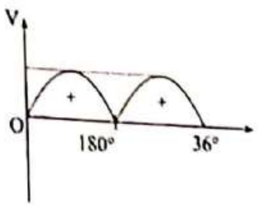
$$= E_{max}$$

Hence, $e_{aa'} \propto \sin\theta$

Thus, the induced emf will be a sinusoidal in the armature, as shown below



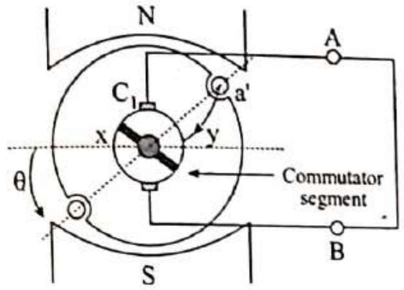




Final o/p due to
Commutator segment and carbon brush

Final o/p due to

Commutator segment R carbon brush?



Cummutator segment rotates with armature where as carbon brush is stationary. The commutator segment & carbon brush helps.

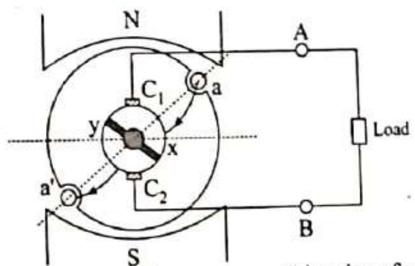
i) no convert ac armature emf into
Determinal voltage (Commutator action)

ii) rotating armature coil.

→ During +ve cycle, as shown above

a' → y → c_1 → A → Load ↓ current flow.
a ← x ← c_2 ← B ←

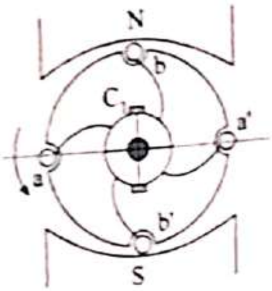
→ During - ve cycle

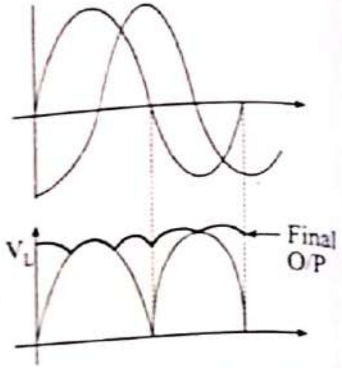


a → x → c_1 → A → current flow ↓ Load
a' ← y ← c_2 ← B ←

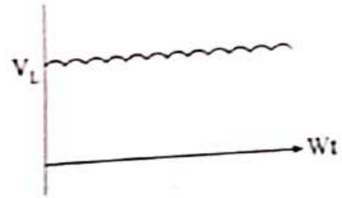
Direction of current through load is unidirectional

→ If there are two coils.

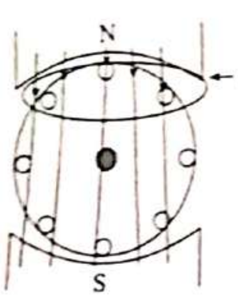




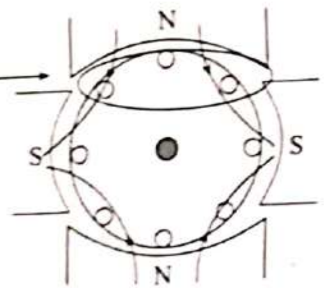
→ If there are many no. of coils, the o/p voltage becomes almost straight line with very few ripple.



EMF equation:



2-pole m/c



4-pole m/c

Let, ϕ = magnetic flux per pole (Wb)

Z = Total no. of armature conductors.

N = Speed of armature (RPM)

A = No. of parallel path in armature winging.

Average value of emf induced per conductor = $d\phi/dt$

When a conductor completes one rotation, magnetic flux cut = $d\phi = \phi.P$.

Also,

Time taken for N revolution = 60 sec.

Time taken for 1 revolution = 60/N sec.

Thus, average emf generated per conductor = $d\phi/dt = \frac{P\phi}{60/N} = \frac{PN\phi}{60}$

We have,

number of conductor in series = Z/A

Thus,

Total emf across the brushes E = $E_{per\ condcutor}$*Z/A

$\Rightarrow \quad e = \frac{PN\Phi}{60} \cdot Z/A$

$\Rightarrow \quad \boxed{E = \frac{ZN\phi}{60} \cdot P/A}$

Thus, $\{E \alpha N\phi\}$

Note: A = P, for lap winding,& A 2 for wave winding

Armature Reaction In DC Machines

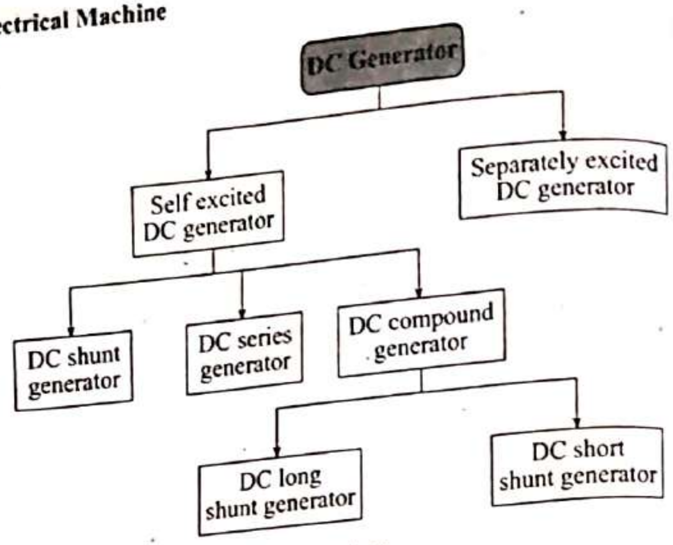
In a DC machine, two kinds of magnetic fluxes are present; 'armature flux' and 'main field flux'. The effect of armature flux on the main field flux is called as **armature reaction.**

EMF is induced in the armature conductors when they cut the magnetic field lines. There is an axis (or, you may say, a plane) along which armature conductors move parallel to the flux lines and, hence, they do not cut the flux lines while on that plane. MNA (Magnetic Neutral Axis) may be defined as the axis along which no emf is generated in the armature conductors as they move parallel to the flux lines. Brushes are always placed along the MNA because reversal of current in the armature conductors takes place along this axis.

GNA (Geometrical Neutral Axis) may be defined as the axis which is perpendicular to the stator field axis.

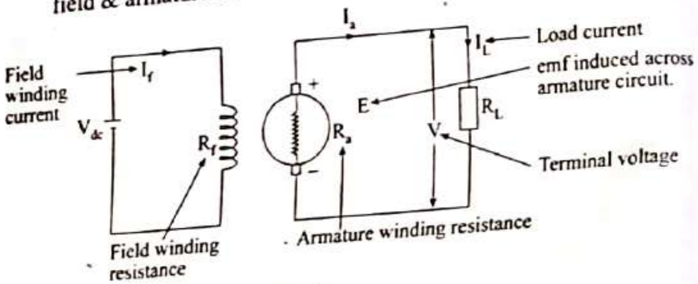
METHODS OF EXCITATION: SEPARATELY & SELF EXCITED TYPES OF DC GENERATOR:

⇒ For any DC generator to operate, the field winding needs to be excited by a DC source so that it can produce the magnetic flux. Depending upon this method of excitation DC generator are classified as follows;



i) Separately excited DC generator:

In separately excited DC generator, the field winding is supplied by different sources. i.e. there is no electrical connection between field & armature circuit.



Using KVL in the armature circuit.

$E = I_A R_a + I_L R_L$ → Terminal voltage across the load

$\therefore \quad E = I_A R_a + V$

$V = E - I_a R_a \;\&\; I_f = V_{dc}/R_f$

· The terminal voltage (V) is always less than the emf induced because of the drop in the armature resistance some voltage drop also take place in the contact resistance between commutator segment & brushes.

$\therefore$ $E - I_a R_a$ - Votage drop in brushes = V

ii) Self excited DC generators:

In self excited generator, the field winding is produced by the armature of the machine itself. i.e. no external DC supply is required for such generators. This means that there will be some electrical connection between the field winding & armature winding. Depending upon the type of connection the self excited DC generators are classified as follows:

2.1 DC shunt Generators

2.2 DC series Generators

2.3 DC compound Generators

DC SHUNT GENERATORS

$R_f >> R_a$

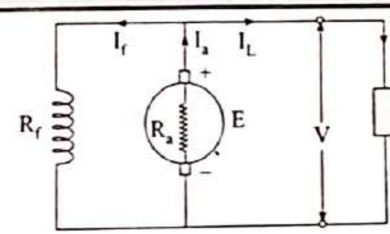
$I_f = V/R_f$

$\rightarrow V = E - I_a R_a$

$\rightarrow I_L = V/R_L$

&

$\rightarrow I_a = I_f + I_L$



Initially, the field current & armature current both are zero and let the armature be rotated by some external means. The induction of emf in the armature require magnetic flux. Even in the absence of the field current, the field poles will have some residual flux which helps in inducing the emf in the armature conductors.

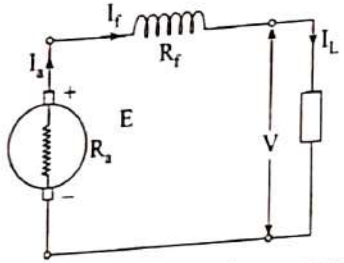
The DC shunt generator are always started without any load, because if started with load the voltage build-up cannot take place.

Since, no-load is connected at starting, all the armature current flows to the field winding, further increasing the flux and consequently emf induced in the armature also increases. Until the generator achieves the rated voltage (field saturates.)

DC SERIES GENERATOR ($R_a \approx R_f$)

→ $I_f = I_a = I_L$

& $V = E - I_aR_a - I_fR_f$



⇒ The voltage build up process is same that of a DC shunt generator but the DC series generator should always be started with load connected otherwise no current flows.

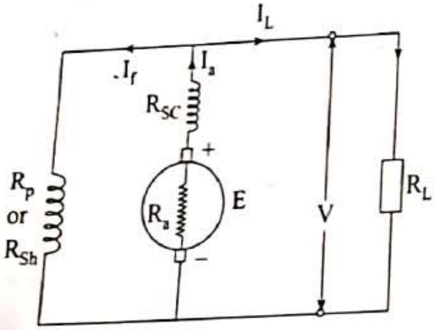
DC COMPOUND GENERATORS:

DC compound generators have two sets of field winding. The two sets may be connected in series with armature winding or load. Thus divided into two types:

(a) Long shunt - DC compound generator

R_{se} - series field winding

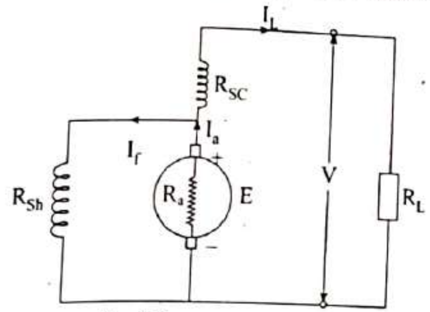
R_{sh}- parallel field winding



$I_f = \frac{V}{R_{Sh}}$; $V = E - I_aR_a - I_aR_{se}$

I_f = V/Rsh; $V = E - I_aR_a - I_AR_{se}$

(b) Short shunt DC Compound Generator



$I_f = \frac{E - I_aR_a}{R_{Sh}}$; $V = E - I_aR_a - I_aR_{se}$

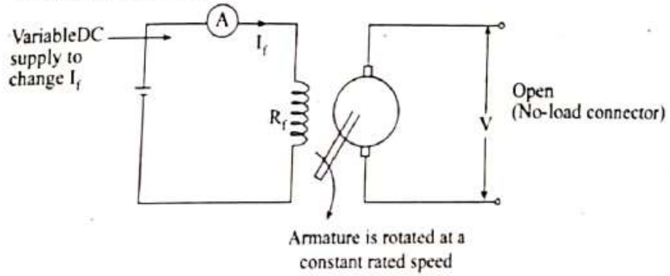
$I_f = \frac{E - I_AR_a}{R_{Sh}}$; $V = E - I_aR_a - I_LR_{se}$

CHARACTERISTICS OF GENERATORS

NO-LOAD CHARACTERISTICS / OPEN CIRCUIT CHARACTERISTICS

No-load characteristics means analyzing the values of emf induced at various value of field current i.e. it is a plot between the induced emf & field current when there is no load connected to the generator.

We will use the following circuit arrangement to trace the no-load characteristic curve.



We know,

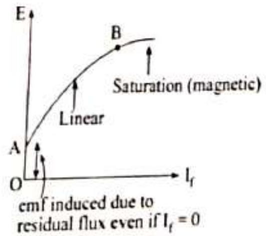
$$E = \frac{Z\phi N}{60} \times \frac{P}{A}$$

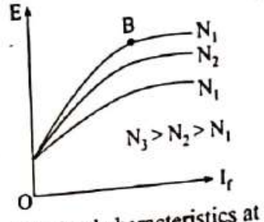
Also, $\phi \propto I_f$

∴ $E \propto N\phi$

⇒ $E \propto NI_f$

∴ $E \propto I_f$ until saturation point 'B'

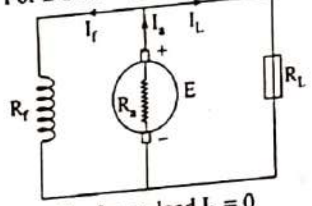


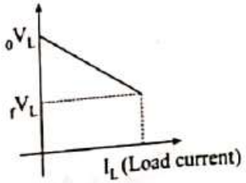


(No-load characteristics at different sped)

LOAD CHARACTERISTICS

⇒ For DC shunt generator V (terminal voltage)





Initially: for no-load $I_L = 0$

⇒ $I_a = I_f$ (which is very small current)

$V = E - I_aR_a$

So, minimum voltage drop in R_a. ∴ $V \approx E$

⇒ $OV_L \approx E[OV_L$ = Terminal voltage at no-load]

- When generator is loaded, $I_L\uparrow$

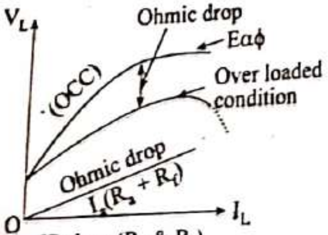
$\Rightarrow (I_a = L + I_f)\uparrow$

Now, load terminal voltage

$V = E - I_aR_a$

- At full load, I_L is maximum, so, $I_aR_a\uparrow\uparrow$ ∴ $V\downarrow\downarrow$

For DC series generator



IR drop (R_a & R_f)

$I_f\uparrow, \phi\uparrow, E\uparrow, E \propto \phi$

$v = E = I_aR_a - I_FR_f$

$I_a = I_f = I_L$ ⇒ $I_L\uparrow = I_f\uparrow = I_a\uparrow$

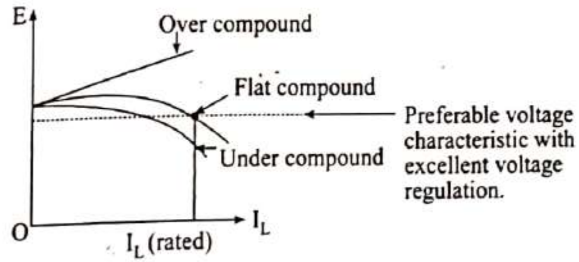
When the Load current I_L increase, I_a current also increases and consequently I_aR_a drop also increases so terminal voltage 'V' will also tend to decrease.

On the other hand, I_f current also increase so the emf included 'e' will also increase (∴ $E \propto I_f$) so terminal voltage 'V' will now tend to increase upto the saturation of flux and then decreases as shown in the figure above.

For DC compound generator

→ We have noticed from the above analysis that a DC shunt generator (shunt field winging) has dropping voltage characteristic & a DC series (series field winding) has rising voltage characteristic. In either case, the voltage regulation from no-load to full load is quite poor.

→ A shunt generator is usually modified with an additional field winding (R_{se}) in series with the armature or load which is called DC compound generator. This generator has very good voltage regulation. As load current increases, the flux produced by R_{se} will also increase and thus 'V' does not decrease.



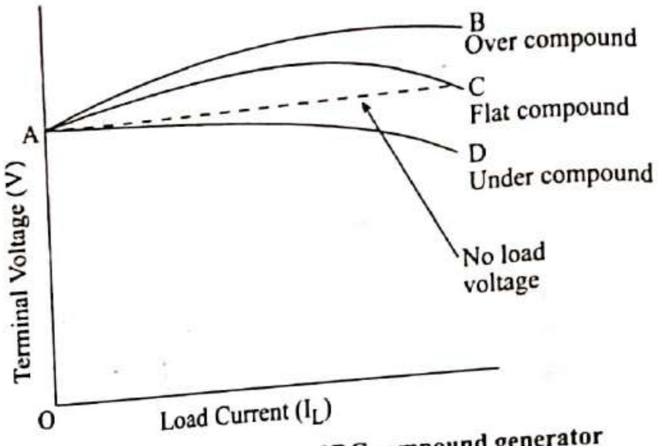
→ By adjusting the number of turns in the series field winding of "DC compound generator, the terminal voltage 'v' can be controlled in various ways.

i) Flat - compound → same terminal voltage at no-load R full load.

ii) Over-compounded → terminal voltage at full load > no-load terminal voltage.

iii) Under compound → terminal voltage at full load < no-load terminal voltage.

CHARACTERISTICS OF DC COMPOUND GENERATOR



External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure.

If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a fla compounded generator is shown by the curve AC.

If the series winding has lesser number of turns than that would b required to be flat compounded, then the generator is called to b under compounded. The external characteristics for an unde compounded generator are shown by the curve AD.

LOSSES IN DC GENERATORS:

There are mainly three types of losses in DC generator.

i) Copper losses:

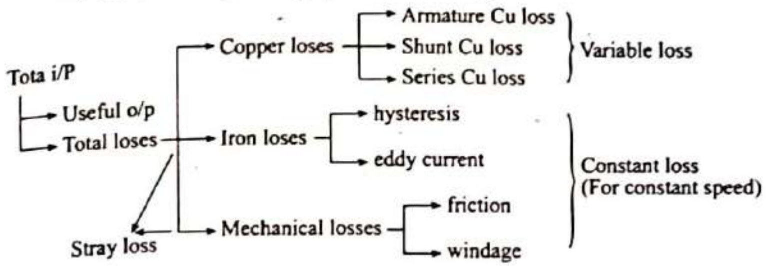
- Armature copper loss ($I_a^2 R_a$)
- Field copper loss → $I_{sn}^2 R_{sn}$ & $I_{se}^2 R_{se}$

ii) Magnetic losses: (Iron loss or core loss)

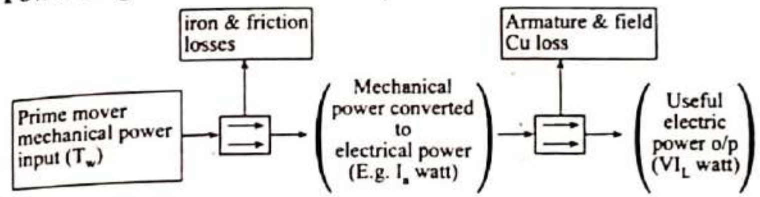
→ hysteresis loss
→ eddy current loss

iii) Mechanical losses:

→ Friction loss at bearings & commutator
→ air-friction (windage) loss of rotating armature.



Power Stage



Efficiency & voltage regulation

i) Mechanical efficiency = $\dfrac{\text{Total electric power genrated in armature}}{\text{mechanical power supplied}}$

$$\Rightarrow \eta_m = \frac{E_f I_a}{\text{O/P of driving engine}}$$

ii) Electrical efficiency = $\dfrac{\text{Watts availabel in load circuit}}{\text{total watts generated}}$

$$\Rightarrow \eta_e = \frac{VI_2}{E_g I_a}$$

iii) Overall efficiency = $\dfrac{\text{Watts available in load ckt}}{\text{mechanical power i/P}}$

$$\Rightarrow \eta = \frac{\text{O/P}}{\text{I/P}} = \frac{\text{O/P }(VI_2)}{\text{O/P }(VI_L) + \text{losses}} = \frac{\text{i/P - losses}}{\text{i/P}}$$

Mechanical power i/P = BHP of prime mover × 735.5
↓
Brake horse power

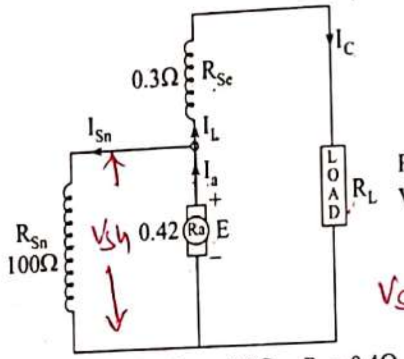
Voltage regulation

$$\%\text{ voltage regulation} = \frac{{}_0V_L - {}_FV_2}{{}_FV_2} * 100\%$$

Tutorial

1. A short shunt cumulative compound dc generator supplies 7 .5 kW at 230V. The shunt field, series field and armature resistance are 100, 0.3 and 0.4 ohms respectively. Calculate the induced emf and the load resistance. [2075]

Solution:



$P_0 = 7.5$ KW
$V = 230V$

$R_{Sn} = 100\Omega$, $R_{Se} = 0.3\Omega$, $R_a = 0.4\Omega$

$R_{sn} = 100\Omega$, $R_{se} = 0.3\ \Omega$, $R_a = 0.4\Omega$

Here,

$$I_L = \frac{P_0}{V} = \frac{7.5 \times 1000}{230} = 32.6086A$$

$\therefore$ Load Resistance $(R_L) = \frac{V}{I_L} = \frac{230}{32.6086} = 7.05\Omega$

Using current division rule,

$$I_L = \frac{R_{sh}}{R_{sh} + R_{se} + R_L} \times I_a$$

or, $32.6086 = \frac{100}{100 + 0.3 + 7.05} \times I_a$

$\therefore$ $I_a = 35.005$ A

Using KVL,

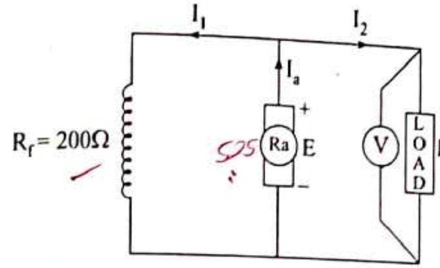
$$E - I_aR_a - I_LR_{se} - V = 0$$

or, $E = V + I_aR_a + I_LR_{se} = 30 + 35.005 \times 0.4 + 32.6086 \times 0.3$

$\therefore$ $E = 253.78$ V.

2. The resistance of the field circuit of a shunt excited dc generator is 200Ω. When the output of the generator is 100 kW, the terminal voltage is 500V and the generated emf 525V. Calculate (a) the armature resistance and (b) the value of the generated emf when the output is 60kW, if the terminal voltage then is 520V. [2074]

Solution:



When $P_0 = 100$ kW, V = 500 V & E = 525 V

(a) Here, $I_L = \frac{P_0}{V} = \frac{100 \times 1000}{500} = 200$ A

Also, $I_f = \frac{V}{R_f} = \frac{500}{200} = 2.5$ A

$\therefore$ $I_a = I_L + I_f = 202.5$ A

So,

$$E - I_a R_a = V$$

or, $\frac{525 - 500}{202.5} = R_a$

$\therefore$ $R_a = 0.1234\ \Omega$

(b) When $P_0 = 60$ kW, V = 520 V,

$$I_L = \frac{P_0}{V} = \frac{60 \times 1000}{520} = 115.384 \text{ A}$$

$$I_f = \frac{520}{200} = 2.6A$$

$\therefore$ $I_a = I_L + I_f = 117.984$

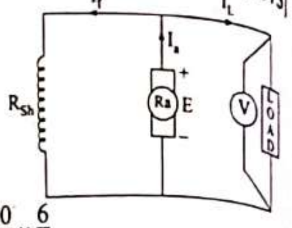
Using KVL,

$$E = V + I_aR_a = 520 + 117.984 \times 0.1234$$

$\therefore$ $E = 534.56$ V.

3. **A 6 pole wave wound shunt generator has 1200 conductors. The useful flux per pole is 0.02Wb, the armature resistance 0.4Ω and the speed 400rpm. If the shunt resistance is 220Ω, calculate the maximum current which the generator can deliver to an external load if the terminal voltage is not to fall below 440V.** [2073]

Solution:



$P = 6, A = 2, Z = 1200, \phi = 0.02$ Wb

$Ra = 0.4\Omega, N = 400$ rpm

$R_{sh} = 220\ \Omega, V = 440$ V

We know,

$$E = \frac{Z\phi N}{60} \times \frac{P}{A} = \frac{1200 \times 0.02 \times 400}{60} \times \frac{6}{2}$$

$\therefore\ E = 480$ N

$$I_f = \frac{V}{P_{sn}} = \frac{440}{220} = 2A$$

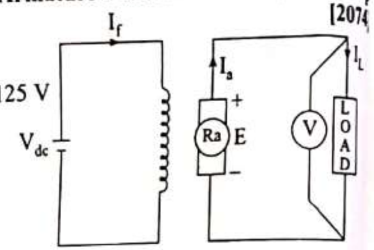
Also, $E - I_a R_a = V$

or, $I_a = \frac{E - V}{R_a} = \frac{480 - 440}{0.4} = 100$ A

$\therefore\ I_L = I_a - I_f = 100 - 2 = 98$ A.

4. **A separately excited generator when running at 1200 rpm supplies 200A at 125V to a circuit of constant resistance. What will be the current when the speed is dropped to 1000 rpm, if the field current is unaltered? Armature resistance =0.04Ω, total drop at brushes = 2V.** [2074]

Solution:



$N_1 = 1200, I_L = 200$ A, $V = 125$ V

$R_a = 0.04\Omega, V_{br} = 2V$

$$R_L = \frac{V}{I_L} = \frac{125}{200} = 0.625\Omega$$

$E_1 - I_L R_a V_{br} = V$

or, $E_1 = 126 + 200 \times 0.04 + 2 = 135V$

Now, when $N_2 = 1000$rpm

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow E_2 = \frac{N_2}{N_1} \times E_1\ [\because I_f \ \&\ \phi \text{ are fixed.}]$$

$$\therefore\ E_2 = \frac{1000}{1200} \times 135 = 112.5V$$

So, $E_2 - I_L R_a - V_{br} = I_L R_L$

or, $112.5 - 2 = (0.04 + 0.625)\ I_L$

$\therefore\ I_L = 166.165$ A.

5. **The armature supply voltage of a dc motor is 230v. The armature current is 12A, the armature resistance is 0.1Ω and the speed is 100 rad/sec. Calculate: (a) the induced emf (b) the electromagnetic torque(c) the electrical power input to the armature (d) the mechanic power developed by the armature (e) the armature copper-losses.** [2070]

Solution:

For generator,

$$I_f = \frac{250}{100} = 2.5 \text{ A}$$

$I_L = 80$ A

$\therefore\ I_a = I_L + I_f = 82.5$A

Hence,

$E_g - I_a R_a = V$

or, $E_g = V + I_a R_a = 250 + 82.5 \times 0.12 = 259.9$ V

For motor

$I_f = 2.5$ A, $I_L = 80$A

$\therefore\ I_a = I_L - I_f = 77.5$A

$E_m = V - I_a R_a = 250 - 82.5 \times 0.12 = 240.1$ V

Now,

$$\frac{N_g}{N_m} = \frac{E_g}{E_m} = \frac{259.9}{240.1} = 1.082.$$

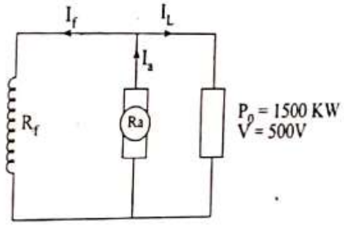
6. **A 1500kW, 500V, 16 pole, dc shunt generator runs at 150 rpm. What must be the useful flux per pole if there are 2500 conductors in the armature; the winding is lap connected and full-load armature copper loss is 25kW? Calculate the area of the pole shoe if the air gap flux density has a uniform value of 0.9Wb/m². Neglect change in speed. Take $R_f = 55\Omega$.**

Solution:

$N = 150$ rpm, $Z = 2500$, $P = A$

$I_a^2 R_a = 25$ kW, $B = 0.9$ T, $R_f = 55\Omega$

Here,



$$I_L = \frac{P_0}{V} = \frac{1500 \times 1000}{500}$$

$= 3000$ A

$$I_f = \frac{500}{55} = 9.09 \text{ A}$$

$\therefore\ I_a = I_L + I_f = 3009.09$A

We have,

$$I_a^2R_a = 25000$$

$$\therefore \quad I_aR_a = \frac{2500}{3009.09} = 8.308 \text{ V}$$

So, $E = V + I_aR_a = 500 + 8.308$

$$\therefore \quad E = 508.308 \text{ V}$$

Now,

$$E = \frac{Z\phi N}{60} \times \frac{P}{A}$$

or, $$508.308 = \frac{2500 \times \phi \times 150}{60}$$

$$\therefore \quad \phi = 0.081 \text{ Wb}$$

Also,

$$\text{Area} = \frac{\phi}{B} = \frac{0.081}{0.9} = 0.09 \text{ m}^2$$

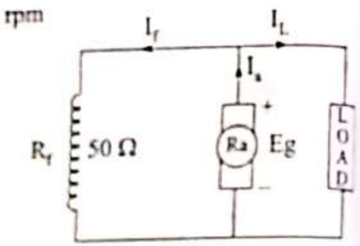
7. **A shunt generator delivers 50 kW at 250 V and 400 rpm. The armature resistance is 0.02Ω and field resistance is 50Ω. Calculate the speed of the machine when running as a shunt motor and taking 50 kW input at 250 V.** [2068]

Solution:

Generator:

$P_o = 50$ kW, $V = 250$ V, $N_g = 400$ rpm

$R_a = 0.02\Omega$, $R_f = 50\Omega$



So, $$I_L = \frac{P_o}{V} = \frac{50 \times 1000}{250} = 200 \text{ A}$$

$$I_f = \frac{250}{50} = 5\text{A}$$

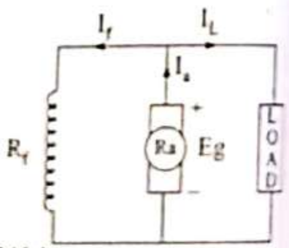
$$\therefore \quad I_a = I_L + I_f = 205 \text{ A}$$

$$E_g - I_aR_a = V \Rightarrow E_g = V + I_aR_a = 250 + 205 \times 0.02$$

$$\therefore \quad E_g = 254.1 \text{ V}$$

Motor:

$P_i = 50$kW, $V = 250$ V



$$I_L = \frac{50 \times 1000}{250} = 200 \text{ A}$$

or, $$\frac{250}{50} = 5\text{A}$$

$$\therefore \quad I_a = I_l - I_f = 195 \text{ A}$$

$$E_m = V - I_aR_a = 250 - 195 \times 0.02 = 246.1$$

Now,

$$\frac{E_m}{E_g} = \frac{N_m}{N_g}$$

$$\therefore \quad N_m = \frac{E_m}{E_g} \times N_g = \frac{246.1}{254.1} \times 400$$

$$\therefore \quad N_m = 387.4 \text{ rpm.}$$

8. **A dc shunt generator has an output of 10 kW at 500 V; the speed being 1000 rpm. The armature circuit resistance is 0.5Ω and the field resistance is 250Ω. Calculate speed when running as a shunt motor taking 50 kW at 500 V.**

Solution:

$R_a = 0.5\Omega$, $R_f = 250\ \Omega$

Generator:

$$I_L = \frac{10 \times 1000}{500} = 20 \text{ A}$$

$$I_f = \frac{500}{250} = 2\text{A}$$

$$\therefore \quad I_a = 20 + 2 = 22 \text{ A}$$

Now, $E_g = V + I_aR_a = 500 + 22 \times 0.5 = 511$ V

$N_g = 1000$ rpm

Motor:

$$I_L = \frac{50 \times 1000}{500} = 100 \text{ A}$$

$$I_f = \frac{500}{250} = 2\text{A}$$

$$\therefore \quad I_a = I_L - I_f = 98\text{A}$$

Then, $E_m = V - I_aR_a = 500 - 98 \times 0.5 = 451$V

We know,

$$\frac{E_m}{E_g} = \frac{N_m}{N_g}$$

$$\therefore \quad N_m = \frac{451}{511} \times 1000 = 882.58 \text{ rpm}$$

9. **A 20kw, 240w dc shunt generator has armature and field resistance of 0.05Ω and 80Ω respectively. Calculate the total armature power developed when working:**
(i) as a generator delivering 20kW output
(ii) as a motor taking 20kw input [2067]

Solution:

Shunt field, current, $I_{sw} = \frac{V}{R_{sh}} = \frac{240}{80} = 3A$

(i) As Generator

Load current, $I_L = \frac{\text{Output in } K_{20} \times 1,000}{V} = \frac{20 \times 1,000}{240} = 83.33A$

Armature current, $I_a = I_L + I_{sh} = 83.33 + 3 = 86.33A$

Generated emf, $E_{fv} = V + I_a R_a = 240 + 86.33 \times 0.05 = 244.32V$

Total armature power developed,

$P_g = \frac{E_g \times I_a}{1,000} = \frac{244.32 \times 83.33}{1,000} = 20.36$ kw

(ii) As motor

Line current, $I_L = \frac{\text{Input in kw} \times 1,000}{V} = \frac{20 \times 1000}{240} = 83.33A$

10. **In a long-shunt compound generator, the terminal voltage is 230v when it delivers 150A. Determine (i) induced emf (ii) total power generated by armature. The shunt field, series field, diverter, and armature resistance are 92, 0.015, 0.03 and 0.032 ohm respectively.**

Solution:

Terminal voltage, v = 230v

Shunt current, $I_{sh} = \frac{V}{R_{sh}} = \frac{230}{92} = 2.5A$

Armature current, I_{ac} = load current, $I_c + I_{sh}$

$< 150 + 2.5 = 152.5A$

Combined resistance of series field and its diverter,

$R_{se\ eq} = \frac{R_{se} \times R_{dir}}{R_{se} + R_{div}} = \frac{0.015 \times 0.03}{0.015 + 0.03} = 0.01\Omega$

(i) Induced emf. $E_g = V + I_a R_a + Ia\ R_{se}$ eg.

$= 230 + 152.5 \times 0.032 + 152.5 \times 0.01 = 246.4v$

(ii) Total power generated, $P_g = \frac{E_g \times I_a}{1000} = \frac{236.4 \times 152.5}{1000} = 36.051kW$

11. **In a 220v compound generator, the armature, series and shunt windings have resistances of 0.3Ω, 0.22 and 60Ω respectively. The load consists of 80 lamps, each rated at 60w and 220v. Find the total, emf and armature current when the machine is connected for long shunt and shunt.**

Solution:

Total lamp load, i_L = Number of lamps × voltage of each lamp

$= 80 \times 60 = 4800w$

Terminal voltage, v = 220v

Load current, $I_L = \frac{P_L}{v} = \frac{4800}{220} = 21.824$

Long shunt connection

Shunt field current, $I_{sh} = \frac{v}{R_{sh}} = \frac{220}{60} = 3.67$

Armature current, $I_a = I_L + I_{sh} = 21.82 + 3.67 = 25.49A$

Generator emf, $E_g = v + I_a R_{aq} + I_{se} R_{se}$

$= 220 + 25.49 \times 0.3 + 25.49 \times 0.2$

$= 232.745v$

Shunt field current, $I_{sh} = V_{sh}/R_{sh} = 224.364/60 = 3.74A$

Armature current, $I_a = I_L + I_{sh} = 21.82 + 3.74A = 25.56A$

Generated emf, $E_g = V + I_{se} R_{se} + I_a R_a$

$= 220 + 21.82 \times 0.2 + 25.56 \times 0.3$

$= 232v.$

12. **A4-pole dc generator has 51 slots and each contains 20 conductors. Flux per pole si 7 mWb and runs at 1500 rpm. Find the produced emf of the machine if its armature is wave wound.**

Solution:

Flux per pole ϕ = 7m Wb = 0.007 Wb

Number of poles, p = 4

speed, N = 1500 rpm

Number of armature conductors,

z = number of slots × number of conductors

$= 51 \times 20 = 1020$

Number of parallel paths, A = 2 ∵ armature is wave wound

Generated emf, $E_g = \frac{\phi ZN}{60} \times \frac{P}{A}$ volts.

$= \frac{0.007 \times 1020 \times 1500}{60} \times \frac{4}{2} = 3657v.$

13. A 6-pole machine has an armature with 90 slots and 8 conductor per slot and runs at 1000 rpm, the flux per pole is 0.045Wb. Determine the induced emf if winding is (i) lap connected (ii) wave connected. [2070]

Solution:

Flux per pole, $\phi = 0.05$ Wb

Number of poles, $p = 6$

Speed, $N = 1000$ rpm

Number of armature conductors,

Z = Number of slots × number of conductors per slot

$= 90 \times 8 = 720$

(i) When machine is lap = connected

Number of parallel paths, $A = P = 6$

$$\text{Induced emf, } E_g = \frac{QZN}{60} \times \frac{P}{A} = \frac{0.05 \times 720 \times 1000}{60} \times \frac{6}{6} = 600v$$

(ii) When machine is weave-connected

Number of parallel paths, $A = 2$

$$\text{Induced emf, } Eg = \frac{A \times Z \times N}{60} \times \frac{P}{A} = \frac{0.05 \times 720 \times 1000}{60} \times \frac{6}{2}$$

$= 1800v$

14. A 4-pole lap-connected armature of a dc shunt generator i required to supply the loads connected in parallel:

(i) 5 kw geyser at 250v and

(ii) 2.5 kw lighting load also at 250v

The generator has an armature resistance of 0.2Ω and a fiel resistance of 250Ω. The armature has 230 conductor in the slots an runs at 1000 rpm. Allowing 1vg per brush for contact drops find (flux per pole, (ii) armature current per parallel path.

<u>At load of 250 kw</u>

$$\text{Load current } IL_2 = \frac{250 \times 1000}{500} = 500A$$

Generated emf, $Eg_2 = 500 + 500 + 0.015 = 507.5v$

$$\text{Speed , } N_2 = \frac{Eg_2}{Eg_1} \times N_1 = \frac{507.5}{515} \times N_1 = 0.9854\ N_1$$

$\because E_g \times N$ with constant excitation

$$\text{Reduction in speed} = \frac{N_1 - N_2}{N1} \times 100 = \frac{N_1 - 0.9854\ N_1}{N_1} \times 100 = 1.46\%$$

15. A 2-pole dc shunt generator charges a 100v battery of negligible internal resistance. the armature of the machine is made up of 1,000 conductors, each of 2mΩ resistance. The charging currents are found to be 10A and 20A for generator sped of 1055 and 1105 rpm respectively. Find the field circuit resistance and flux per pole of the generator. Neglect armature reaction effects.

Solution:

Number of armature conductors,

$Z = 1000$

Number of poles, $P = 2$

Number of parallel paths, $A = 2$

Armature resistance per path = Number of conductors per path × resistance of each conductor

$$= \frac{1000}{2} \times 2 \times 10^{-3} = 1\Omega$$

Armature resistance,

$$R_a = \frac{\text{Armature resistance per path}}{\text{Number of parallel paths}} = \frac{1}{2} = 0.5\Omega$$

Let the generated emfs speeds N_1 of 1055 rpm and N_2 of 1105 rpm be E_1 and E_2 volts respectively.

$$\text{Then } \frac{E_2}{E_1} = \frac{dzd_i \times \frac{1}{A} \times 60}{aZN_1 \times \frac{i}{A}/60} = \frac{N_2}{N_1} = \frac{1105}{1055} \quad ...(i)$$

Terminal voltage, $V = 100$

Let the shunt field current be of I_{sh} amperes.

Load current at sped of 1055 rpm,

$T_{L1} = 10A$

Armature current at speed of 1055 rmp

$I_a1 = I_{L1} + I_{sh} = (10 + I_{sh})$

Similarly, armature current at sped of 1105 rpm,

$I_{a2} = (20 + I_{sh})$

Now induced emf,

$E_1 = v + I_a, R_a = 100 + (10 + I_{sh}) \times 0.5 = 105 + 0.5\ I_{sh}$

and $E_2 = v + Ia_2\ Rq = 100 + (20 + I_{sh}) \times 0.5 = 110 + 0.5\ I_{sh}$

$$\text{and } \frac{E_2}{E_1} = \frac{110 + 0.5\ I_{sh}}{105 + 0.5\ I_{sh}} \quad ...(ii)$$

Comparing Eqn (i) and (ii) we have

$$\frac{1105}{1055} = \frac{110 + 0.5I_{sh}}{105 + 0.5\ I_{sh}}$$

or, Shunt field current $I_{sh} = IA$

Field circuit resistance, $R_{sh} = \frac{v}{I_{sh}} = \frac{100}{1} = 100\Omega$

Substituting, $E_1 = 105 + 0.5 \times 1 = 105.5\ v_1$ z= 1000 conductors, $N_1 = 1055$ rpm, P = 2, A = 2 in emf equation we have

$$105.5 = \phi \times \times 1000 \times \frac{1055}{60} \times \frac{2}{2}$$

or, $\phi = \frac{105.5 \times 60}{1000 \times 1055} = 6$ mWb

16. Find the resistance of the load which takes a power of 5kw form a dc shunt generator whose external characteristic is given by the equation: cv = 250 - 0.5 I_L

Solution:

$v = 250 = 0.5I_L$ ...(i)

and power output, $P = VI_L$

or, $VI_L = 5 \times 1000 = 5000$ w ...(i)

Substituting $I_L = \frac{5000}{v}$ from Eq^n (ii) in Eqn (i) we have

$$v = 250 - 0.5 \times \frac{5000}{v}$$

or, $v^2 - 250 + 2500 = 0$

or, $v = \frac{250 \pm \sqrt{250^2 - 4 \times 2500}}{2} = 239.56$v or 10.44v

Rejecting lower value 10.44v of v, as it is not practicable

We, have,

$v = 239.56$v

$I_L = \frac{5000}{239.56} = 20.87$A

Load resistance, $R_L = \frac{V}{I_L} = \frac{239.56}{20.87} = 11.48\Omega$

17. Find the flux per pole and armature current if the total load is 7.5 kW and load voltage is 250 V in DC shunt generator. The field winding resistance and armature resistance are 250Ω and 0.2Ω respectively.

Solution:

Total load to be supplied, P = 5 + 2.5 = 7.5kW

Load current, $I_L = \frac{P}{v} = \frac{7.5 \times 1000}{250} = 304$

Shunt field current $I_{sh} = \frac{V}{R_{sh}} = \frac{250}{250} = IA$

Armature current, $I_a = I_L + I_{sh} = 30 + 1 = 31A$

Generated emf, $E_g = V + I_aR_a$ + brush contact drop

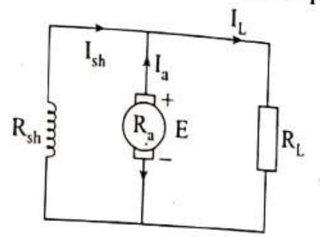
$= 250 + 31 \times 0.2 + 2 \times 1 = 258.2v$

(i) Flux per pole, $\phi = \frac{E_g \times 60}{Z \times N} \times \frac{A}{P} = \frac{258.2 \times 50}{120 \times 1000} \times \frac{4}{4}$

$= 129.1$ mWb

(ii) Current per armature path, $I_c = \frac{I_a}{A} = \frac{31}{4} = 7.75A$

18. A 4-pole dc shunt generator with lap connected armature has field and armature has field and armature resistance of 50Ω and 0.1ω respectively. It supplies power to sixty numbers of 100v, 40w lamps. Calculate the armature current and the generated emf. Allow a contact drop of 1v (brush and interpole and compensating winding drops; are 0.5v/pole and 0-.25 v/pole respectively.



Solution:

Total lamp load, P_L = Number of lamps × voltage of each lamp

$= 60 \times 40 = 2400$ w

Terminal voltage v = 100v

Load current, $I_L = \frac{P_L}{v} = \frac{2400}{100} = 24A$

Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{100}{50} = 2a$

Total armature current, $I_a = I_L + I_{sh} = 24 + 2 = 26A$

Generated emf, $E_g = v + I_aR_a$ + brush drops

$= 100 + 26 \times 0.1 + 2 \times 1 + 2 \times 0.5 + 2 \times 0.25$

$= 106.1v$

19. Estimate the reduction is sped of a generator with constant excitation on bus bars to decrease its load from 500 kw to 250 kw. The resistance between terminals is 0.015Ω. The bus bar voltage is 500v.

Solution:

Bus bar voltage, v = 500v

Resistance between terminals, R - 0.015Ω

At load of 500 kw

Load current, $IL_1 = \frac{\text{load in kw} \times 1000}{\text{Busbar voltage}} = \frac{500 \times 1000}{500} = 1000A$

Generated emf, $Eg_1 = v + IL_1R = 500 + 1000 \times 0.015 = 515v$

Sped $= N_1$ rpm (say)

20. An 8-pole d.c. shunt generator with 778 wave-connected armature conductors and running at 500 rpm supplies a load of 12.5Ω resistance at nominal voltage of 250 V. he armature resistance is 24Ω and the field resistance is 250Ω. Find the armature current, the induced emf and the flux per pole.

Solution:

$P = 8, Z = 778, A = 2$ (wave connected)

$N = 500$ rpm, $Re = 12.5\,\Omega$, $V = 250$ V

$Ra = 0.24\Omega$, $R_f = 250\Omega$

$Ia = ?, E = ?, \phi = ?$

Now,

$$I_f = \frac{V}{R_f} = \frac{250}{250} = 1\text{ A}$$

$$I_L = \frac{250}{R_L} = 20\text{ A}$$

$\therefore \quad Ia = I_f + I_L = 21$ A

Now,

$$E = IaRa + 250 = 255.04\text{ V}$$

Again,

$$E = \frac{Z\phi N}{60} \times \frac{P}{A}$$

$$\phi = \frac{E \times 60 \times A}{Z \times N \times P} = \frac{255.04 \times 60 \times 2}{778 \times 500 \times 8}$$

$\therefore \quad \phi = 9.8344 \times 10^{-3}$ Wb

21. A 440 V dc compound generator has an armature series field and shunt field resistance of 0.5, 1 and 900Ω respectively. Calculate generated voltage white delivering 40A to external load in case of (i) long shunt (ii) short shunt connections.

Solution:

Given,

$V = 440$ V

$Ra = 0.5$

$Rse = 1$

$Rsh = 200\,\Omega$

(i) Long Shunt Connection

$I_L = 40$ A

$$I_f = \frac{V}{Rsh} = \frac{440}{200} = 2.2\text{ A}$$

$I_a = I_L + I_f = 42.2$ A

$\therefore \quad E = I_aR_a + I_aR_{se} + V = 42.2 \times 0.5 + 42.2 \times 1 + 440 = 503.3$ V

(ii) Short Shunt Connection

Here, voltage across shunt field

Winding $(V_{sh}) = I_LR_{se} + V = 40 \times 1 + 440$

$\therefore \quad Vsh = 480$ V

Now,

$$I_f = \frac{Vsh}{Rsh} = \frac{480}{200} = 2.4\text{ A}$$

$$I_a = I_f + I_L = 2.4 + 40 = 42.4\text{ A}$$

And,

$$E = Ia\,Ra + I_L\,R_{se} + V = 42.4 \times 0.5 + 40 \times 1 + 440$$

$\therefore \quad E = 501.2$ V

22. A 50 kw short shunt compound generator works on full load with a terminal voltage of 230 V. The armature series and shunt winding resistances are 0.01, 0.05 Ω and 115 Ω respectively. The friction and iron loss of machine is 2 kw. Calculate

(i) emf generated at full load

(ii) Full load copper loss

(iii) BHP of driving engine

(iv) Full load efficiency

Solution:

Power delivered (P) = 50 kw

Terminal voltage (V) = 230 V

$Rse = 0.05\,\Omega$

$Rsh = 115\,\Omega$

$Ra = 0.01\,\Omega$

Friction loss + Iron loss of machine = 2 kw

Now,

$$I_L = \frac{P}{V} = \frac{50}{230} = 0.21739\text{ kA} = 217.39\text{ A}$$

Voltage across shunt field winding $= I_L\,Rse + V$

$= 217.39 \times 0.05 + 230$

$= 240.869$ V

Also,

$$I_f = \frac{240.869}{115} = 2.0945 \text{ A}$$

$\therefore$ $I_a = I_L + I_f = 219.485$ A

(i) Emf generated at full load (E)= $I_a R_a + I_L R_{se} + V$

$$= 219.485 \times 0.01 + 217.39 \times 0.05 + 230$$

$$= 243.0643 \text{ V}$$

(ii) Full load copper loss (P_C) = $I_f^2 R_{sh} + I_L^2 R_e$

$$= 2.0945^2 \times 115 + 217.39^2 \times 0.05$$

$$= 2867.418 \text{ w}$$

$$= 2.867 \text{ kw}$$

(iii) BHP of driving engine = ?

Total input power of the machine (P_T)

$$= 243.06 \times 219.48 + 2867.418 + 200$$

$$= 58.214 \text{ kw}$$

Since,

746 W = 1BHP

$$1 \text{ w} = \frac{1}{746} \text{ BHP}$$

58.214 kw = 78.035 BHP

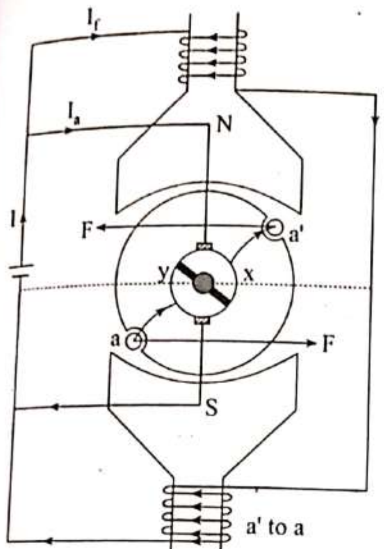
(iv) Full load efficiency ($\eta_{\text{full load}}$) $= \frac{P}{P_T} \times 100\ \% = \frac{50000}{58214} = 85.$[illegible]

□□□

CHAPTER 4 D.C. Motor

WORKING PRINCIPLE OF TORQUE EQUATION

Operating principle: A current carrying conductor placed in a magnetic field experiences a force in the direction given by Fleming's left hand rule.



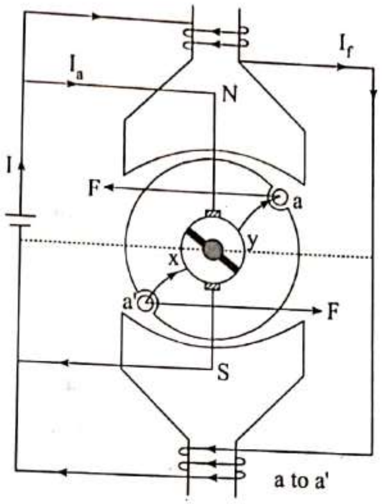


Fig (a) **Fig (b): After 180° rotation.**

In Fig (a), the conductor a & a' are supplied with some current and is inside the magnetic field B developed by field winding. Therefore the force is developed on conductors a & a' & the armature starts to rotate in anticlockwise direction.

If there were no carbon brush & commutator, we can't get the continuous rotation because the direction of force won't reverse on the conductor.

The carbon brush & commutator segment reverse the current direction, after half cycle & the force reverse an conductor a & a' as shown in the Fig (b).

∴ Armature rotates continuously.

Torque Equation (Equation of torque produced by DC Motor)

Let, N = speed of the armature in RPM

r = radius of armature coil.

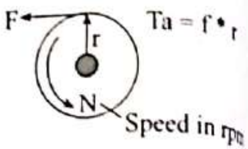
If 'T_a' is the torque produce by the armature,

$T_a = I * r (N - M)$

Then,

Work done by this force in one complete rotation

$= F*2\pi r = T_a*2\pi$



&

The time for N revolution = 60secs

$\therefore$ The time for N revolution $= \frac{60 \text{ sec.}}{N}$

$\therefore$ Power developed by the armature

= Rate of doing work

$= \frac{\text{Work done}}{\text{Time}} \Rightarrow P_a = \frac{T_a*2\pi}{60/N}$

$\therefore \Rightarrow \boxed{P_a = \frac{2\pi NT_a}{60}}$ watts ...(i)

Now, the rotating armature conductors are cutting the magnetic flu[x] so emf will be induced across the armature coils (according t[o] faraday's law). This emf is known as back emf given by

$$E_b = \frac{Z\phi N}{60} \times \frac{P}{A}$$

This flux approves the applied voltage and this opposition converts th[e] electrical power to the mechanical power. Then, the power develope[d] by armature also can be written as,

$P_a = E_b * I_a$

or, $\frac{2\pi NT_a}{E_0} = \frac{Z\phi N}{60} \times \frac{P}{A} \times I_a$

or, $\boxed{T_a = \frac{1}{2\pi} Z\phi I_a * \frac{P}{A}}$

$\therefore \boxed{T_a \propto \phi\, I_a}$

BACK EMF:

- Some emf is induced in the rotating armature conductor due to generator action in DC motor.
- According to Lenz's law, the direction of emf induced across the armature winding is opposite to the applied voltage, so this opposing, induced emf is known as Back emf

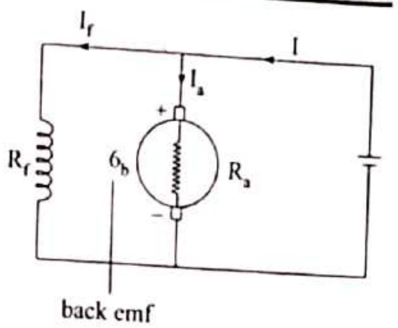


Fig. DC shunt motor

V pushes the current 'I_a' through the armature against the action of back emf 'E_b'.

$\therefore \quad I_a = \frac{V - E_b}{R_a}$ where, $E_b = \frac{Z\phi N}{60} \times \frac{P}{A}$

or, $I_a R_a = V - E_b$

Multiplying both sides of this equation by I_a

$I_a^2 R_a = Vf_0 = E_b I_a$

or, $Vf_a - I_a^2 R_0 = E_b I_a$

$\left\{ \begin{array}{l} \therefore \text{ Input powr to - copper loss = power developed} \\ \text{amature in armature by armature} \end{array} \right\}$

- Back emf plays an essential role in operation of a DC motor, without any back emf the motor would not have been able to convert the electrical input power to mechanical output. The back emf provides an inherent feedback mechanism in DC motors. Due to the action of back emf the motor is able to draw as much current as it it required to develop the required load torque (torque to drive the load)

Following are some important aspects of back emf

(1) Back emf protects the armature from short circuit during normal operating condition.

$\Rightarrow$ We know, the armature current $(I_a) = \frac{V - E_b}{Ra}$

If there is won no back emf i.e. $E_b = 0$

$\therefore \ I_a = V/Ra$

R_a (armature resistance) is very low in DC motor so from abo[ve] equation we can see that current I_a will be very large just like short circuit.

(2) Back emf acts as a feedback mechanism in a DC motor help[s] to produce the required amount of torque according to incre[ase] or decrease in mechanical load.

⇒ If the load on the shaft increases, the speed of the shaft tend[s] decrease.

Thus, $E_b\downarrow = \frac{Z\phi N\downarrow}{60} \cdot \frac{P}{A}$

so, according to above equation when speed decrease the b[ack] emf also decrease.

Similarly,

$\uparrow I_a = \frac{V - E_b\downarrow}{R_a}$

The decrease in emf causes the armature current 'I_a' to increase [as] seen from above equation.

Then,

$\uparrow T_a \propto \phi I_a \uparrow$

Hence, the increase in armature current (I_a) increases the tor[que] of the motor.

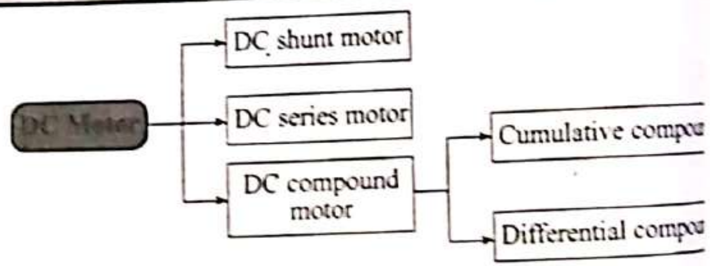
– In the same manner, if the load on the shaft decreases, the sp[eed] of the shaft increases.

$N\uparrow \longrightarrow E_B\uparrow \longrightarrow \& \ Ia\downarrow \longrightarrow Ta\uparrow$

Thus, increase in induced emf will cause the armature curre[nt] to decrease and hence the torque also decrease.

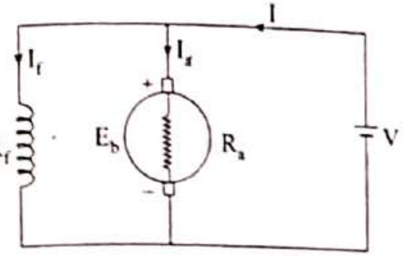
3. It acts as an opposing agent required for energy conversion f[rom] mechanical energy to electrical energy.

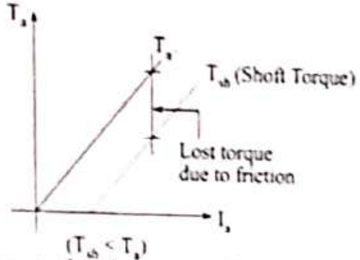
METHOD OF EXCITATION, TYPES OF DC MOTOR:



TORQUE-AMATURE CURRENT CHARACTERISTICS (ELECTRICAL CHARACTERISTICS)

T_a- I_a characteristic is a curve showing the variation of torque with change in armature current.





$\therefore\ T_a \propto I_f . I_a$

For DC shunt motor,

$I_f = \frac{V}{R_f}$ constant $\left(\begin{matrix}\text{for constant}\\ \text{source}\end{matrix}\right)$

So, we now write,

$T_a \propto I_a$

Thus, increase in armature current (I_a) the torque (T_a) increases linearly as shown in the figure.

However, it is important to know that the net shaft torque (T_{sh}) is always less than armature torque (T_a) due to friction loss. so that T_{sh} curve lies below T_a as shown figure.

However, it is important to know that the net shaft torque (T_{sh}) is always smaller than armature torque (T_a) due to friction loss. so, the T_{sh} curve lies below T_a in shown figure. Speed depends on torque (not vice-versa)

SPEED-TORQUE CHARACTERISTICS (MECHANICAL CHARACTERISTICS)

We know,

The back emf developed by the armature is given by,

$E_b = \frac{Z\phi N}{60} \times \frac{P}{A}$

$\Rightarrow\ N = \frac{E_b}{\phi} \times \frac{60 \times A}{Z \times P} \Rightarrow N \propto \frac{E_b}{\phi}$

But we know the flux is almost constant in a DC shunt motor.

So, we can write,

$N \propto E_b$

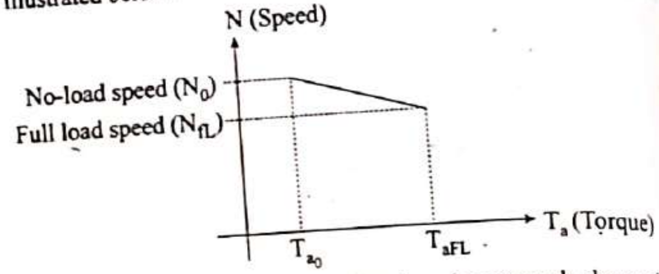
Also, $I_a = \frac{V - E_b}{R_a}$

- We can now explain the N-T_a chock of a DC shunt motor by using the above eq^n.
- When the speed of the DC motor (N) decreases the back emf 'E_b' also decrease ($\therefore$ N $\propto$ E_b).
- The decrease in 'E_b' will cause an increase in armature current 'I_a'

$I_a = \frac{V - E_b}{R_a}$

Again, $T \propto \phi I_a \Rightarrow \phi$ = constant

So, the torque increase with decrease in motor speed as illustrated below:



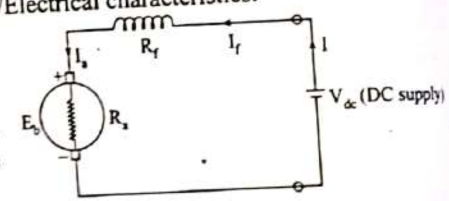
- It is clear from the above curve that there is not much change in the speed of a DC motor even if there is a large variation in the load torque (from $T_{a_0} \rightarrow T_{aFL}$ speed changes only from $N_0 \rightarrow N_{fL}$)

So, DC shunt motor usually find application where constant speeds are required even when the motor is carrying different amount of load.

DC SERIES MOTOR:

(a) T_a - I_a characteristics/Electrical characteristics:

In DC series motors, the current in the field winding & the armature winding are the same,



We know,

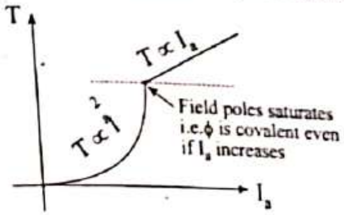
$T_a \propto \phi I_a$

But $\phi \propto I_f$ and $I_f = I_a$

So,

$T_a \alpha I_f I_a \Rightarrow \boxed{T_a \alpha I_a^2}$

If I_a is increased 'T_a' will increase in parabolic nature.



- After the saturation of field poles at points (S), the magnetic flux does not increase even if armature current 'I_a' increases.

So, $\boxed{T_a \alpha I_a}$

(b) N-T_a characteristics/mechanical characteristics:

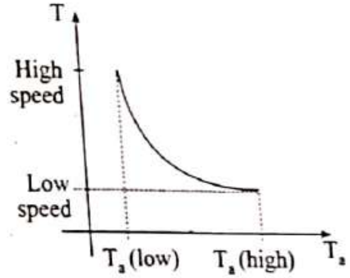
At heavy torque

(T_a (high))

→ The armature current (tends to be) very high ($\because$ $T_a \alpha I_a^2$)

→ Therefore,. the back emf will be less to allow high armature current)

($\because$ $\downarrow E_b = V - I_0(R_a+R_f)\downarrow$



→ At the same time the flux per pole (ϕ) will increase to very high value ($\because$ $\phi \propto (I_f = I_a)$). But the increase in flux very high compared to decrease is back emf.

So, the motor speed is low at high torque $\left\{\because N\downarrow \alpha \frac{E_b\downarrow}{\phi N}\right\}$

Similarly at low torque ($T_{a\,low}$)

→ The armature current is low, therefore the back emf will be high to allow low armature current. Then, the flux per pole will be very low.

Hence, the motor speed is high at low torque

$\left(\because N\uparrow \alpha \frac{E_b}{\phi\downarrow\downarrow}\right)$ Ta (light load) → $I_a \downarrow\downarrow$, for this $E_b\uparrow$ → $\phi\downarrow\downarrow$; $N\uparrow \propto \frac{E_b\uparrow}{\phi\downarrow\downarrow}$

→ From above characteristic curve we can see that the DC series motor have very high starting torque. So, they ease suitable for use in electric vehicles, trains and etc.

Q. Why DC series motors should not be started without any load? [20…

Ans: Because at no-load, the load-torque (T_a) becomes very low & at … point the speed of the DC series motor is very high which may … cause mechanical damage.

DC compound motors:

→ DC compound motor have two sets of field winding; the se… and shunt field windings.

→ If the series field winding produce the flux in the same direc… as produced by the shunt field winding, then such a moto… known as DC cumulative compound motor.

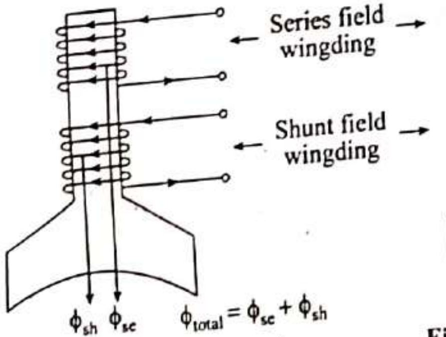


Fig. Commulative Compound

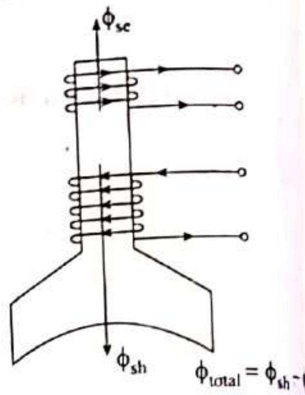
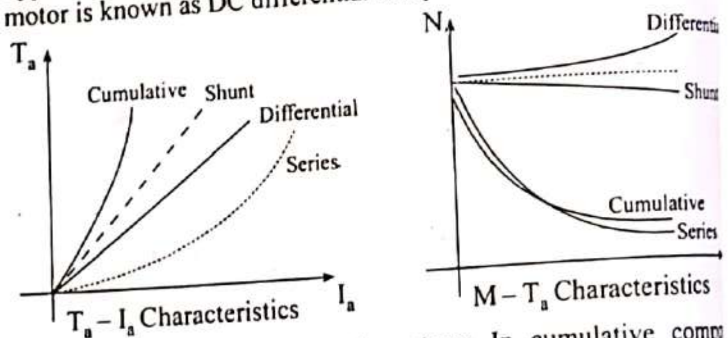


Fig. Differential Compound

On the other hand, if the series field winding produces the flux in … opposite direction as produced by the shunt field winding, then su… motor is known as DC differential compound motor.



→ **Commulative compound motors:** In cumulative comp… motor, the flux from both windings support each other, henc… flux per pole will be higher with increase in armature curre… T_a - I_a curve above that of DC shunt motor shows. Similarly, … particular value of torque, the flux per pole will be more com… to that of DC shunt motor $\left(N \alpha \frac{1}{\phi}\right)$. Hence, the N - … characteristics is more sloping, but less than DC series motor…

→ **Differential compound motors:** In this case, the flux opposes each other so, $\phi\downarrow$ with increase in $I_a \Rightarrow$ the T_a-I_a curve lies below that of DC shunt motor. Similarly, the ϕ at a particular value of Toruqe, will be less compare to DC shunt motor. Hence, N-T_a characteristics lies above that of DC shunt motor.

STARTING OF DC MOTORS: 3 POINTS AND 4 POINTS STARTERS.

Before understanding the operating mechanisms of various DC motor starts we have to understand why we need DC motor starters to begin with

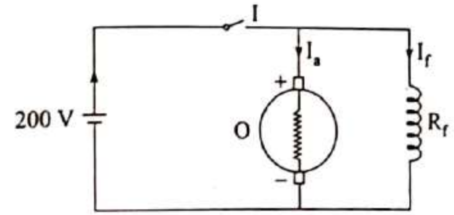
→ We have already seen that the value of the armature current is given by the equation

$$I_a = \frac{(V - E_b)}{R_a}$$

→ Initially, when the motor is at rest, there is no back emf (E_b) developed in the armature $\left(E_b = \frac{Z\phi N}{60} \times P/A \Rightarrow E_b = 0\right)$. The armature current '$I_a$' will be very large.

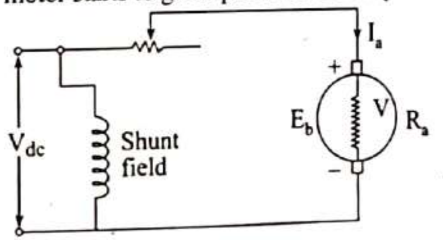
$$\left(I_a = \frac{V - \cancel{E_b}^{\,0}}{R_a} \Rightarrow \text{Thus } I_a \text{ become large value}\right)$$

(R_a ← Very small)

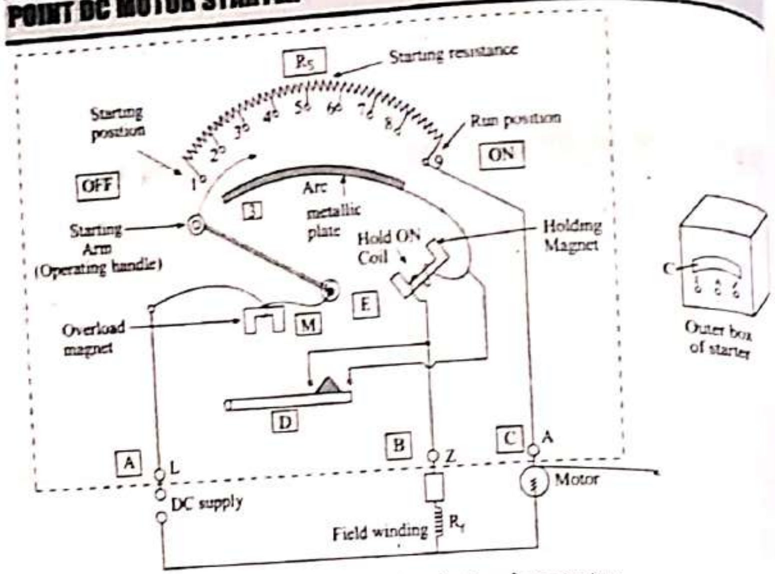


$$I_a = \frac{V - E_b}{R_a} = \frac{200 - 0}{0.1} = 2000 \text{ A.}$$

→ Such a high armature current can damage the commutators and the brushes. Hence, comes the need for a DC motor starter. In most basic DC motor starter a resistance is introduced in series with the armature winding for a short duration in the starting period only (5→10 sec) the starting resistance is then gradually cut-out as the motor starts to gain speed and develops the back emf.



POINT DC MOTOR STARTER



Point A, B & C are the terminals of a 3 points starter

→ To start the motor the DC supply is first turned ON. Then the starting arm is slowly moved to the right. When the starting arm makes contact with R_S. No. 1 the field winding is directly connected across the line through the arc connecting with starting arm and at the same time the full starting resistance is connected in series to the armature winding. The starting current drawn by the armature is thus reduced to,

$$I_a = \frac{V}{R_a + R_s} \leftarrow \text{the full starting resistance}$$

armature winding resistance.

→ As the motor starts to gain speed, the starting arm is further cut-out by gradually moving it to the right as indicated by the dotted arrow as shown in the figure. When the arm reaches the running position (ON-position) all of the starting resistance is cut-out (Thus normal current flows).

→ Note that the arm moves towards the right against a strong spring force which tends to pull the standing arm back to the off position.

→ There is a soft iron piece [S] attached to the arm which in the full ON position is attached & held by an electromagnet [E] energized by the field winding current flowing through 'If' as shown in the figure.

→ The DC motor starter also acts as a protective device for the DC motor:

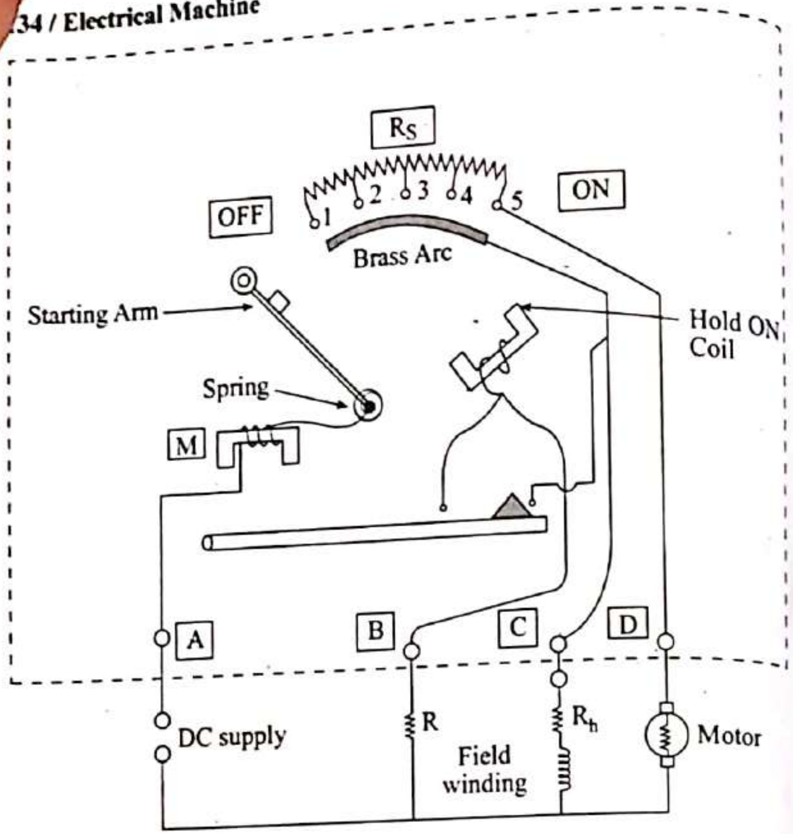
(1) During normal operation of the motor the HOLD-ON coil, holds on the starting arm in the ON position. But in case of failure or disconnecting of the field. But in case of failure of disconnecting of the field current the HOLD-ON coil get demagnetized thus releasing the starting arm to the OFF position, turning OFF the motor. This is important because the field current is cut-off when the motor is running, the motor may over speed $\left(\because N \alpha \frac{1}{I_f}\right)$

(2) In addition to above mentioned protection, the 3 points starter can also provide over current protection. If the DC motor draws a very large current from the DC supply the coil 'M' would get highly energized thus putting the iron piece 'D'. This causes the triangular section to short circuit the HOLD-ON coil through point 1&2, thus demagnetizive the HOLD-ON coil. This will cause the starting arm to get released to the OFF position. Thus providing over current protection.

In the above arrangement, a series resistance 'R_h' is placed with the field winding. By hanging R_h we can increase the speed of the DC motor by decreasing the field current $\left(N\alpha \frac{1}{I_f}\right)$. But this may cause I_f to become so low that the hold-ON coil 'E' may get demagnetized, this releasing the starting arm back to off position. To prevent this situation on 4 point starter should be used.

Four point starts

→ When compared to a 3 point starter, the most important change has been made in the configuration of the HOLD-ON coil. The HOLD-ON coil has been taken out of the field winding circuit & connected directly across the line through a protective resistance 'R'.



"Point A, B, C, D are the terminals of the D point starter".

→ Now, the current through the protective resistance 'R' & field winding is independent of each other. Even if we reduce, the field current to a low value, the starting arm won't be thrown back to off position as 'E' is still magnetized by unchanged current flowing through 'R' as was the problem in the 3-point starter. The rest of the operation is basically same as that 3-point starter.

SPEED CONTROL OF D.C. MOTORS

(1) Speed control of DC shunt motor:

Before understanding the speed control techniques of a DC motor. Let us understand which factors the speed of a DC motor depends on.

→ the following equations will give us a better understanding of the aspects of speed control in every DC motor.

→ The back emf developed by the armature is given by,

$$E_p = \frac{Z\phi N}{60} * \frac{P}{A}$$

or, $$N = \frac{E_b}{\phi} * \frac{60 \times A}{Z p}$$

$$\therefore \quad \boxed{N \alpha \frac{E_b}{\phi}}$$

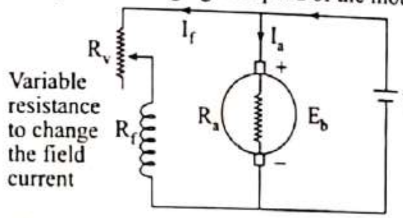
Hence the factors controlling the speed of DC motors are

$$\therefore \quad \boxed{N \alpha \frac{V - I_0 R_a}{\phi}}$$

(1) Applied voltage (V)
(2) Armature Resistance (R_a)
(3) Flux per pole (ϕ)

FLUX CONTROL METHOD (FIELD CONTROL METHOD):

We can see from the equation $N\alpha \frac{V - aR_a}{\phi}$ the speed of a DC shunt motor is inversely proportional to the flux per pole. In flux control method, a variable resistance (R_v) is connected in series with the field winding (R_f), so, that the field current (I_f) can be varied. Varying I_f means that flux per pole (ϕ) will also vary thus changing the speed of the motor.



The variable resistance (R_v) can thus reduce the field current below its rated value, thus decrees the flux. So, if we go increasing 'R_v', I_f decreases and hence the flux per pole decreases. This will cause the speed of the motor to increase above its rated speed. Hence this method is suitable for speed control above the sated sped value.

Case I: When R_v not connected $I_{f_1} = V/R_f$, $I_{a1} = I_1 - I_{f_1}$

$$E_{b1} = V - I_{a1} R_a$$

Case II: When 'R_V' is connected

$$I_{f_2} = \frac{V}{R_f + R_V}; \; E_{b_2} = V - I_{a_2} R_a$$

$$\boxed{N_2 = N_2 \times \frac{Eb_2}{Eb_1} \times \frac{I_{f1}}{I_{f2}}}$$

ARMATURE CONTROL METHOD

Here, the field winding 'R_f' is supplied by a constant DC voltage, so, I_f and flux per pole (ϕ) also remains constant.

If we assume, that the load is connected to the shaft is constant the current drawn from the armature 'I_a' should also remain constant.

According to the equation

$I_a \ \alpha \ \phi I_a$

Constant — Constant $\Rightarrow I_a$ should also remain constant.

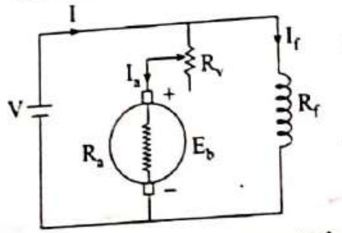


Fig. Arrangement for armature control method

If 'I_aR_a' voltage drop increases, the speed will decrease

$$(E_b \downarrow = V - (I_a(R_a)\uparrow)\uparrow \Rightarrow \ N\downarrow \alpha \frac{E_b\downarrow}{\phi})$$

We add a resistance 'R_v' in series with armature resistance 'R_a' as shown in the figure above the drop now increases to $(R_a + R_v)I_a$ and the speed further decreases.

Armature control method → Reduces the speed of the DC shunt motor below Rated speed.

If N_1 = Speed of the motor when $R_v = 0$

N_2 = Speed of the motor when R_v = full value,

Since, the flux per pole is constant & the load torque is also constant the armature current will also remain constant in both cases.

$\therefore \quad I_{a_1} = I_{a_2} \ [\because T_{a_1} = T_{a_2} \ \& \ \phi_1 = \phi_2]$

Then, back emf in each case is given by

$E_{b1} = V - I_{a1}R_a$

$E_{b2} = V - I_{a2}(R_a + R_v)$

We know,

$$\therefore \quad N \ \alpha \ E_b \Rightarrow \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} * \frac{\phi_2}{\phi_1}$$

(ϕ_2 → Constant, ϕ_1 → Constant)

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{V - I_{a_2}(R_a + R_v)}{V - R_{a_1}R_a}$$

SPEED CONTROL OF DC SERIES MOTORS:

(a) Field Diverter Method

- In this method, by hanging the value of the diverter resistance 'R_v' the current (I_f) flowing in the field winding can be reduced thus increasing the speed.
- When this variable resistance is connected some of the field current will get diverted and pass through R_V.

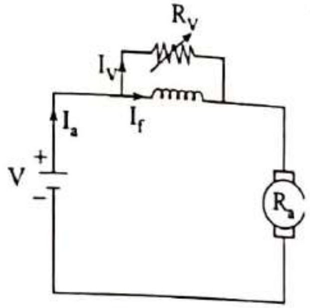
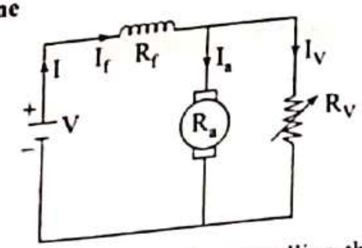


Fig. 3: Field diverter method

- Any desired amount of current can be passed through the field winding by adjusting the value of R_V.
- Hence, flux can be decreased and speed can be increased.

(b) Armature diverter method:

- In this method, a variable resistance is connected across the armature winding as shown in Fig. 4.
- When this variable resistance is connected, source of the armature current will get diverted and pass through R_V.
- For a constant load torque, if the armature current I_a is reduced due to diverter R_V, then the flux per pole must increase to produce constant torque ($\because T_a \propto \phi I_a$).
- This results are an increase in main line current taken from the supply and a fall in speed ($\because N \propto \frac{1}{\alpha}$)
- The variation in speed can be controlled by varying the value of diverter resistance 'R_V'.



- This method is only suitable for controlling the speed below the normal rated speed.

(c) **Tapped field control method:**

- In this method, the series field winding is provided with numbe[r] of tappings as shown in Fig 5.
- The number of series field turns in the circuit can be changed b[y] the tap changer.
- With full field winding, the motor runs at its minimum speed.
- The speed can be raised in steps by cutting out some of the serie[s] turns.

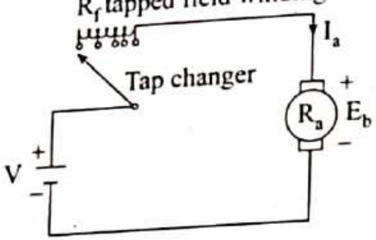


Fig. 5: Tapped field control method.

$E_b = V - I_aR_f - I_aR_a = V - I_a(R_f + R_a)$

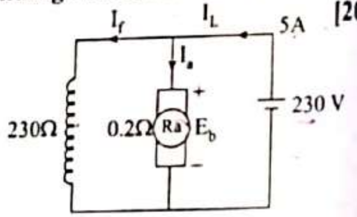
If $R_f \downarrow$, $E_b \uparrow$, $N \uparrow$

$$E_b = \frac{Z\phi N}{60} \times \frac{P}{A}$$

Tutorial

1. A 230 V dc shunt motor takes 5 A at no load and runs at 100[0] rpm. Calculate the speed when loaded and taking a current of 3[0] A. The armature and field winding resistance are 0.2 ohm an[d] 230 ohm respectively. [2071]

Solution:



Here, $I_f = \frac{230}{230} = 1A$

$\therefore \quad I_a = 5 - 1 = 4A$

So, $E_{b_1} = V - I_aR_a = 230 - 4 \times 0.1 = 229.2$ V

Now, when the motor takes 30 A,

$I_a = 30 - 1 = 29$ A

So, $E_{b_2} = 230 - 29 \times 0.2 = 224.2$V

Since, $E_b \propto N\phi$ and $\phi \propto I_f$ (Constant)

$\therefore \quad E_b \propto N$

Hence, $\frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1}$

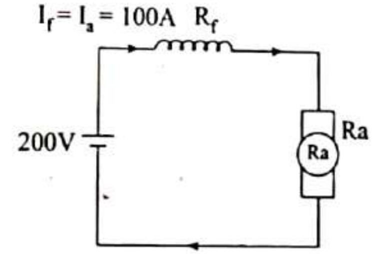
$\therefore \quad N_2 = \frac{24.2}{229.2} \times 1000 = 978.18$ rpm.

2. A 200 V series motor rakes a current of 100 A and runs at 1000 rpm. The total resistance of the motor is 0.1 ohm and the field is unsaturated. Calculate:

(a) Percentage change in torque and speed if the load is so changed that motor current is 50 A.

(b) Motor current and speed if the torque is halved. **[2073]**

Solution:



Here, $R_a + R_f = 0.1\Omega$

$N_1 = 1000$ rpm

When $I_f = I_a = 100A$,

$E_{b_1} = 200 - 100 \times 0.1 = 190V$

Now,

(a) When, $I_a = I_f = 50$ A

$E_{b_2} = 200 - 50 \times 0.1 = 195$ V

We know,

$T_a \propto \phi I_a$

or, $T_a \propto I_a^2 \; [\because \phi \propto I_a]$

So, $\frac{T_{a_2}}{T_{a_1}} = \left(\frac{I_{a_2}}{I_{a_1}}\right)^2 = \left(\frac{50}{100}\right)^2 = 0.25$

Hence, % change in torque $= \frac{T_{a_1} - T_{a_2}}{T_{b_1}} \times 100\%$

$= (1 - 0.25) \times 100\%$

$= 75\%$

Also,

$$N \propto \frac{E_b}{\phi} \Rightarrow N \propto \frac{E_b}{I_a}$$

$$\therefore \frac{N_2}{N_1} = \frac{E_{b_2}}{I_{a_2}} \cdot \frac{I_{a_1}}{E_{b_1}} = \frac{195 \times 100}{190 \times 50} = 2.052$$

$$\therefore \text{ \% change in speed} = \frac{N_2 - N_1}{N_1} \times 100\% = (2.052 - 1) \times 10\text{...}$$

$$= 105.2\%$$

(b) If torque is halved, let I_a be motor current and N be speed.

$$\because T \propto I_a^2$$

So, $$\left(\frac{I_{a_2}}{I_{a_1}}\right)^2 = \frac{1}{2}$$

$$\therefore I_a = \frac{1}{\sqrt{2}} \times 100 = 70.7\text{A}$$

Then, $E_b = 200 - 70.7 \times 0.1 = 192.93$ V

Also,

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

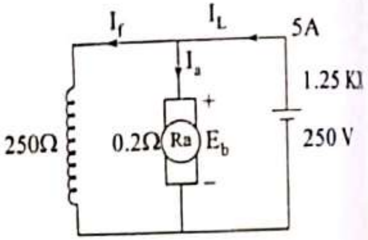
So, $$\frac{N}{N_1} = \frac{E_b}{I_a} \times \frac{I_{a_1}}{E_{b_1}}$$

or, $$N = 1000 \times \frac{192.93}{70.7} \times \frac{100}{190}$$

$$\therefore N = 1436.2 \text{ rpm}$$

3. A 1.25 kW, 250 V dc shunt motor on no load runs at 1000 rp... The armature and field circuit resistance are 0.2 ohm and 25... ohm respectively. Calculate the speed of motor when it is loade... and draw current of 50 A. Assume armature reaction weakens th... field by 3 %. **[207...**

Solution:



$N_1 = 1000$ rpm

Here, $I = \frac{1.25 \times 10^3}{250} = 5\text{A}$

$$I_f = \frac{250}{250} = 1\text{A}$$

$$\therefore I_a = 5 - 1 = 4\text{A}$$

$$\Rightarrow E_{b_1} = 250 - 4 \times 0.2 = 249.2 \text{ V}$$

When, I = 50 A,

$$I_a = 50 - 1 = 49 \text{ A}$$

$$\therefore E_{b_2} = 250 - 40 \times 0.2 = 240.2 \text{ V}$$

Armature reaction weakens the field by 3% so,

$$\frac{\phi_2}{\phi_1} = \frac{97}{100}$$

Now,

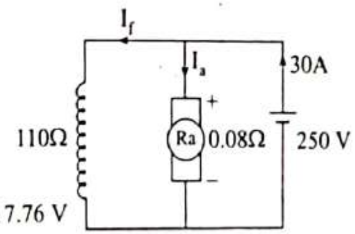
$$E \propto N\phi$$

So, $$\frac{E_{b_2}}{E_{b_1}} = \frac{N_2 \phi_2}{N_1 \phi_1}$$

$$\therefore N_2 = \frac{249.2}{249.2} \times 1000 \times \frac{100}{97} = 993.69 \text{ rpm.}$$

4. A 220 V dc shunt motor draws a current of 30A and drives a load at 1500 rpm. Given that armature-winding resistance is 0.08 ohm and field resistance is 110 ohm. If a resistance of 0.05 ohm is connected in series with the armature circuit keeping the load torque constant, calculate the speed of the motor. **[2074]**

Solution:



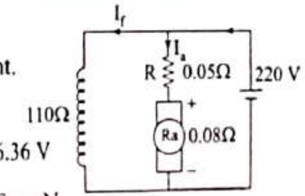
$N_1 = 1500$ rpm

$$I_f = \frac{220}{110} = 2\text{A}$$

$$\therefore I_a = 30 - 2 = 28 \text{ A}$$

$$E_{b_1} = 220 - 28 \times 0.08 = 217.76 \text{ V}$$

Case II:



For constant T_a & ϕ, I_a is also constant.

So, $I_a = 28$ A

$$\therefore E_{b_2} = 220 - 28 \times (0.05 + 0.08) = 216.36 \text{ V}$$

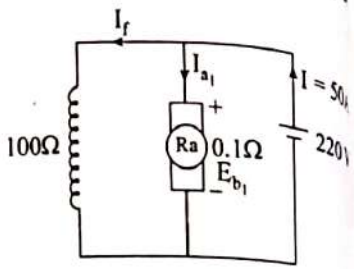
Since, $E_b \propto N\phi$ and ϕ is constant $\Rightarrow E_b \propto N$

$$\therefore \frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}}$$

$$\Rightarrow N_2 = 1500 \times \frac{216.36}{217.76} = 1490.36 \text{ rpm}$$

5. A 220V dc shunt motor drives a centrifugal pump where torque is proportional to the square of the speed. The motor draws a current of 50A when running at 1000 rpm. What value of resistance must be inserted in the armature circuit in order to reduce the speed to 800 rpm. Given that armature resistance is 0.1 ohm and field resistance is100 ohm. [207..]

Solution:



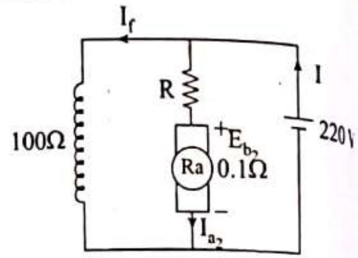
$N_1 = 1000$ rpm, $N_2 = 800$ rpm

$I_f = \frac{220}{100} = 2.2A$

Case I:

$\therefore \quad I_{a_1} = 50 - 2.2 = 47.8A$

$E_{b_1} = 220 - 47.8 \times 0.1 = 215.22$ V



We have, $T_a \propto N^2$

Also, $T_a \propto \phi I_a \Rightarrow T \propto I_a$

$[\because \phi \propto I_f$ is constant]

$\therefore \quad I_a \propto N^2$

or, $\frac{I_{a_2}}{I_{a_1}} = \left(\frac{N_2}{N_1}\right)^2$

or, $I_{a_2} = 47.8 \times 0.8^2 = 30.592$ **Ans.**

Case II:

$E_{b_2} = 220 - I_{a_2}(R + Ra)$

or, $E_{b_2} = 220 - 30.592(R + 0.1)$ ...(i)

Also, $E_{b_2} = \frac{N_2}{N_1} \times E_{b_1} = 0.8 \times 215.22 = 172.176$ V

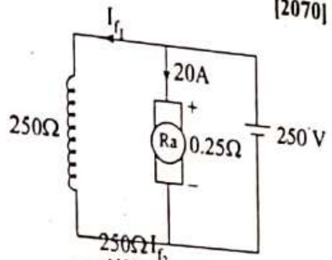
Hence, from (i),

$R = \frac{220 - 172.176}{30.592} - 0.1$

$\therefore \quad R = 1.46\ \Omega$ **Ans.**

6. A 250V dc shunt motor draws an armature current of 20 A and runs with a speed of 1500 rpm. If a resistance of 250 ohm is inserted in series with field winding keeping the load torque constant, find the new speed and armature current. Given that armature winding resistance is 0.25 ohm and field winding resistance is 250 ohm. [2070]

Solution:

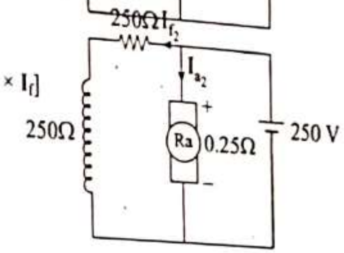


$N_1 = 1500$ rpm,

$I_{f_1} = \frac{250}{250} = 1$ A

$E_{b_1} = 250 - 20 \times 0.25 = 245$ V

Case II:



$I_{f_2} = \frac{250}{250 + 250} = 0.5$ A

$\therefore \quad T_a \times \phi I_a \Rightarrow I_a \times I_f I_a\ [\because \phi \times I_f]$

Here, T_a is constant. So,

$I_{f_1} I_{a_1} = I_{f_2} I_{a_2}$

or, $I_{a_2} = \frac{1 \times 20}{0.5} = 40$ A

Hence, $E_{b_2} = 250 - 40 \times 0.25 = 240$ V

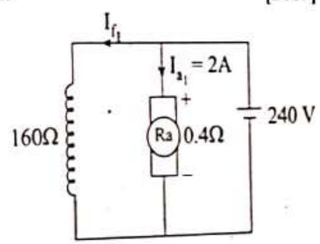
Now, $E_b \times N\phi \Rightarrow E_b \times NI_f$

or, $\frac{E_{b_2}}{E_{b_1}} = \frac{N_2 I_{f_2}}{N_1 I_{f_1}}$

or, $N_2 = \frac{240}{245} \times 1500 \times \frac{1}{0.5} = 2938.77$ rpm.

7. A 240 V dc shunt motor having armature and field resistance equal to 0.4 ohm and 160 ohm respectively runs on no load at 800 rpm, the armature current being 2 A. Calculate the resistance required in series with shunt winding so that the motor may run at 950 rpm when taking the current of 30 A. Assume that the flux is proportional to field current. [2069]

Solution:



$N_1 = 800$ rpm, $N_2 = 950$ rpm

Case I:

$I_{f_1} = \frac{240}{160} = 1.5$ A

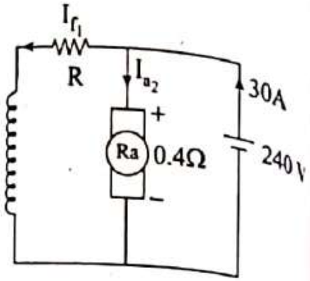
$E_{b_1} = 240 - 2 \times 0.4 = 239.2$ V

Case II:

$$I_{f_2} = \frac{240}{160 + R}$$

$E_b \times N\phi \Rightarrow E \times NI_f$

So, $\frac{E_{b_2}}{E_{b_1}} = \frac{N_2 I_{f_2}}{N_1 I_{f_1}}$



or, $\frac{E_{b_2}}{239.2} = \frac{950}{800} \times \frac{1}{1.5} \times \frac{240}{160 + R}$

∴ $E_{b_2} = \frac{4548}{160 + R}$

Also, $E_{b_2} = 240 - I_{a_2} \times 0.4$

or, $\frac{45448}{160 + R} = 240 - \left[30 - \frac{240}{160 + R}\right] \times 0.4$

or, $\frac{45448}{160 + R} = 240 - 12 + \frac{96}{160 + R}$

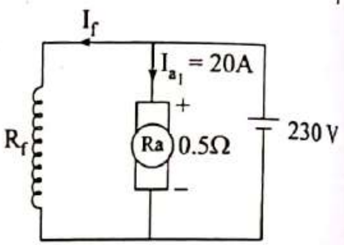
or, $45448 = 228\,(160 + R) + 96$

∴ $R = 38.91\Omega$

8. **A 230 V dc shunt motor takes an armature current of 20 A on a particular load. The armature circuit resistance is 0.5 ohm. Find the resistance required in series with the armature to reduce the speed by 50 % if (a) the load torque is constant and (b) the load torque is proportional to the square of the speed.** [2068]

Solution:

Here, $E_{b_1} = 230 - 20 \times 0.5 = 220$ V

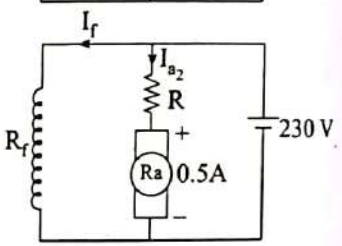


$\frac{N_2}{N_1} = 0.5$

∵ $E_b \propto N\phi \Rightarrow E_b \propto \phi N$

$[\phi = \text{constant}]$

So, $\frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1} \Rightarrow E_{b_2} = 110$ V



(a) If T_a = Constant

$T_{a_2} = I_{a_1} = 20A$

∴ $E_{b_2} = 230 - 20\,(R + 0.5)$

or, $110 = 230 - 20(R + 0.5)$

∴ $R = 5.5A$

(b) If $T_a \propto N^2 \Rightarrow \phi I_a \propto N^2 \Rightarrow I_a \propto N^2$

or, $I_{a_2} = I_{a_1} \times \left(\frac{N_2}{N_1}\right)^2 = 20 \times 0.5^2 = 5A$

Hence, $E_{b_2} = 230 - 5 \times (R + 0.5)$

or, $110 = 230 - 5(R + 0.5)$

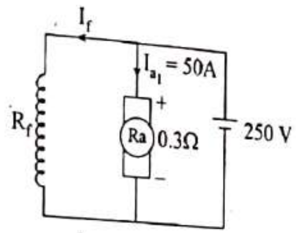
∴ $R = 23.5\Omega$ **Ans.**

9. **A 250 V dc shunt motor has speed of 1000 rpm at full load. Calculate the resistance to be connected in series with the armature to reduce the speed with the full load torque to 800 rpm, the full load armature current being 50 A. If the load torque is then halved, at what speed will the motor run? Take armature-winding resistance to be 0.3 ohm. The armature reaction effect is to be neglected.** [2067]

Solution:

$N_1 = 1000$ rpm, $N_2 = 800$ rpm

$E_{b_1} = 250 - 50 \times 0.3 = 235$ V

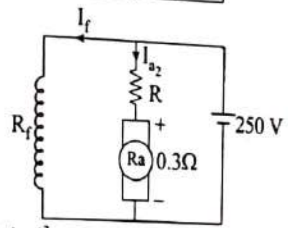


$\frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1}$

⇒ $E_{b_2} = 235 \times 0.8 = 188$ V

If torque remains at full load,

$I_{a_2} = I_{a_1} = 50$ A



So, $E_{b_2} = 250 - 50(R + 0.3)$

∴ $R = 0.94\Omega$

Now, if torque is halved,

$T_a \propto \phi I_a \Rightarrow T_a \propto I_a$ [∵ ϕ = Constant]

So, $\frac{I_{a_2}}{I_{a_1}} = \frac{1}{2} \Rightarrow I_{a_2} = 25$ A

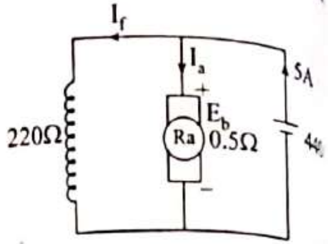
So, $E_{b_2} = 250 - 25(0.94 + 0.3) = 219$ V

Also,

$$N_2 = N_1 \times \frac{E_{b_2}}{E_{b_1}} = 1000 \times \frac{219}{235}$$

∴ $N_2 = 931.91$ rpm.

10. **A 440 V dc motor taking 5A at no load has armature and field winding resistances are 0.5 ohm and 200 ohm respectively. Calculate the efficiency when the motor takes 50 A on full load. Also calculate the percentage change in speed from no load to full load.**



Solution:

On no-load,

$$I_f = \frac{440}{220} = 2A$$

$\therefore \quad I_a = 5 - = 3A$

So, Armature Cu loss $= I_a^2 R_a = 9 \times 0.5 = 4.5$ W

Input power $= 440 \times 5 = 2200$ W

Hence, constant loss, $W_C = 2200 - 4.5 = 2195.5$ W

$E_{b_1} = 440 - 3 \times 0.5 = 438.5$ V

On full-load,

$I_a = 50 - 2 = 48A$

$E_{b_2} = 440 - 48 \times 0.5 = 416$ V

Cu loss in ormature $= 48^2 \times 0.5 = 1.152$ W

Hence, total loss $= 1152 + W_C = 1152 + 2195.5 = 3347.5$

Input power on full load $= 440 \times 50 = 22{,}000$

Output power = Input – loss $= 22{,}000 - 3347.5 = 18652.5$W

Hence,

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100\% = \frac{18652.5}{22000} \times 100\%$$

$\therefore \quad \eta = 84.7\%$

Also, for constant ϕ,

$$\frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}} = \frac{416}{438.5}$$

$$\text{Hence, change in speed} = \frac{N_1 - N_2}{N_1} \times 100\% = \left(1 - \frac{N_2}{N_1}\right) \times 100\%$$

$$= \left(1 - \frac{416}{38.5}\right) \times 100\%$$

$$= 5.13\%$$

11. **A dc series motor with series field, and armature resistance of 0.06Ω and armature resistance of 0.04Ω respectively connected across 220v mains. The armature takes 40A and its speed is 900 rpm. Determine its sped when the armature takes 75A and excitation is increased by only 75% due to saturation.**

Solution:

Given

Resistance of Field winding $(R_f) = 0.05\Omega$

Resistance of Armature winding $(R_a) = 0.05\Omega$

Supply voltage $(V_1) = 220$v

$N_1 = 900$ rpm

$I_{a_1} = 40A = I_{f_1}$

$\phi_1 = \phi_2$

$N_2 = ?$ for $I_{a_1} = 75A = I_{f_2}, \phi_2 = 1.15\phi$

$Eb_1 = 4 - I_{a_1}(R_a + R_f) = 220 - 40 \times 0.1 = 216$V

$Eb_2 = v_2 - Ia_2(R_f + R_a) = 220 - 75 \times 0.1 = 212.5$V

Now,

$$\frac{Eb_2}{Eb_1} = \frac{N_2}{N_1} \times \frac{\phi_2}{\phi_1}$$

$$\text{or,} \quad \frac{212.5}{216} = \frac{N_2}{900} \times \frac{1.15}{1}$$

$N_2 = 769.9$ rpm

12. **A dc shunt motor is supplied by a source of 200V. It draws a current of 20A and runs of speed of 1500rpm. The armature and field winding resistance are 0.08Ω and 110Ω respectively. A resistance of 0.02Ω is added in series with armature and load torque is increased by 30%, Calculate new speed. [2073 Magh]**

Solution:

$V = 200$ V

$I_a = 20A$

$N_1 = 1500\eta$'m

$R_a = 0.08\Omega$

$R_f = 110\Omega$

$Ra' = 0.08 + 0.02 = 0.10\Omega$

$T' = 1.37$ (30% increment in torque)

$$If_1 = \frac{V}{R_f} = \frac{200}{110} = 1.1818 \text{ A}$$

$Eb_1 = V - Ia_1R_a = 200 \;\; 20 \times 0.08 = 198.4$ V

Now,

$Eb_1 = V - Ia_2Ra, If_2 = \frac{V}{R_f} = 1.1818$ A (Same)

$Eb_2 = 200 - Ia_2 \times 0.1$ ...(i)

Since we have,

$$\frac{T_2}{T_1} = \frac{If_2}{If_1} \times \frac{Ia_2}{Ia_1}$$

or, $\frac{1.3T}{T} = 1 \times \frac{Ia_2}{Ia_1} \Rightarrow Ia_2 = 26A$

From (i) $Eb_2 = 197.4$ V

Also,

$$\frac{Eb_2}{Eb_1} = \frac{N_2}{N_1} \times \frac{If_2}{If_1}$$

or, $\frac{197.4}{198.4} = \frac{N_2}{1500} \times 1$

$\therefore$ $N_2 = 1492.439$ rpm

13. A 250 V dc shunt motor draws an armature current of 20 A and runs with speed at 1500 rpm. If a resistance of 250 Ω is inserted in series with field winding keeping the wad torque constant. Find out new speed and armature current where Ra = 0.05 Ω and Rf = 250 Ω. [2070]

Solution:

$V = 250$ V

$I_{a1} = 20$ A

$N_1 = 1500$ rpm

$R_a = 0.05\ \Omega$

$R_f = 250\ \Omega$

Now,

$$I_{f_1} = \frac{V}{R_f} = \frac{250}{250} = 1A$$

$$E_{b_1} = V - I_{a_1} R_a = 250 - 20 \times 0.05 = 249 \text{ V}$$

In the next case,

$\because$ Here we have inserted a resistance of 250 Ω resistance

Here, $R_T = R_f + 250 = 250 + 250 = 500\ \Omega$

Now, $I_{f_2} = \frac{V}{R_T} = \frac{250}{500} = 0.5$ A

Since we have,

$$\frac{T_2}{T_1} = \frac{I_{f_2}}{I_{f_1}} \times \frac{I_{a_2}}{I_{a_1}}$$

As we are given the load torque constant then $T_1 = T_2$

Now,

$$1 = \frac{I_{f_2}}{I_{f_1}} \times \frac{I_{a_2}}{I_{a_1}}$$

or, $I_{a_2} = \frac{I_{f_1} \times I_{a_1}}{I_{f_2}} = \frac{1 \times 20}{0.5} = 40$ A

$\therefore$ New armature current $(Ia_2) = 40A$

Now,

$$I_{b_2} = V - I_{a_2} \times R = 250 - 40 \times 0.05 = 248 \text{ V}$$

Also,

$$\frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1} \times \frac{I_{f_2}}{I_{f_1}}$$

$$\frac{248}{249} = \frac{N_2}{1500} \times \frac{0.5}{1}$$

$$N_2 = \frac{248 \times 1500}{249 \times 0.5} = 2987.95 \text{ rpm}$$

14. A 440 V dc shunt motor drains a current of 30 A and runs at speed of 1500 rpm. Given that the armature winding resistance is 0.05Ω and field winding resistance of 220 Ω. Calculate the values of resistance to be connected in series with the armature to operate the motor at a speed of 1300 rpm at constant load torque. [2071]

Solution:

$V = 440$ V

$I = 30$ A

$N_1 = 1500$ rpm

$R_a = 0.05\ \Omega$

$R_f = 220\ \Omega$

Now, let, 'R' be the resistance to be connected in series with armature to operate the motor at a speed.

$N_2 = 1300$ rpm

$T_1 = T_2$ (for constant load torque)

Here,

$$I_{f_1} = \frac{V}{R_f} = \frac{440}{220} = 2 \text{ A} = I_{f_2} \text{ (constant)}$$

$$I_{a_1} = I - I_{f_1} = 30 - 2 = 28 \text{ rpm}$$

Since we have,

For constant load torque,

$\therefore$ $I_{a_1} = I_{a_2} = 28$ A

Now,

$E_{b_1} = V - I_{a_1}(R_a) = 440 - 28 \times 0.05 = 438.6\ V$

$E_{b_2} = V - I_{a_2}(R_a + R) = 440 - 28\,(0.05 + R) = 438.6 - 28\,R$

$\therefore \quad \frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}} = \frac{438.6}{438.6 - 28\,R} = \frac{1300}{1500}$

15. **A 200 V dc series motor runs at 1000 rpm taking 20 A. Combined resistance of armature and field is 0.4 Ω. A resistance is connected in series with the current and the speed was found to be reduced to 800 rpm. Assuming that torque varies at square of the speed. Find the value of resistance inserted.** **[2074]**

Solution:

$V = 200\ V$

$N_1 = 1000\ rpm$

$I_{a_1} = I_{f_1} = 20A$

$(R_a + R_f) = 0.4\ \Omega$

Let 'R' be the resistance to be connected in series.

$N_2 = 800\ rpm$

$T \alpha N^2$

$R = ?$

$\text{Back emf } (E_b) = \frac{Z\phi N}{60} \times \frac{P}{A}$

Before insertion of the 'R'

$E_{b_1} = V - I_{a_1}(R_a + R_f) = 200 - 20 \times 0.4 = 192\ V$

Since,

$T_1 = KN_1^2$

$T_2 = KN_2^2$ ....(i)

Since, $T \propto \phi\, Ia$

Here, $\phi \propto I_f : I_f = I_a$

$\therefore \quad T \propto I_a^2$

$T_1 = KIa_1^2$

$T_2 = KIa_2^2$

$\frac{T_2}{T_1} = \frac{Ia_2^2}{Ta_1}$ ....(ii)

From (i) and (ii)

$\frac{Ia_2^2}{Ia_1^2} = \frac{N_2^2}{N_1^2}$

$Ia_2^2 = \frac{N_2^2}{N_1^2} \times Ia_1^2 = \frac{(800)^2}{(1000)^2} \times (200)^2$

$\therefore \quad Ia_2 = 16\ A = I_{f_2}$

Now,

$E_{b_2} = V - Ia_2\,(Ra + Rf + R) = 200 - 16\,(0.4 + R) = 193.6 - 16\,R$

$\frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1} \times \frac{I_{f_2}}{I_{f_1}}$

$\frac{193.6 - 16\,R}{192} = \frac{800}{1000} \times \frac{16}{20}$

$\therefore \quad R = 4.42\ \Omega$

16. **A 250 V d.c. shut motor having an armature resistance of 0.25Ω carries an armature current of 50 A and runs at 750 r.p.m. if the flux is reduced by 10 %. Find the speed. Assume that the load torque remains the same.** **[2072]**

Solution:

Initial conditions

$V = 250\ V,\ i_{a_1} = 50\ A,\ R_a = 0.25\ \Omega,\ N_1 = 750\ r.p.m$

$E_1 = V - I_{a_1} R_a = 250 - 50 \times 0.25 = 237.5V$

Condition after reducing the flux

$\Phi_2 = 0.9\,\Phi_1$

Load torque $\tau \propto \Phi I_a$

Since the load torque remains the same

$\tau_2 = \tau_1$

$\Phi_2 I_{a_2} = \Phi_1 I_{a_1}$

$I_{a2} = \frac{\Phi_1}{\Phi_2}\ Ia_1 = \frac{50}{0.9} = 55.56\ A$

$E_2 = v - Ia_2 R_a = 250 - 55.6 \times 0.25 = 236.1\ V$

$\frac{N_2}{N_1} = \frac{E_2\Phi_1}{E_1\Phi_2}$

$N_2 = \frac{E_2\Phi_1}{E_1\Phi_1}\ N_1 = \frac{236.1 \times 750}{237.5 \times 0.9} = 828.5\ r.p.m.$

17. **A 120 V d.c. shunt motor having an armature circuit resistance of 0.2 Ω, and fields circuit resistance of 60 Ω, draws a line of 40 A at full load. The brush voltage drop is 3 V and rated full-load speed is 1800 r.p.m. Calculate : (a) the speed at half load; (b) the speed at 125 percent full load.** **[2073]**

Solution:

$V = 120\ V,\ R_a = 0.2\ \Omega,\ R_{sh} = 60\ \Omega$

$I_{sh} = \frac{V}{R_{sh}} = \frac{120}{60} = 2\ A,\ I_L = 40\ A$

$I_{a_1} = I_L - I_{sh} = 40 - 2 = 38$ A

$E_1 = V - I_aR_a - 40 - 2 = 38\text{ A} = 120 - 38 \times 0.2 - 3 = 109.4$ V

At rated speed of 1800 r.p.m.,

$E_1 = 109.4$ V and $I_{a_1} = 38$ A (full load)

(a) At half load

Line current $I_{L_2} = 40 \times 1.25 = 50$ A

Armature current $I_{a_1} = I_{L_1} - R_a$ - brush drop

$= 120 - 48 \times 0.2 - 0.3 = 107.4$ V

If N_3 is the speed at 125 percent load

$$N_3 = \frac{E_3}{E_1} \times N_1 = \frac{107.4}{109.4} \times 1800 = 1767 \text{ rpm}$$

18. A shunt wound motor has an armature resistance of 0.1 Ω. It is connected across 220 V supply. The armature current taken by the motor is 20 A and the motor runs at 8:00 r.p.m. Calculate the additional resistance to be inserted in series with the armature to reduce the speed to 520 r..m. Assume that there is no change in armature current. [2070]

Solution:

$$E_1 = V - I_{a_1}R_{a_1} = 220 - 20 = 218 \text{ V}$$

$$E_2 = \frac{N_2\Phi_2}{N_1\Phi_1} E_1$$

Since $I_{sh} = \frac{V}{R_{sh}}$, the shunt field current I_{sh} remains constant, and therefore

$$\Phi_2 = \Phi_1$$

$$E_2 = \frac{N_2}{N_1} E_1 = \frac{520}{800} \times 218 = 141.7 \text{ V}$$

If R_A is the additional resistance inserted in the armature circuit

$$E_2 = V - I_{a_2}(R_{a_1} + R_A)$$

$$141.7 = 220 - 20(0.1 + R_A)$$

$$R_A = 3.815\ \Omega$$

19. A 240 V dc series motor takes 40 A when giving its rated output at 1500 r.p.m. Its resistance is 0.3 Ω. Calculate the value of resistance that must be added obtain the rated torque (a) at starting. (b) at 1000 r.p.m. [2074]

Solution:

Rated voltage V = 240 V

Rated current $I = I_a = 40$ A

$N_1 = 1500$ r.p.m., $R_a = 0.3\ \Omega$

$E = V - I_aR_a = 240 - 40 \times 0.3 = 228$ V

(a) At starting, back emf is zero. In order to obtain rated torque at rate current, an additional resistance R_1 is connected in series with the armature.

$$E_1 = V - I_a(R_a + R_1)$$

$$0 = 240 - 40(0.3 + R_1)$$

$$R_1 = \frac{240 - 12}{40} = 5.7\ \Omega$$

(b) Let R_2 be the resistance connected in series with the armature to obtain the rated torque at a speed of 1000 rpm.

$$E_2 = V - I_a(R_a + R_2) = 240 - 40(0.3 + R_2) = 228 - 40R_2$$

$$\frac{N_2\Phi_2}{N\Phi} = \frac{E_2}{E} \Rightarrow \frac{N_2I_{a_2}}{NI_a} = \frac{E_2}{E}$$

Since, $I_{a_2} = I_a$

$$\frac{N_2}{N} = \frac{E_2}{E}$$

$$\frac{1000}{1500} = \frac{228 - 40R_2}{228},\ R_2 = 1.9\ \Omega$$

□□□

CHAPTER 5

Three Phase Induction Machine

There are two types of 3-phase induction motor based on the type of rotor used:

Squirrel cage induction motor.

Slip ring induction motor.

Slip-ring induction motor over squirrel cage Induction motor

Advantages:

- It is possible to speed control by regulating rotor resistance.
- High starting torque of 200 to 250% of full load voltage.
- Low starting current of the order of 250 to 300% of the full load current.
- Hence slip ring induction motors are used where one or more of the above requirements are to be met.

1. CONSTRUCTIONAL DETAILS

Conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In A.C. motors, rotor receives electric power by induction in exactly the same way as the secondary of a two-winding transformer receives its power from the primary. Hence such motors are known as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate.

An induction motor essentially consists of two main parts:

STATOR AND ROTOR

Stator:

- The stator of an induction motor is in principle, the same as that of a synchronous motor (or) generator.
- It is made up of a number of stampings, which are slotted to receive the windings.
- The stator carries a 3-phase winding and is fed from a 3-phase supply.
- It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed.
- The number of poles are higher, lesser the speed and vice-versa.

- The stator winding, when supplied with a 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves at synchronous speed ($N_s = 120 \times f / p$).
- This revolving magnetic flux induces emf in rotor by mutual induction.

Rotor:

(i) **Squirrel cage Rotor:**

Motors employing this type of rotor are known as squirrel cage induction motor.

(ii) **Phase wound (or) slip-ring Rotor:**

Motors employing this type of rotor are widely known as "phase-wound" motors or wound motor or "slip-ring" motors.

SQUIRREL CAGE ROTOR:

Almost 90 percentage of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible.

The Rotor consists of cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consists of heavy bars of copper, aluminium or alloys.

- One bar is placed in each slot; rather the bars are inserted from the end when semi-enclosed slots are used.
- The rotor bars are brazed or electrically welded or bolted to two heavy and stout short circuiting end-rings, thus giving us, what is called a squirrel cage construction.
- The Rotor bars are permanently short-circuited on themselves; hence it is not possible to add any external Resistance in series with the Rotor circuit for starting purposes.
- The rotor slots are not quite parallel to the shaft but are purposely given a slight skew. This is useful in two ways.
- It helps to make the motor run quietly by reducing the magnetic hum and
- It helps in reducing the locking tendency of the rotor. i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

PHASE-WOUND ROTOR:

- This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils are used in alternators.

- The Rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even when the stator is wound for two-phase.
- The three phases are shorted internally.
- The other three winding terminals are slip-rings mounted on the shaft with brushes resting on them.
- These three brushes are further externally connected to a 3-phase star connected Rheostat.
- This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor.
- When running under normal conditions, slip-rings are automatically short circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together.

Frame:

Made of close-grained alloy cast iron.

Stator and Rotor core:

Built from high quality low loss silicon steel laminations and flash enameled on both sides.

Stator and Rotor windings:

- Have moisture proof tropical insulation and embodying mica and high quality varnishes.
- Are carefully spaced for most effective air circulation and are rigidly braced to withstand centrifugal forces and any short circuit stresses.

Air gap:

The stator rabbets and bore are machined carefully to ensure uniformity of air gap.

Shaft and Bearings:

- Ball and roller bearings are used to suit heavy duty, trouble free running and for enhanced service life.

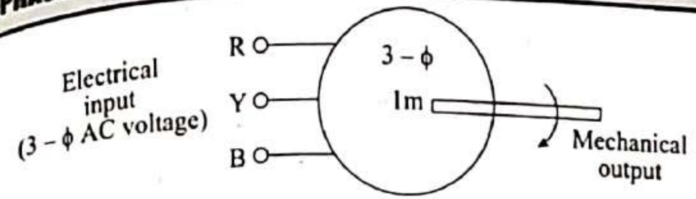
Fans:

- Light aluminium fans are used for adequate circulation of cooling air and are securely keyed onto the Rotor shaft.

Slip-Rings and Slip-Ring Enclosures:

- Slip rings are made of high quality phosphor bronze and are of molded construction.

THREE PHASE INDUCTION MOTOR



Conclusion:

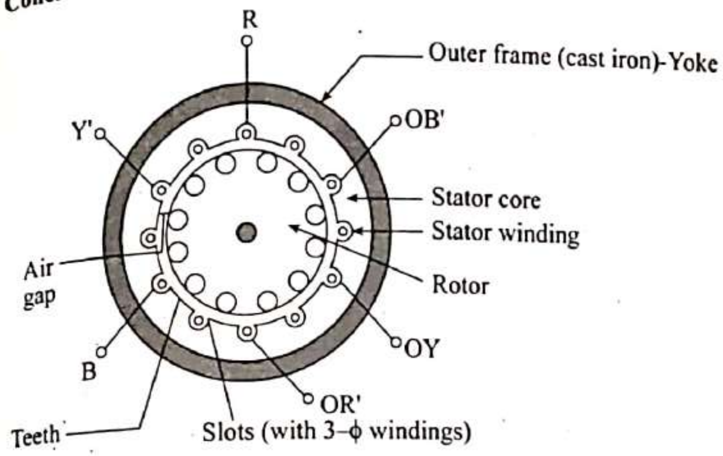


Fig.: 3-phase Induction Motor

Stator:- If is the static (non-moving) part of the IM.

– It has 3-ϕ winding placed in the slots.

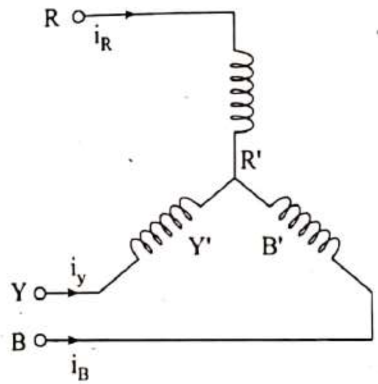


Fig.: Equivalent ckt of stator

Rotor

→ It is the actual rotating part of the IM

→ It is of 2 types:

(i) Squirrel cage rotor

(ii) phase wound rotor.

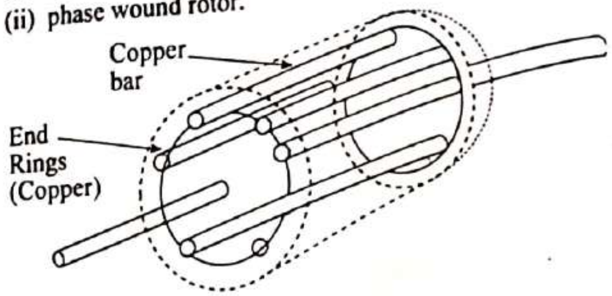


Fig. Squirrel cage rotor

Phase wound rotor:

- Such a rotor is wound with an isolated winding similar to stator (bu less number of slots & fewer number of turns/phase of a heavie conductors).

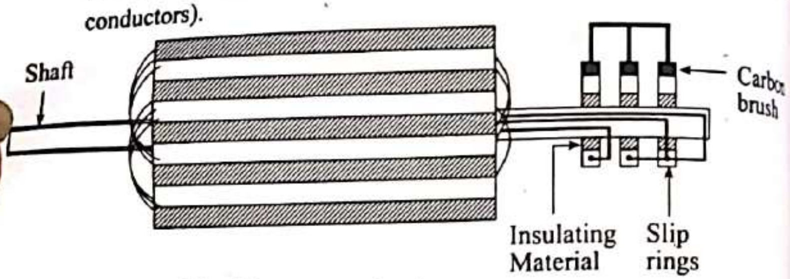
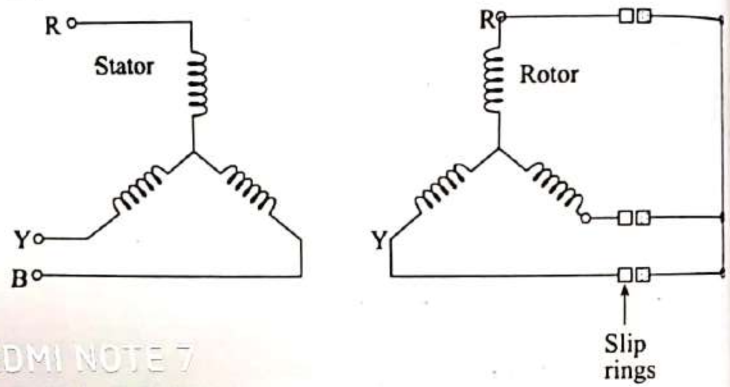


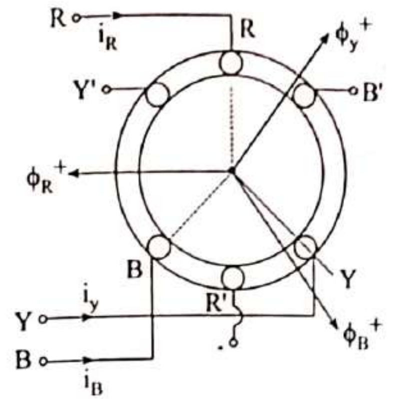
Fig. Phase wound rotor

Equivalent circuit of IM:



OPERATING PRINCIPLE, ROTATING MAGNETIC FIELD, SYNCHRONOUS SPEED, SLIP, INDUCED EMF, ROTOR CURRENT AND ITS FREQUENCY TORQUE EQUATION.

(i) Operating Principle:



The flux produced by their 3-ϕ currents will also can be written as,

$\phi_R = \phi m \sin\omega t$

$\phi_Y = \phi m \sin(\omega t - 120°)$

$\phi_B = \phi m \sin(\omega t + 120°)$

} time varying flux produced by time varing 3-ϕ current

The net flux in the air gap will be the sum of ϕ_R, ϕ_Y & ϕ_3

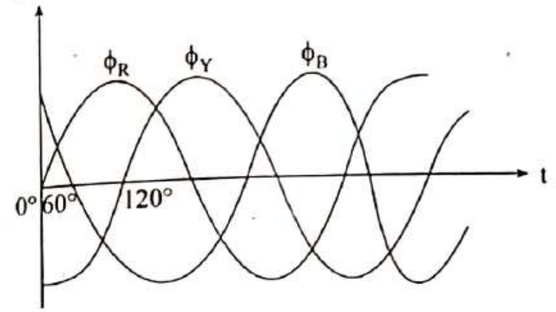
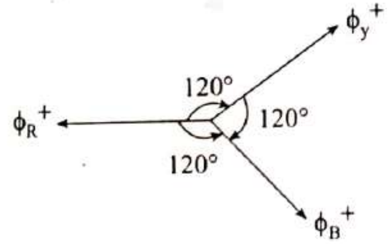


Fig: Waveform of ϕ_R, ϕ_Y & ϕ_B

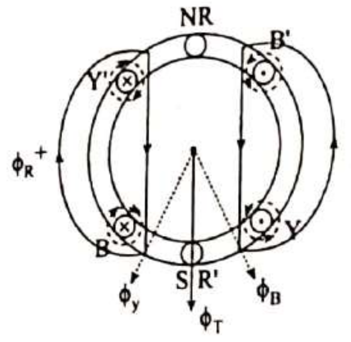


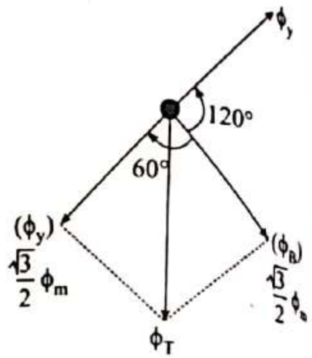
At wt = 0° (electrical angle)

($i_R = 0$) $\quad \phi_R = \phi_m \sin 0° = 0°$

(i_Y coming out) $\quad \phi_Y = \phi_m \sin(0° - 120°) = -\sqrt{3}\ \phi_m$

(i_B going in) $\quad \phi_B = \phi_m \sin(0° - 240°) = +\frac{\sqrt{3}}{2}\ \phi_m$





$\therefore$ Total flux: $\phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2 \times \left(\frac{-\sqrt{3}}{2}\right)\left(\frac{\sqrt{3}}{2}\right)\phi_m^2 \cos 60°}$

at $\omega t = 0° = \frac{3}{2}\ \phi_m$

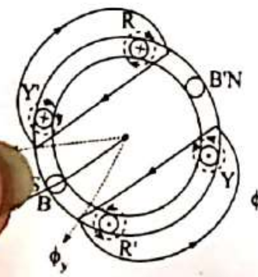
$\Phi_T = \frac{3}{2}\phi_m$

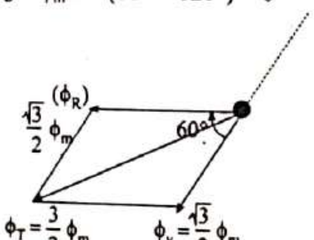
At $\omega t = 60°$

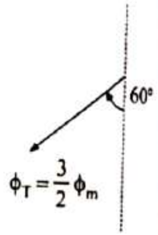
(i_R +) $\quad \phi_R = \phi_m \sin 60° = +\frac{\sqrt{3}}{2}\ \phi_m$

(i_Y −) $\quad \phi_Y = \phi_m \sin(60° - 120°) = \frac{\sqrt{3}}{2}\ \phi_m$

(i_B 0) $\quad \phi_B = \phi_m \sin(60° + 120°) = 0$







$\frac{60}{N_s} = \frac{1}{f}$ (P = 2) $\frac{60}{N_s} = 2\frac{1}{f}$ (P = 4) $\Rightarrow \frac{60}{N_s} = \left(\frac{P}{2}\right)\frac{1}{f}$

Hence, we can see that, the resultant flux ϕ_T has constant magnitude but its direction is changing, in clockwise direction for this particular case of winding as shown above. Such a magnetic field is known as rotating magnetic field.

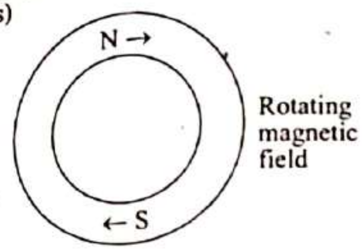
The speed of rotation of ϕ_T depends on the supply frequency as well as the no. of poles as shown below,

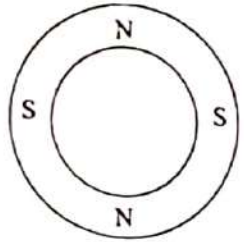
$$N_s = 120 * \frac{f}{p}$$

f → Supply frequency

p → No. of magnetic pole for which the stator winding is wound.

The speed of the rotating magnetic field is called synchronous speed (Ns)

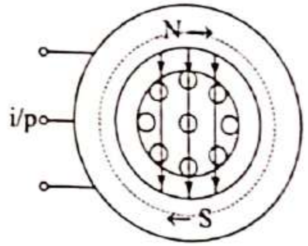




4-pole

How does rotor rotates?

→ When stator winding is supplied by 3-ϕ voltage sources, 3-ϕ currents i_{R1}, i_Y & i_B will flow. This will produce a rotating magnetic flux in the air-gap.



→ This rotating magnetic flux cuts the rotor conductor. Thus, according to the Faradays' law of electromagnetic induction, emf will be induced on rotor conductor.

→ Since, rotor conductors are short circuited (by end rings), current will flow in it.

→ Now, current carrying rotor conductor are lying in the magnetic field. ∴ Force will be produced in these rotor conductors. Hence, rotor rotates.

→ Here, main cause of induced current in rotor.

At starting, if N is sped of rotor, N = 0

∴ Relative speed = $N_s = N = N_s =- 0 = N_s$.

Therefore, according to Lenz's law the direction of force will be such that to reduce the relative sped (i.e. it tries to decrease the flux cut process).

Therefore, Rotor rotates in the same direction as that of N_s.

→ As rotor approaches synchronous speed, $N = N_s$.

The relative speed = 0 & flux doesn't cut rotor conductor. Hence, induced emf = 0 & rotor current = 0 and 0. Hence, rotor slows i.e. N decreases. Once when $N<N_s$ the again cuts the conductor & emf ≠ 0 rotor current ≠ 0 & F ≠ 0. Thus, IM cannot rotate at the synchronous speed but rotates a speed N which is little less than Ns continuously. That is they are also called asynchronous motor.

The difference between the speed of the stator field, known synchronous speed (N_s) and the actual speed of the rotor (N), known as the slip & is denoted by 'S'. Normally, it is expressed as a fraction of synchronism speed i.e.

$$\boxed{S = \frac{N_s - N}{N_s} \text{ (p.u.)}}$$ If N_s = 1500 rpm & N = 1450 rpm

$$S = \frac{1500 - 1450}{1500} = 0.033 \text{ (pu)}$$

Slip of I.M. = 3.3%

Analysis of starting condition & Running condition of Induction Motor.

The operation of 3-ϕ induction motor is very much similar to transformer.

3-ϕ	Transformer
Stator winding ⟶	P.W.
Rotor winding ⟶	S.W.

The only difference between them is that the rotor rotates but S.W. of Tr. does not rotates.

∴ Equivalent circuit of 3-ϕ IM can be drawn from the idea of eqvt circuit of transformer.

Perphase Eqvt circuit of 3-ϕ IM at starting (at standstill):

Let, V_s = the applied voltage to stator winding.

E_1 = the emf induced in stator winding

(E_1 opposes v_s)

E_2 = the emf induced in rotor ckf at starting.

Then, eqvt circuit is as follows:

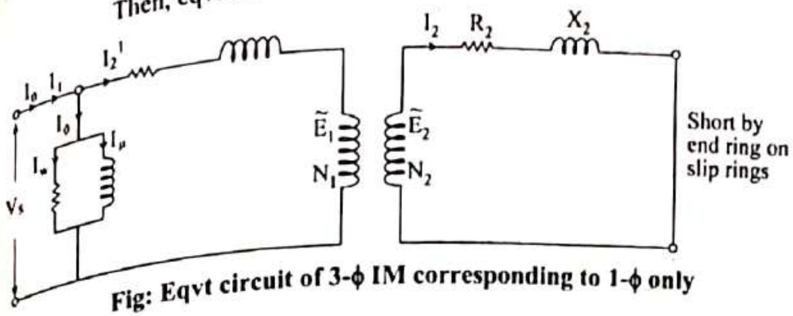


Fig: Eqvt circuit of 3-ϕ IM corresponding to 1-ϕ only

Then,

$$\tilde{E}_1 = \tilde{V}_s - \tilde{E}_2 (R_1 + JX_1)$$

Approximately we can with $\tilde{I}_1 \approx \tilde{I}_2^1$

$$(\because \tilde{I}_1 \approx \tilde{I}_2^1 + \tilde{I}_0 \;\&\; \tilde{I}_0 << \tilde{I}_2^1)$$

Again,

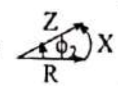
$$|\tilde{I}_2^1| = \frac{|\tilde{E}_2|}{(|R_2^2 + X_2^2|)} \text{ (from ohm's law)}$$

We know that

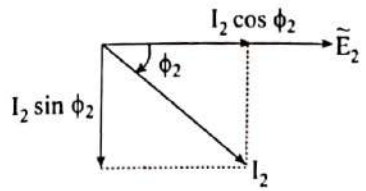
$\tilde{I}_2$ lags $\tilde{E}_2$ by an angle ϕ_2.

Where,

$$\phi_2 = \cos^{-1}\left[\frac{R_2}{\sqrt{R_2^2 + X_2^2}}\right]$$

[∵ ]

Phasor diagram is,



Here, the 90° component of current doesn't produce any torque, but is only useful for magnetic flux production. Only active component of current is responsible for production of torque.

Using the knowledge that the torque is proportional to the value of flux & the current, the starting torque produced by rotor can be written as,

$$T_s \alpha \phi * I_2 \cot\phi_2$$

We also know that, in term of magnitude,

$\phi \alpha V_s \alpha E_1 \alpha E_2$

Hence, we can write

$T_s \alpha E_2 I_2 \cot\phi_2$

or, $T_s = kE_2 . I_2 \cot_2$

or, $T_s = k.E_2 \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}} \cdot \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$

$\Rightarrow$ $\boxed{T_s = \dfrac{K E_2^2 R_2}{R_2^2 + X_2^2}}$ at standstill

 # Analysis of Running condition: During running. condition many changes occur in eqvt circuit due to rotor rotation.

I[st] Change : When rotor rotates, rate of cutting of flux of rotor conductor decreases.

∴ *emf induced in rotor circuit decreases & is given by,* $\boxed{{}^{"}sE_2{}^{"}}$

where, $S = \dfrac{Ns - N}{Ns}$

2[nd] change: At starting, frequency of $E_2 = f$

But, when rotor rotate frequency of E_2 decrease and is given by

$f_r = \dfrac{(N_S - N)P}{120}$ $\left[\because f = \dfrac{N_sP}{120} = \dfrac{(N_S - 0)P}{120}\right]$

& At standstill, at starting

$f = \dfrac{N_SP}{120}$

∴ $\dfrac{f_r}{f} = \dfrac{(N_S - N)(P/120)}{N_S(P/120)} = \dfrac{N_S - N}{NS} = s$

∴ $\boxed{f_r = sf}$ frequency induced emf in running cond[n]

3[rd] change: The value of rotor leakage reactance on the rotor frequency $X_2 = 2\pi f_r L$

4[th] change: Now, $I_2 = I_r = \dfrac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Then the impedance diagram is

I_R lags sE_2 by ϕ_R where, ϕ_R is

$\phi_R = \cos^{-1}\left[\dfrac{R_2}{\sqrt{R_2^2 + s^2 X_2^2}}\right]$

Thus, the equivalent circuit at running condition is as follows:

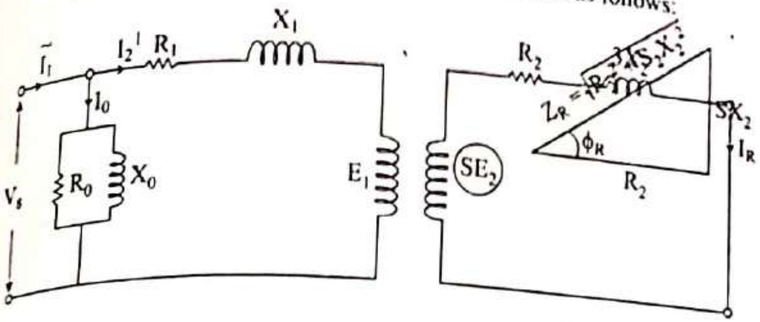


Fig: Perphase equivalent circuit for runing condition

Torque developed by rotor at running condition is,

$T_R \alpha \phi . I_R \cos\phi_R$

$\Rightarrow$ $T_R \alpha E_2 . I_R \cos\phi_R$ $\quad \because \phi \alpha V_s \alpha E_1 \alpha E$ (Stand still toror indad emf)

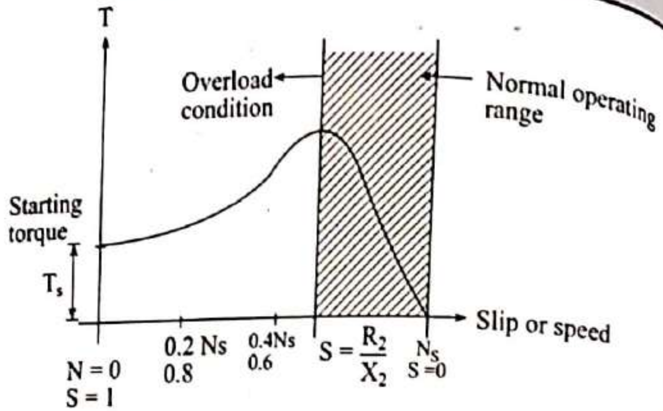
or, $T_R = kE_2 . \dfrac{SE_2}{\sqrt{P_2^2 + S^2 X_2^2}} \cdot \dfrac{R_2}{\sqrt{R_2^2 + S^2X_2^2}}$

or, $\boxed{T_R = \dfrac{K SE_2^2 R_2}{\left(R_2^2 + S^2X_2^2\right)}}$ At running condition (Torque Equation)

At starting condition, $N = 0, \Rightarrow S = 1$.

∴ $\boxed{T_S = \dfrac{KE_2^2 R_2}{\left(R_2^2 + X_2^2\right)}}$ At standstill.

TORQUE SLIP CHARACTERISTICS OR TORQUE-SPE CHARACTERISTICS:



At Normal operating range:

$N \approx N_S$ but $N < N_s$

∴ s will be very small at Normal operating range.

$\therefore\ s^2 \times X_2^2 << R_2^2$

if we neglect $S^2X_2^2$, then,

$$T_R = \frac{KsE_2^2R_2}{R_2^2} = \frac{KsE_2^2}{R_2}$$

$$\Rightarrow \left\{T_R \,\alpha\, \frac{s}{R_2}\right\}$$

If R_2 is kept constant then,

$$\boxed{T_R \,\alpha\, s}$$

∴ T_R V_s s curve is a straight line (in this range) when load on shaft increase↑ then N↓ which motor can develop mar torque.

We can find out the max torque limit as follow:

$$T_R = \frac{ksE_2^2R_2}{R_2^2 + s^2X_2^2}$$

$$\text{Let } Y = \frac{1}{T_R} = \frac{R_2^2 + s^2X_2^2}{KsE_2^2R_2}$$

For max. T_R, ⇒ Y will be minimum,

For this,

$$\frac{dY}{ds} = 0$$

We have, $Y = \frac{R_2^2}{KsE_2^2R_2} + \frac{s^2X_2^2}{KsE_2^2R_2} = \frac{R_2}{KsE_2^2} + \frac{sX_2^2}{KE_2^2P_2}$

Thus,

$$\frac{dY}{ds} = \frac{-R_2}{Ks^2E_2^2} + \frac{X_2^2}{KE_2^2R_2} = 0$$

or, $\frac{R_2}{Ks^2E_2^2} = \frac{X_2^2}{KE_2^2R_2}$ or, $S^2 = \frac{R_2^2}{X_2^2}$

$\Rightarrow S = \frac{R_2}{X_2}$ ∴ $\boxed{R_2 = SX_2}$

This implies that max. torque occurs at

$$\boxed{s_M = \frac{R_2}{X_2}}$$

If the shaft is over loaded beyond $s = \frac{R_2}{X_2}$ speed decrease by large amount and 's' will be large.

& ∴ $s^2X_2^2$ will not be negligible, infact, practically, in this range, R_2^2 will be negligible.

w.r.t. $s^2X_2^2$ $T_R = \frac{KE_2^2R_2}{sX_2^2}$

$\boxed{T_R \,\alpha\, \frac{R_2}{s}}$ TR ϕ s inverse relation in this range.

Effect of R_2 on T-S chac:

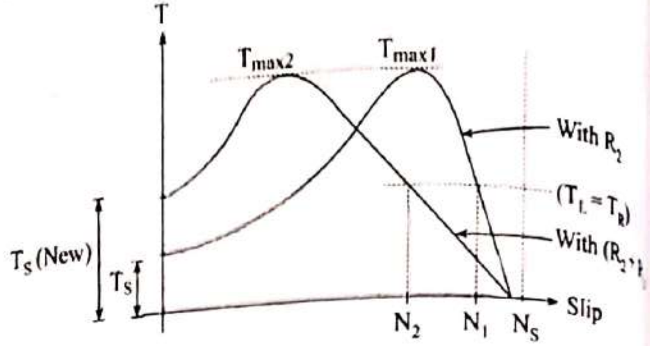
In normal operating range's

$T_R \,\alpha\, \frac{s}{R_2}$ ...(1)

& for overload condition:

$T_R \,\alpha\, \frac{R_2}{s}$

From eq^n (1) if $R_2\uparrow$; then $T_R\downarrow$ in normal operating range:



The starting torque is greater than previous case as shown ab... $T_S(new) > T_S$

But remember, the max. torque doesn't change by changing R... $T_{max1} = T_{max2}$ instead the T_{max2} occurs at different point during s... curve.

We have,

$$T_R = \frac{KsE_2^2R_2}{R_2^2 + s^2X_2^2}, \text{ for max torque, } s_m = \frac{R_2}{X_2}$$

$$\therefore \quad T_{Rmax} = \frac{K.\frac{R_2}{X_2}.E_2^2R_2}{R_2^2 + \frac{R_2^2}{X_2^2}X_2^2} = \frac{K.E_2^2R_2^2/X_2}{2R_2^2}$$

$$\Rightarrow \boxed{\left(T_{max} = \frac{KE_2^2}{2X_2}\right)} \text{ independent of } R_2.$$

NO-LOAD AND BLOCKED ROTOR TEST ON

Three Phase Induction Motor

Aim of the Experiment:

1. To obtain the variation of no load power and current and blocked ro... power and current with changes in the applied voltage to the stator.
2. To determine the equivalent circuit parameters of an induction moto...

No load test:

Theory:

The no load test is similar to the open circuit test on a transformer. It is performed to obtain the magnetizing branch parameters (shunt parameters) in the induction machine equivalent circuit. In this test, the motor is allowed to run with no-load at the rated voltage of rated frequency across its terminals. Machine will rotate at almost synchronous speed, which makes slip nearly equal to zero. This causes the equivalent rotor impedance to be very large (theoretically infinite neglecting the frictional and rotational losses). Therefore, the rotor equivalent impedance can be considered to be an open circuit which reduces the equivalent circuit diagram of the induction machine (Fig. 1) to the circuit as shown in Fig. 2. Hence, the data obtained from this test will give information on the stator and the magnetizing branch. The no load connection circuit diagram of no load test is shown in Fig. 3. The no load parameters can be found from the voltmeter, ammeter, and wattmeter readings obtained when the machine is run at no load as shown below:

Readings Obtained:

1. Line to line voltage at stator terminals : volts *nlV*
2. Stator Phase Current : amps *nlI*
3. Per phase power drawn by the stator : watts *nlP*

Calculations:

$$Z_{nl} = \frac{(V_{nl}/\sqrt{3})}{I_{nl}} \text{ ohms}$$

$$r_{nl} = \frac{P_{nl}}{I_{nl}^2} = r_1 + r_c \text{ ohms}$$

$$X_{nl} = \sqrt{Z_{nl}^2 - R_{nl}^2} = X_1 + X_m \text{ ohms}$$

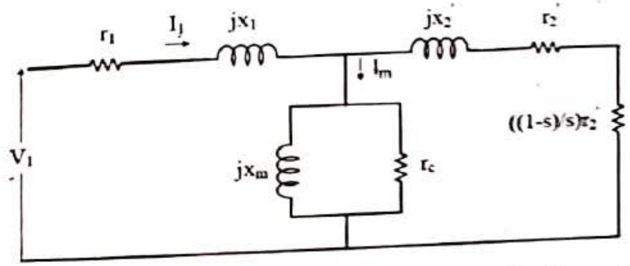


Fig. 1: Per phase equivalent circuit of 3-phase induction motor

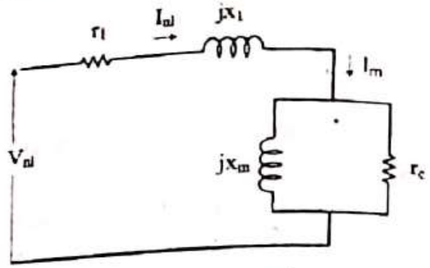


Fig. 2: Approximate Equivalent Circuit for No-Load Test

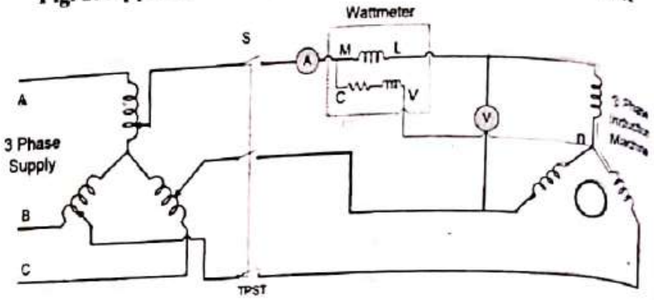


Fig. 3: Connection diagram for performing No-load and Blocked Rotor tests on 3 phase induction machine

Blocked rotor test:

Theory: Blocked rotor test is similar to the short circuit test on a transformer. It is performed in the to calculate the series parameters of the induction machine i.e., its leakage impedances. The rotor is blocked to prevent rotation and balanced voltages are applied to the stator terminals at a frequency of 25 percent of the rated frequency at a voltage where the rated current is achieved. Under the reduced voltage condition and rated current, core loss and magnetizing component of the current are quite small percent of the total current, equivalent circuit reduces to the form shown in Fig. 4.

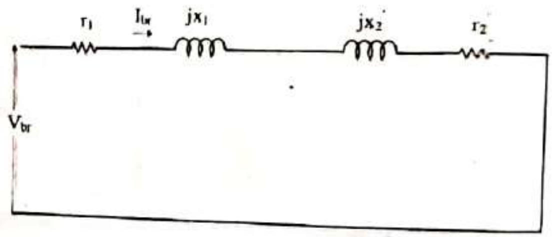


Fig.4: Equivalent Circuit for Blocked Rotor Test

The slip for the blocked rotor test is unity since the rotor is stationary. The resulting speed-dependent equivalent resistance **r2'{(1/s)-1}** goes to zero and the resistance of the rotor branch of the equivalent circuit becomes very small. Thus, the rotor current is much larger than current in the excitation branch of the circuit such that the excitation branch can be neglected. Voltage and power are measured at the motor input.

Readings Obtained:

Line to line voltage at stator terminals : *Vbr* volts

Stator Phase Current : *Ibr* amps

Per phase power drawn by the stator : *Pbr* watts

Calculations:

$$Z_{br} = \frac{(V_{br}/\sqrt{3})}{I_{nl}} \text{ ohms}$$

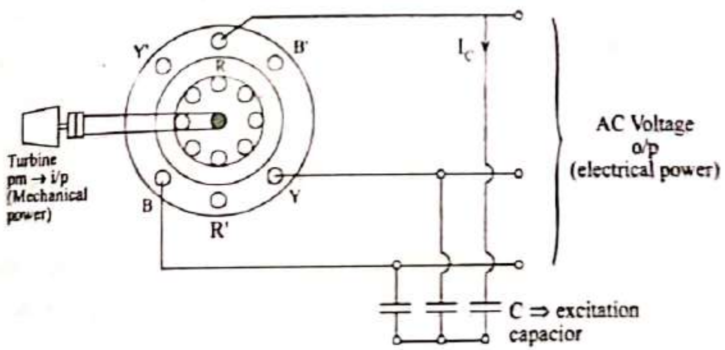
$$r_{br} = \frac{P_{br}}{I_{br}^2} = r_1 + r_2' \text{ ohms}$$

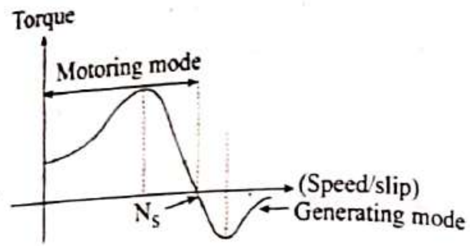
$$X_{br} = \sqrt{Z_{br}^2 - R_{br}^2} = X_1 + X_2' \text{ ohms}$$

If it is assumed that $X_1 = X_2'$, then $X_1 = X_2' = \frac{X_{br}}{2}$ ohms

THREE PHASE INDUCTION GENERATOR

WORKING PRINCIPLE, VOLTAGE BUILD UP IN INDUCTION GENERATOR.





An induction motor also can be used as generator by diving it above the synchronous speed, provided there is magnetic flux in the air gap to generate an emf of frequency of standard value.

Let, required frequency = 50 Hz

P = 4

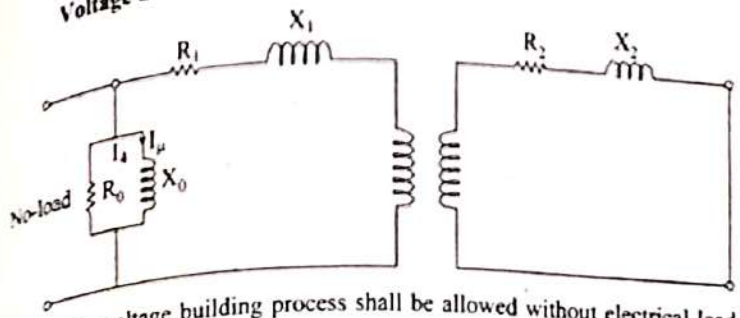
Synchronous speed $N_s = \frac{120f}{P} = 1500$ rpm.

When the rotor rotates (driven by turbine) the rotor conductor cuts the air gap flux.

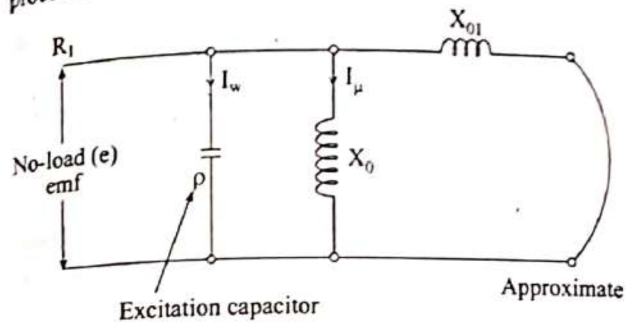
∴ emf will be induced is the rotor conductor. Accordingly emf will also induce in stator winding by transformer action.

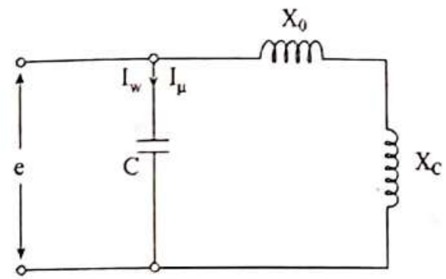
In order to produce air gap flux, reactive power is required. But the mechanical turbine cannot support to generate reactive power. However, there will be residual air gap flux in the machine if it was used as motor in the previous operation. Because of this residual air gap flux, small amount of emf will. Induce in the rotor circuit and accordingly small amount of emf will induce in the stator circuit by transformer action. If excitation capacitors are connected across the each phase of stator winding, these capacitor will draw leading current I_C (90°) & generates some reactive power. Hence, air gap flux will increase. Then emf in rotor circuit and stator will increase. Because of this increased emf the capacitor current will be increased and air gap flux will increase. In this way the voltage in stator winding builds up continuously & finally produces a rated steady voltage in the stator winding

Voltage Build up Process:

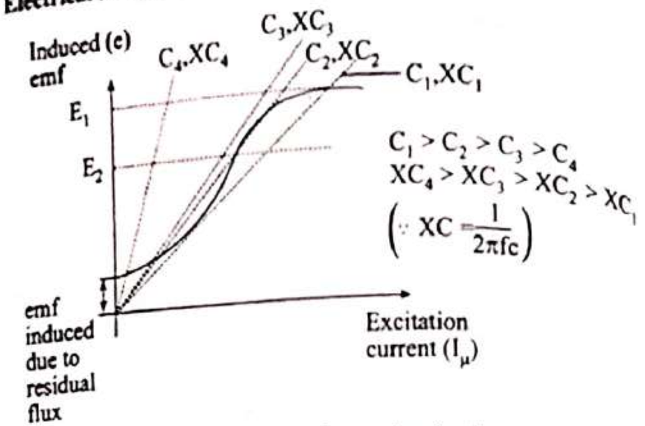


The voltage building process shall be allowed without electrical load connected across the stator. Since, copper loss is negligible at no-load operation, R_1 & R_2 can be neglected to explain voltage build up process. Since, $I_\mu > I_w$, we can also neglect R_0 to explain the voltage build up process. Hence, the equivalent circuit during voltage build up process can be simplified as follows:





The residual magnetism in the magnetic circuit of the machine is sufficient to induce a small ac voltage in the stator. Such a voltage across the capacitor causes the current to flow in the capacitor.



→ If the appropriate value of capacitor is chosen the magnetizing current can be sufficient to increase the existing air gap flux.

→ With an increased air-gap flux, the induced voltage further increases resulting in more magnetizing current.

→ This cyclic process continuous to build up more and more voltage.

→ The maximum voltage built up is limited by the capacitor value. For example, if capacitance is C_1 voltage build up is E_1, If capacitance is C_2 voltage build up is E_2.

→ If capacitance is C_3, the line is tangent to the curve hence voltage will just build up. Thus, C_3 is also known as critical capacitance.

→ If capacitance is further reduced to C_4, the line of capacitance does not interact the curve the curve, the voltage build up process cannot take place.

For voltage build process to take place, only if this condition is satisfied, the reactive power consumed by combination of ($X_M + X_...$) can be produced by X_c.

POWER STAGES

[Power Input in Stator (VA)] – [Stator Cu & Iron Losses (W)] = [Rotor Power input (w)] – [Rotor Cu loss (w)]

= [Mechanical power developed in Rotor (w)] – [friction loss] = [Power output from shaft (w)] – [Reactive power (var)] → Air gap flux

Fig. Induction Motor Power stage.

→ Stator: Iron loss (consisting of eddy & hysteresis losses) depends on the supply frequency & the flux density in the iron case. It is technically constant stator cu loss = 3I, $3I^2R_s$.

→ the iron loss of the rotor is, however, negligible because frequency of rotor currents under normal saving conditions is always small. Total rotor Cu loss = $3\, I_2^2 R_2$

$$\eta = \frac{\text{Net power output fromk shaft}}{\text{Active power Input to states}} \times 100\%$$

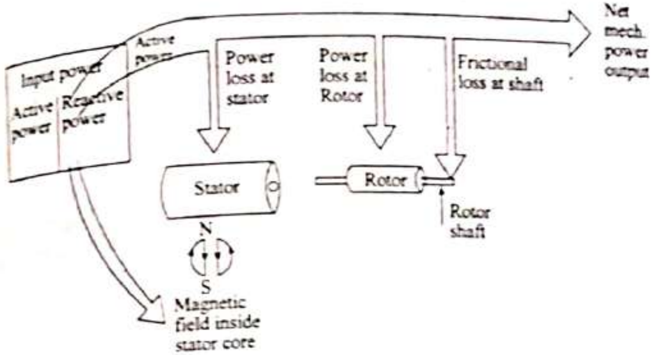


Fig. Power stage of an Induction Motor

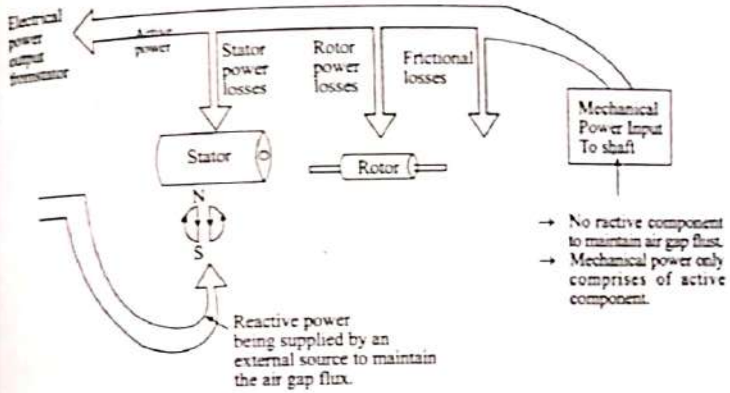


Fig. Power stage of an Induction Generator

SOME MATHEMATICAL RELATION: IN INDUCTION MOTOR

Let T_R = Torque developed by rotor at speed of 'N' rpm.

The power developed by rotor,

$$\left\{P = \frac{2\pi N T_R}{60}\right\}$$

$$\begin{bmatrix}\text{Power i/p} \\ \text{to rotor}\end{bmatrix} - \begin{bmatrix}\text{Rotor} \\ \text{cu loss}\end{bmatrix} = \begin{bmatrix}\text{Power develoepd} \\ \text{by Rotor}\end{bmatrix}$$

i.e. If there were no cu-loss in Rotor circuit then power in put to rotor from stator = Power developed by rotor & Rotor would rotated at N_s.

Then, $\left\{P_r = \frac{2\pi N T_R}{60}\right\}$

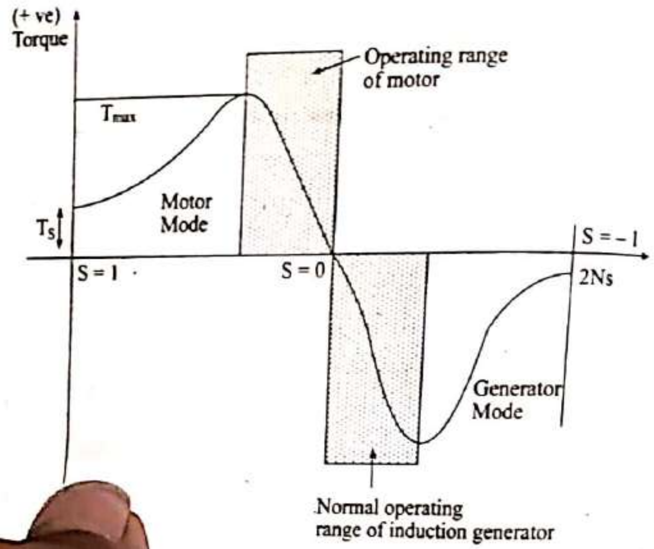
Then, $\begin{matrix}\text{Cu loss} \\ \text{in Rotor}\end{matrix} = \frac{2\pi N_S T_R}{60} - \frac{2\pi N T_R}{60} = \frac{2\pi T_R}{60}[N_s - N]$

or, Rotor cu loss $= \frac{2\pi T_R}{60}[N_s - N]$

$\therefore \quad \frac{\text{Rotor Cu loss}}{\text{Input power to rotor}} = \frac{(2\pi T_R.60)[N_S - N]}{\frac{2\pi TR}{60} \times Ns} = \frac{N_s - N}{N_s} = 1$

$\Rightarrow$ **Rotor Cu loss = s × Input Power to rotor**

rotor efficiency $(\eta) = \frac{\text{Power devleoepd by Rotor}}{\text{Power input to rotor}} = \frac{2\pi N T_R/60}{2\pi N s\, T_R/60} = \frac{N}{N_s}$



. T-S. characteristics of induction machine

Tutorial

1. **A 400V, 4-pole, 50Hz, 3 phase, 10 HP, Star connected induction motor has a full slip of 4%. Given that efficiency and power factor of the motor at full load are of 92% and 0.8 lag respectively. Calculate :**
   - **a) Synchronous Speed**
   - **b) Speed at Full load**
   - **c) Frequency of rotor current at Full load**
   - **d) Full load torque.**
   - **e) Full load stator current** **[2065]**

Solution:

$P = 4,\ f = 50Hz,\ P_{out} = 10HP,\ \eta = 92\%\ \cos\phi = 0.8$ (lag)

So,

(a) $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

(b) At full load, $S = 4\% = 0.04$

$\therefore \quad 0.04 = \frac{1500 - N}{1500}$

$\therefore \quad N = 1440$ rpm

(c) $f_r = sf = 0.04 \times 50 = 2$ Hz

Now,

(d) $P_{at} = \frac{T \times 2\pi N}{60}$

$\therefore \quad T = \frac{10 \times 746 \times 60}{2\pi \times 1440} = 49.47$ N-m

(e) $P_{in} = \frac{P_{out}}{\eta} = \frac{10}{0.92} = 10.86$ HP

Now, $P_{in} = \sqrt{3}\, V_l I_l \cos\phi$

or, $10.86 \times 746 = \sqrt{3} \times 400 \times I_L \times 0.8$

$\therefore \quad I_L = 14.61$ A

2. A 400V, 4-pole, 50Hz, 3 phase, slip ring induction motor has delta connected stator winding and a star connected rotor winding. At standstill the voltage between the two slip rings is 190V. The stator impedance is 0.5 + j2.5 ohm. The rotor resistance and reactance at standstill are 0.06 ohm and 0.3 ohm respectively and it develops a maximum torque of 150 N-m. Calculate :

a) Slip at which the motor develops the maximum torque.

b) Torque, power output at full load, Given that full load slip is 0.04. [2064]

Solution:

$P = 4, f = 50Hz,$

Stator: $R_1 = 0.5\Omega, X_1 = 2.5\Omega$

Rotor: $R_2 = 0.06\Omega, X_2 = 0.3\Omega$

$T_{max} = 150\ N-m$

(a) $S_{max} = \frac{R_2}{X_2} = \frac{0.06}{0.3} = 0.2$

Now, I_L = Torque at full load.

(b) $I_f = \frac{K_1 S E_2^2 R_2}{R_2^2 + S^2 X_2^2}$

$T_{max} = \frac{K_1 E_2^2}{2X_2}\left[\text{Put } S = \frac{R_2}{X_2}\right]$

So, $\frac{T_l}{T_{max}} = \frac{SR_2}{R_2^2 + S^2X_2^2} \times 2X_2$

At full load, S = 0.04

$\frac{T_l}{T_{max}} = \frac{0.04 \times 0.06}{0.06^2 + 0.04^2 \times 0.3^2} \times 2 \times 0.3$

$\frac{T_l}{T_{max}} = \frac{5}{13}$

$\therefore\ T_l = \frac{5}{13} \times 150 = 57.69$ N-m

Now,

$S = \frac{N_S - N}{N_S} \Rightarrow N = -(0.04 \times N_S) + N_S$

$\therefore\ N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

$\therefore\ N = 1500 - (0.04 \times 1500) = 1440$ rpm

$\therefore$ Output at full load $= \frac{2pNI_f}{60} = \frac{2\pi \times 1440 \times 57.63}{60} = 11.66$ hp.

3. ***The data obtained from the test of a 3-phase star connected 400V induction motor are as follow:***

No-Load Test: V_1 = 400V, I0 = 20A, W_1 = 5000W and W_2 = -3200 W.

Blocked rotor test: Vsc = 50V, Isc = 60A, W_1 = 2300W and W_2 = 750W.

Calculate the equivalent circuit parameters refer to stator side. [2066]

Solution:

No-load test:

$V_1 = 400$ V, $I_0 = 20$A, $W_1 = 5000$ W, $W_2 = 3200$ W

$\therefore\ W_0 = 5000 - 3200 = 1800$ W

$W_0 = \sqrt{3}\, V_1\, I_0 \cos\phi_0$

$\therefore\ I_0 \cos\phi_0 = \frac{W_0}{\sqrt{3}\, V_1} = \frac{1800}{\sqrt{3} \times 400} = 2.598$ A

$\therefore\ I_W = 2.598$A

$I_\mu = \sqrt{20^2 - 2.598^2} = 19.83$ A

$\therefore\ R_0 = \frac{\frac{V_1}{\sqrt{3}}}{I_W} = \frac{\frac{400}{\sqrt{3}}}{2.598} = 88.89\Omega$

$X_0 = \frac{\frac{V_1}{\sqrt{3}}}{I_\mu} = \frac{\frac{400}{\sqrt{3}}}{19.83} = 11.645\Omega$

Blocked Rotor Test:

$V_{SC} = 50V, I_{SC} = 60$ A, $W_1 = 2300$ W and $W_2 = 750$ W

$\therefore\ Z_{01} = \frac{V_{SC}/\sqrt{3}}{I_{SC}} = \frac{50/\sqrt{3}}{60} = 0.4811$

$R_{01} = \frac{W_1 + W_2}{3 \times I_{SC}^2} = \frac{2300 + 750}{3 \times 60^2} = 0.282\ \Omega$

$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{0.4811^2 - 0.282^2} = 0.3897\Omega$

4. A 150 kW, 3000V, 50Hz, 6 pole star-connected induction motor has a star-connected slip ring rotor with a transformation ratio of 3.6 (stator to rotor). The rotor resistance is 0.1 ohm/phase and rotor inductance is 3.61 mH per phase. Neglecting the stator impedance, calculate:

a) Starting current and torque on rated voltage with slip ring short circuited.

b) Necessary external resistance to reduce the rated voltage starting current to 30A and corresponding starting torque. [206..]

Solution:

Power input $(P_i) = 50$ kW

Stator loss $(W_S) = 2$kW

Hence, Power input to rotor $(P_2) = 50 - 2 = 48$ kW

(a) Now,

$$\text{Slip} = \frac{\text{Rotor Power loss}}{\text{Power input to Rotor}}$$

or, $0.03 = \frac{W_r}{48}$

$\therefore$ $W_r = 1.44$ kW

Hence, Total Mechanical power by rotor $= P_r - W_r$

$P_{mech} = 48 - 1.44 = 46.56$ kW

$\therefore$ $P_{mech} = \frac{46.56 \times 1000}{746} = 62.41$ HP

(b) Output power of motor $(P_{out}) = P_{mech} - P_{friction} = 46.56 - 1 = 45.56$ kW

$\therefore$ $P_{out} = 45.56$ kW $= 61.07$ HP

(c) Efficiency $(\eta) = \frac{P_{out}}{P_i} \times 100\% = \frac{45.56}{50} \times 100\% = 91.12\%$

5. The power input to a 3-phase induction motor is 50kW and the corresponding stator losses are 2kW. Calculate (a) Total mechanical power developed by rotor and rotor copper loss when the slip is 3%. (b) Output horse power of the motor if the friction and windage losses are 1 kW and (c) efficiency of the motor. [2069]

Solution:

$V = 3000$ V, $f = 50$ Hz, $P = 6$

$K = \frac{1}{3.6} \Rightarrow \frac{1}{k} = 3.6$

$R_2 = 0.1\ \Omega$

$X_2 = 2\pi \times 50 \times 3.61 \times 10^{-3} = 1.3\Omega$

$\therefore$ $R_2' = R_2/K^2 = 0.1 \times 3.6^2 = 1.3\ \Omega$

$X_2' = \frac{X_2}{K^2} = 1.13 \times 3.6^2 = 14.64\ \Omega$

(a) Now,

$$I_{st} = \frac{V/\sqrt{3}}{\sqrt{R_2'^2 + X_2'^2}} = \frac{300/\sqrt{3}}{\sqrt{1.3^2 + 14.64^2}} = 117.84 \text{ A}$$

$$N_S = \frac{120 f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm} = 16.67 \text{ rps}$$

Hence,

$$\text{Starting torque} = \frac{K E_2^2 R_2'}{R_2'^2 + X_2'^2} = \frac{3}{2\pi NS} \times \frac{R_2'}{R_2'^2 + X_2'^2}\left[\because K = \frac{3}{2\pi N_S}\right]$$

$$= \frac{3}{2\pi \times 16.67} \times \frac{\left(\frac{3000}{\sqrt{3}}\right)^2 \times 1.3}{1.3^2 + 14.64^2}$$

$= 517.1$ N-m.

(b) Let, required external resistance = R.

$\therefore$ $R' = R/K^2 = R \times 3.6^2 = 12.96$ R

Now, for $I_{st} = 30$ A

$$30 = \frac{V/\sqrt{3}}{\sqrt{(R_2' + R')^2 + X_2'^2}}$$

or, $$30 = \frac{3000/\sqrt{3}}{\sqrt{(1.13 + 12.96A)^2\,(14.64)^2}}$$

$\therefore$ $R = 4.22\Omega \Rightarrow R' = 12.96 \times 4.22 = 54.69\ \Omega$

Then,

$$T_{st} = \frac{3}{2\pi N_S} \frac{\left(\frac{V}{\sqrt{3}}\right)^2 (R_2' + R')}{(R_2' + R')^2 + X_2'^2}$$

$$= \frac{3}{2\pi \times 16.67} \frac{\left(\frac{3000}{\sqrt{3}}\right)^2 (1.3 + 54.69)}{(1.3 + 54.69)^2 + 14.64^2}$$

$\therefore$ $T_{st} = 1436.46$ N-m **Ans.**

6. A 4 pole, 3-phase, 50Hz slip-ring type induction motor rotates at 1440 rpm with the slip-ring terminals short circuited. The per phase rotor resistance and reactance are 0.1 ohm and 0.6 ohm respectively at standstill. If an extra external resistance of 0.1 ohm per phase is added to the rotor circuit, what will be the new full load speed? [illegible]

Solution:

$$P = 4,\ f = 50\ \text{Hz},\ N_S = \frac{120f}{P} = 1500$$

$$N_1 = 1440$$

$$\therefore\quad S_1 = \frac{N_S - N_1}{N_S} = \frac{1500 - 1440}{1500} = 0.04$$

Now,

$$T_1 = \frac{KS_1E_2^2R_2}{R_2^2 + S_1^2X_2^2} = \frac{K \times 0.04 \times E_2^2 \times 0.1^2}{0.1^2 + 0.042 \times 0.6^2}$$

$$\text{or,}\quad T_1 = \frac{0.004\ KE_2^2}{0.010576} = \frac{250}{661}KE_2^2$$

Now, when $R = 0.1\Omega$ is added,

$$T_2 = \frac{KS_2E_2^2(R_2 + R)}{(R_2 + R)^2 + S_2^2X_2^2} = \frac{KS_2E_2^2\,(0.1 + 0.1)}{(0.1 + 0.1)^2 + S_2^2 \times 0.6^2}$$

$$T_2 = \frac{0.2\ KS_2E_2^2}{0.04 + S_2^2\,0.26}$$

Since, torque isn't changed, $T_1 = T_2$.

$$\text{So,}\quad \frac{250}{661}KE_2^2 = \frac{0.2\ KS_2E_2^2}{0.04 + S_2^2\,0.36}$$

$$\text{or,}\quad 10 + 90S_2^2 = 132.2S_2$$

$$\text{or,}\quad 90S_2^2 - 132.2S_2 + 10 = 0$$

$$\therefore\quad S_2 = 1.38 \text{ or } 0.08$$

Since, $1.38 > 1 \Rightarrow S_2 = 0.08$

Hence, $0.08 = \frac{N_S - N_2}{N_S} \Rightarrow N_2 = 1380$ rpm.

7. A three-phase, 4 pole, induction motor has rotor resistance of 0.04 ohm per phase. The maximum torque occurs at 1200 rpm. Calculate the starting torque as a percentage of maximum torque. **[2071]**

Solution:

$P = 4$ Pole

$R_2 = 0.04\Omega$

Assuming $f = 50$ Hz, $N_S = \frac{120 \times 50}{4} = 1500$ rpm.

Max. torque occurs at N = 1200 rpm when,

$$\text{Slip, } S = \frac{N_S - N}{N_S} = \frac{1500 - 1200}{1500} = 0.2$$

$$\text{Also, } S = \frac{R_2}{X_2} \Rightarrow X_2 = \frac{0.04}{0.2} = 0.2\ \Omega$$

Now,

$$T_{St} = \frac{KE_2^2R_2}{R_2^2 + X_2^2}\ (S = 1)$$

$$T_{max} = \frac{KE_2^2}{2X_2}$$

Hence,

$$\frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2 + X_2^2} \times 2X_2 = \frac{0.04 \times 2 \times 0.2}{0.04^2 + 0.2^2} = 0.3846$$

$$\therefore\quad \frac{T_{st}}{T_{max}} = 38.46\%\ \textbf{Ans.}$$

8. The power input to a 500V, 50Hz, 6-pole, 3-phase induction motor running at 975 rpm is 40 kW. The stator losses are 1 kW and friction loss is 2 kW. Calculate: (a) slip (b) Rotor copper loss (c) Output HP (d) Efficiency. **[2072]**

Solution:

$V = 500$ V, $f = 50$ Hz, $P = 6$

$P_{in} = 40$ kW, $N = 975$ rpm.

$$\text{(i)}\quad \text{Slip, } s = \frac{N_S - N}{N_S} = \frac{\frac{120f}{P} - 975}{\frac{120f}{P}} = \frac{1000 - 975}{1000}$$

$$\therefore\quad s = 0.025$$

(ii) Here, stator loss = 1 kW

Friction loss = 2 kW

∴ Power input to rotors = 40 – 1 = 39 kW

We know,

$$\text{Slip} = \frac{\text{Rotor Power loss}}{\text{Rotor Input Power}}$$

∴ Rotor power loss = 0.025 × 33 = 0.975kW = 975 W

(iii) Output power = Power tortor – Friction loss – Rotor loss

P_{out} = 39 – 2 – 0.975 = 36.025 kW = 48.29 HP

(iv) $\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{36.025}{40} \times 100\% = 90.06\%$

9. **An 8-pole, 50Hz, 3-phase induction motor develops a maximum torque of 150 N-m at 650 rpm. The rotor resistance is 0.5 ohm per phase. Find the torque at 4 % slip. Neglect the stator impedance.** [20..]

Solution:

P = 8, f = 50 Hz

T_{max} = 150 N – m at N_1 = 650 rpm

$R_2 = 0.5\ \Omega$

Here,

$$N_S = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

$$s = \frac{N_S - N_1}{N_S} = \frac{750 - 650}{750} = 0.133$$

$$\text{Also, } s = \frac{R_2}{X_2} \Rightarrow X_2 = \frac{R_2}{s} = \frac{0.5}{0.133} = 3.75\Omega$$

$$T_{max} = \frac{KE_2^2}{2X_2}$$

$$\text{St } S = 0.04,\ T = \frac{KE_2^2 \times 0.04 \times 0.5}{0.5^2 + S^2 \times 3.75^2}$$

$$\text{So, } \frac{T}{T_{max}} = \frac{0.04 \times 0.05}{0.5^2 \times 0.04^2 \times 3.75^2} \times 2 \times 3.75$$

$$\therefore \frac{T}{150} = \frac{60}{109}$$

∴ T = 82.56 N-m Ans.

10. **The power input to a 500 V, 50 Hz, 6 - pole, 3-phase induction motor running at 975 rpm is 40 kw. The stator losses are 1 kw friction loss is 2 kw. Calculate (a) slip (b) Rotor Copper Loss (c) Output HP (d) Efficiency**

Solution:

Given,

Voltage (V) = 500 V, 3 - ϕ IM

Speed (N) = 975 rpm

Input power ($P_{i/p}$) = 40 kW

Stator loss = 1 kW

friction loss = 2 kW

(a) $N_s = \frac{120 f}{P} = 1000$

$s = \frac{N_s - N}{N_s} = 0.025$

(b) Rotor Cu loss = s × power i/p to rotor

= s × ($P_{i/p}$ – stator loss)

= 0.025 (40 – 1) × 10^3

= 975 W

(c) Output power = $P_{i/p}$ – stator loss – rotor cu loss – friction loss

= (40 –1 – 0.975 – 2) kW

= 36.025 kW $\left(\because 1 \text{ kW} = \frac{1000}{746} \text{ Hp}\right)$

= 48.29 Hp

(d) $\eta = \frac{P_{o/p}}{P_{i/p}} \times 100\ \% = \frac{36.025}{40} \times 100\%$

∴ η = 90.06%

11. **A 6 pole 50Hz 3 ϕ slip ring induction motor has star connected stator & rotor windings. The rotor windings have impedance of 0.8 + j 4Ω, phase stand still. The induced emf between slip rings at stand still is 400 V. The stator to rotor turn ratio is 4. The motor runs at 960 rpm at no load. Calculate the current drawn by the motor at stand still and no load.** [2073]

Solution:

Number of pole (P) = 6

E_2 (line to line) = 400 V

$E_{ph} = \frac{400}{\sqrt{3}}$ V (∵ rotor winding is star connected)

Now,

$$\text{Synchronous speed } (N_S) = \frac{120\,f}{p} = 1000 \text{ rpm}$$

And,

$$\text{the slip } (S) = \frac{N_S - N}{N_S} = \frac{1000 - 960}{1000} = 0.04$$

∴ The emf induced in the rotor winding at slip = 0.04 is

$$E_R = SE_2 = 0.04 \times \frac{400}{\sqrt{3}} = 9.238 \text{ V}$$

Now, the rotor current can be calculated as,

$$I_R = \frac{SE_2}{\sqrt{R_2^2 + (S^2 \times 2^2)}} = \frac{9.38}{\sqrt{0.8^2 + 0.04 \times 4^2}}$$

$$\therefore \quad I_R = 11.323 \text{ A/phase}$$

Similarly,

$$\frac{I_S}{I_R} = \frac{N_R}{N_S}$$

$$I_S = 2.83 \text{ A/phase}$$

Also the rotor current at stand still (S = 1)

$$\therefore \quad I_R = \frac{SE_2}{\sqrt{R_2^2 + (S^2 \times 2^2)}} = \frac{(400/\sqrt{3})}{\sqrt{0.8^2 + (1^2 \times 4^2)}} = 56.613 \text{ A}/\phi$$

Similarly,

$$\frac{I_S}{I_R} = \frac{N_S}{N_R}$$

$$\therefore \quad I_S = 14.153 \text{ A/phase}$$

Hence, currents drawn at stand still = 14.153 A/phase.

12. A 3 ph Induction motor having a 6-pole, Y connected stator winding rund on 240 V, 50 Hz supply the rotor resistance & standstill reactance are 0.12 Ω & 0.85 Ω per phase. The ratio of stator to rotor turns is 1.8. Full load slip is 4%. Calculate the developed torque at full load, maximum torque & speed at maximum torque. [2072]

Solution:

$$K = \frac{\text{rotor turns/phase}}{\text{stator turns/phase}} = \frac{1}{1.8}$$

$$E_2 = KE_1 = \frac{1}{1.8} \times \frac{240}{\sqrt{3}} = 77\text{V}$$

$$S = 0.04$$

$$N_S = \frac{120\,f}{p} \times 120 \times \frac{50}{6} = 1000 \text{ rpm} = \frac{50}{3} \text{ rps}$$

$$T_r = \frac{3}{2\pi N_S} \times \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2} = \frac{3}{2\pi\left(\frac{50}{3}\right)} \times \frac{0.04 \times 77^2 \times 0.12}{0.12^2 + (0.14 \times 0.85)^2} = 52.4 \text{ N-m}$$

For maximum torque,

$$s = \frac{R_2}{X_2} = \frac{0.12}{0.85} = 0.14$$

$$\therefore \quad T_{max} = K_2 \frac{E_2^2}{2X_2} = \frac{3}{2\pi N_S} \times \frac{E_2^2}{2X_2} = \frac{3}{2\pi \times \left(\frac{50}{3}\right)} \times \frac{77^2}{2 \times 0.85} = 99.9 \text{ N-m}$$

Speed corresponding to maximum torque,

$$N = 1000\,(1 - 0.14) = 860 \text{ rpm}$$

13. A 4 - pole, 50 Hz, 3 ϕ induction motor develops torque of 162.8 N-m at 1365 rpm. The resistance of the star connected rotor is 0.2 Ω/phase. Calculate the value of the resistance that must be series with each rotor phase to produce a starting torque equal to half the maximum torque. [2075]

Solution:

$$N_S = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

∴ Slip corresponding to maximum torque is

$$S_m = \frac{1500 - 1365}{1500} = 0.09$$

$$S_m = \frac{R_2}{X_2}$$

$$\therefore \quad X_2 = \frac{0.2}{0.09} = 2.22\ \Omega$$

Now,

$$T_{max} = \frac{KE_2^2}{2X_2} = \frac{KE_2^2}{2 \times 2.22} = 0.335\ KE_2^2$$

Let 'r' be the external resistance introduce per phase in the rotor circuit, then

Starting torque,

$$T_{st} = \frac{KE_2^2\,(R_2 + r)}{(R_2 + r)^2 + (X)^2} = \frac{KE_2^2\,(0.2 + r)}{(0.2 + r)^2 + (2.22)^2}$$

By the question,

$$T_{st} = \frac{1}{2} T_{max}$$

$$\text{or,} \quad \frac{KE_2^2\,(0.2 + r)}{(0.2 + r)^2 + (2.22)^2} = \frac{0.225 \times KE_2^2}{2}$$

$$\therefore \quad r = 0.4\ \Omega$$

Q.14. Calculate the torque exerted by an 8-pole 50 Hz, 3 φ induction motor operating with a 4% slip which develops a max. Torque of 150 kgm at a speed of 660 rpm. The resistance per phase of the rotor is 0.5Ω. [2071]

Solution:

$$Ns = 120 \times \frac{50}{8} = 750 \text{ rpm}$$

Speed at maximum torque = 660 rpm

Corresponding slip,

$$S_m = \frac{750 - 660}{750} = 0.12$$

For maximum torque

$$S_m = \frac{R_2}{X_2}$$

$$\therefore \quad X_2 = \frac{0.5}{0.12} = 4.167\ \Omega$$

$$T_{max} = \frac{KE_2^2}{2X_2} \text{ ....(i)}, K = \frac{3}{2\pi N_S}; N_S \text{ at rps}$$

When slip = 4%

$$T = \frac{KE_2^2 \times 0.04 \times 0.5}{0.5^2 + (0.04 \times 4.167)^2} = \frac{0.02\ KE_2^2}{0.2778} \text{ ....(ii)}$$

Dividing (ii) by (i)

$$T_{max} = \frac{0.02\ KE_2^2}{0.2778} \times \frac{2X_2}{KE_2^2}$$

$$\therefore \quad T = 90 \text{ kg - m}$$

15. A 3 - ph, slip ring, induction motor with star connected rotor has an induced emf of 120 v between slip ring at stand still with normal voltage applied to the stator. The rotor winding has resistance per phase of 0.3 Ω & stand will leakage reactor per phase of 1.5 Ω. Calculate the current per phase when running short circuited at 4% slip. [2072]

Solution:

According to the question the emf induced between the slip rings at stand still with normal voltage applied to stator (E_2) = 120 V {line to line}.

Now, the per phase voltage is given by

$$E_2 = \frac{120}{\sqrt{3}} = 69.282 \text{ V \{rotor is star connected\}}$$

The actual emf induced when the induction motor is operating at slip of 4% is given by

$$E_R = SE_2 = 0.04 \times 69.282$$

$$\therefore \quad E_R = 2.771 \text{ V}$$

Now, to calculate the current per phase voltage

We have,

$$I_R = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} = 9.057 \text{ A}$$

16. **Calculate the torque exerted by on 8 - pole 50 Hz 3 - Ph induction motor operating with a 4% slip which develops a maximum torque of 150 kg - m at speed of 660 rpm. The resistance per phase of the rotor is 0.5 Ω.** [2073]

Solution:

$$N_S = 120 \times \frac{50}{8} = 750 \text{ rpm}$$

Speed at maximum torque = 660 rpm

Corresponding slip,

$$S_b = \frac{750 - 660}{750} = 0.12$$

For maximum torque

$$S_b = \frac{R_2}{X_2}$$

$$\therefore \quad X_2 = \frac{R_2}{S_m} = 4.167\ \Omega$$

$$T_{max} = \frac{KE_2^2}{2X_2} \text{ ....(i)}$$

where,

$$K = \frac{3}{2\pi N_S}, N_s = \text{Synchronous speed at rps}$$

when slip is 4%

$$T = \frac{KsE_2^2 R_2}{R_2^2 + s^2 X_2^2} = \frac{KE_2^2 \times 0.04 \times 0.5}{0.5^2 + (0.04 \times 4.167)^2}$$

$$\therefore \quad T = \frac{0.02\ KE_2^2}{0.2778} \text{ ....(ii)}$$

Dividing equation (ii) by (i)

$$\frac{T}{T_{max}} = \frac{0.02\ KE_2^2}{0.2778} \times \frac{2X_2}{KE_2^2}$$

$$\therefore \quad \boxed{T = 90 \text{ kg - m}}$$

17. **A 400 V, 4 - pole, 50 Hz, 3 ph, slip ring induction motor has delta connected stator winding ϕ a star connected rotor winding. At standstill the voltage between the two slip rings is 190 V. The stator impedance is 0.51 J 2.5 Ω. The rotors resistance a reactance at standstill are 0.06 Ω and 0.3 Ω respectively. It develops maximum torque of 150 N-m. Calculate:**

(a) Slip at which the motor develops the maximum torque.

(b) Torque, power output at full load, given that full load slip is 0.04 [2067]

Solution:

Given,

400 V, P = 4, f = 50 Hz, 3 - ϕ, Δ/Y

$R_1 + jX_1 = 0.5 + J\,2.5\,\Omega$

$R_2 + jX_2 = 0.06 + J\,0.3$

$T_{max} = 150$ N-m

(a) $S_m = \frac{R_2}{X_2} = \frac{0.06}{0.3} = 0.2$

(b) $T_{FL} = \frac{K\,SE_2^2\,R_2}{R_2^2 + S^2 \times X_2^2}$

$T_{max} = \frac{KE_2^2}{2X_2}$

$\therefore \quad \frac{T_{FL}}{T_{max}} = \frac{SR_2}{(R_2^2 + S^2X_2^2)} \times 2X_2 = \frac{0.04 \times 0.06 \times 2 \times 0.3}{(0.06^2 + 0.04^2 \times 0.3^2)} \times 150$

$\therefore \quad T_{FL} = 57.69$ N-m

Also,

$N_S = \frac{120f}{P} = N_S = 1500$ rpm

$N = N_S(1 - s) = 1440$ rm

$\therefore \quad P = \frac{2\pi NT}{60} = \frac{2\pi \times 1440 \times 57.69}{60} = 11.66$ HP

18. **A 8 - pole, 50 Hz, 3 - ph induction motor develops a starting torque of 50 N-m. The rotor winding has an impedance of (0.8 + j4) Ω per phase. At what speed the motor will develop maximum torque a calculate the maximum torque.** [2070]

Solution:

Given,

No. of poles (P) = 8

Frequency (f) = 50 Hz

Starting Torque (T_S) = 50 N-m

Rotor winding impedance = $R_2 + j\,X_2 = (0.8 + j4)\Omega$

We have, the general torque equation $TR = \frac{K_1 s\,E_2^2\,R_2}{R_2^2 + s_2 X_2^2}$

Now, At starting S = 1

or, $50 = \frac{K_1 E_2^2 \times 0.8}{0.8^2 + 4^2}$

$\therefore \quad K_1E_2^2 = 1040$

The motor will develop maximum torque when

$\therefore \quad S = \frac{R_2}{X_2} = \frac{0.8}{4} = 0.2$

The synchronous speed $(N_S) = \frac{120f}{P} = 750$ rpm

So, the speed at which the motor will develop maximum torque can be calculated as follows;

$S = \frac{N_S - N}{N_S} = N = 600$ rpm

$T_{max} = \frac{K_1 SE_2^2 R_2}{R_2^2 + S_2 X_2^2}$

$\therefore \quad T_{max} = 130$ Nm

19. **A 400 V, 4 - pole, 50 Hz, 3 ph, 10 HP star connected induction motor has a full slip of 4%. Given that efficiency and power factor of the motor at full load are of 92% & 0.8 lag respectively. Calculate**

(a) Synchronous speed **(b) Speed at full load**

(c) Frequency of rotor current at full load

(d) Full load torque **(e) Full load stator current** [2074]

Solution:

Given,

V = 400 V (line voltage)

P = 4,

f = 50 Hz, 3-ϕ Y CONNECTED

(a) $N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

(b) $S = \frac{N_S - N}{N_S}$

$N = N_S(1 - S) = 1500(1 - 0.04) = 1440$ rpm

(c) $f_r = sf = 0.04 \times 50 = 2$ Hz

(d) $P = \frac{2\pi NT}{60}$

$T = \frac{P \times 60}{2\pi N} = \frac{(10 \times 746) \times 60}{2\pi \times 1440}$

$\therefore \quad T = 49.471$ N-m

(e) $P_{i/p} = \sqrt{3}\,V_L I_L \cos\phi$

$\eta = \frac{P_{o/p}}{P_{i/p}} = 92\%$

$P_{i/p} = \frac{P_{o/p}}{\eta} = 10.86$ HP

$\therefore \quad P_{i/P} = 8101.56$ W

□□□

CHAPTER 6

3-Phase Synchronous Machine

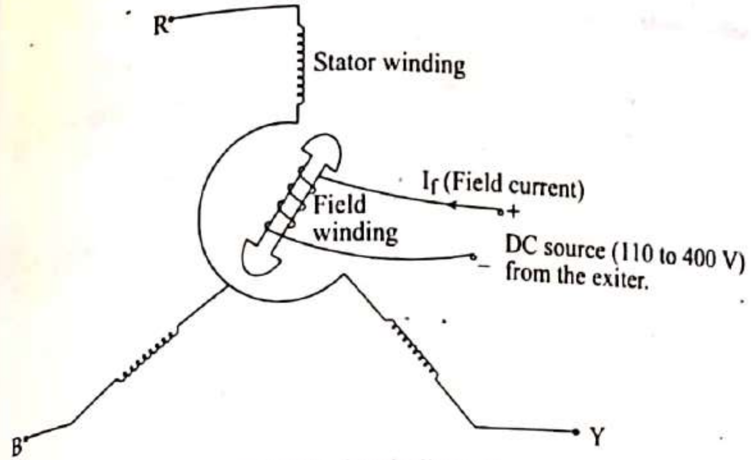
SYNCHRONOUS GENERATORS (ALTERNATORS)

- AC generators are usually called alternators because they generate AC currents and voltages.
- Rotating machines that rotate at a speed fixed by the supply frequency and the number of poles are called synchronous machines.

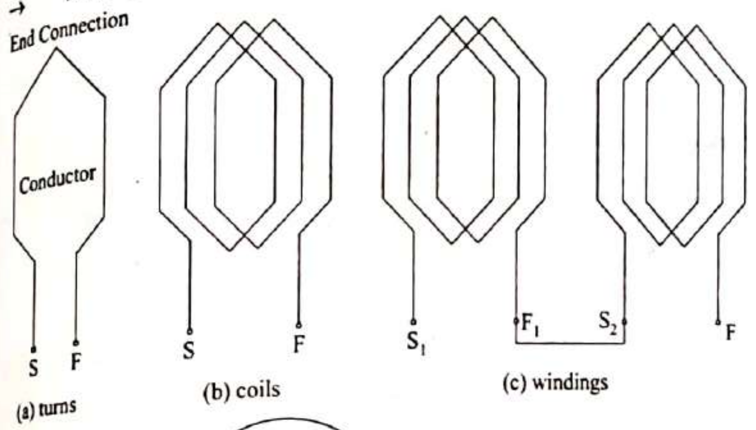
  $N_s = \frac{120f}{P}$; runs at synchronous speed
- A synchronous generator is a Machine for converting mechanical power from a prime mover to ac electric power at a specific voltage and frequency.
- Unit of synchronous generators in kVA or MVA. (Unit/specification)
- Generation voltage : 6.6kV, 11kV & 33kV
- The main parts of a synchronous generator are
  - (i) Stator or armature:
  - (ii) Rotor
  - (iii) Exciter

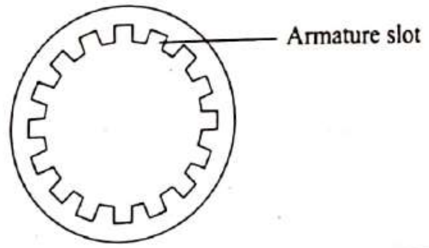
STATOR:

- It is the stationary part of the machine
- It is just like a cylinder having hollow space at the center.
- It is made up of number of circulator stamping.
- The inner circumference of the stator core has alternate number of slots and the and which stator windings are placed.
- Generally, three phase windings are provided in these slots which are uniformly distributed and each phase windings are spaced 120, electrically apart.
- The windings are insulated from the slats with the help of insulating papers.
- Stator core is protected by the outer covering called as yoke made of cast iron.



→ Windings are spaced 120° electrically apart.





ROTOR

- It is the rotating part of th machine with numbers of magnetic pole excited by the dc source (110 to 400v) form exciter.
- There are two types of rotor namely.
  - i) salient pole rotor.
  - ii) cylindrical type rotor.

Salient pole rotor:

- This type of rotor has got projected pole as shown in Fig. 1.
- Construction of this type of rotor is easier and cheaper than the cylindrical rotor.
- Salient pole rotors have concentrated windings on the poles.

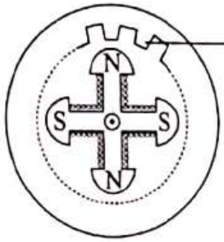


Fig. (i) Alternator with salient pole rotor.

- This type of rotors are generally used in the generators driver by low and medium speed prime movers such as $\frac{\text{water turbine}}{\text{in hydro power}}$, diesel engine.

Cylindrical type rotor.

- This type of rotor has got smooth magnetic poles in the form of a closed cylinder as shown in Fig. 2.

Fig. 2: Alternator with cylindrical type rotor

- Construction of rotor is more compact and robust with compared to salient pole rotor.
- This type of rotors are generally used in the generators driven by high speed prime movers like steam turbine, gas turbine.
- The winding is of distributed type.

EXCITER:

Exciter is a self excited dc generator mounted on the shaft of the alternators.

- This will provide dc current required to magnetize the magnetic poles of the rotor.
- The dc current generated by the exciter is fed to the field winding of the alternator through slipping and carbon brush.

$\phi \propto I_f$

WORKING PRINCIPLE OF SYNCHRONOUS GENERATOR:

- Like DC generator, synchronous are also operated in the principle of electromagnetic induction.
- But there is one important difference between the two.
- In DC generator, the field poles are stationary and armature conductors (windings) are rotating.
- But in synchronous generator, the field poles are rotating and armature conductor (stator conductors) are stationary.
- In DC generator, the field poles are stationary and armature conductors (windings) are rotating.
- But in synchronous generator, the field poles are rotating and armature conductor (stator conductors) are stationary.
- The shaft of the machine is driven by the prime mover at a constant speed equal to the synchronous speed.
- For example,

if the number of pole, P = 2; $N_s = \frac{120f}{P}$ = 3000 rpm for 50 HZ.

- The exciter (dc generator) builds up its voltage by self excitation and supplies dc current to the field winding of the main generator.
- The magnetic flux produced by the rotor poles will cut the stationary three phase stator winding.
- Hence, according to Faraday's law of electromagnetic induction, three phase emf will induce in the stator winding.
- In an actual power generating station, speed governor is used to keep the speed of the machine constant automatically at any load condition so that the frequency of generated emf is constant.

EMF equation:

Let, Z = total no. of conductors or coil sides in series per phase.

or, Z = 2T

Where, T = total no. of coils or turns per phase.

P = no. of magnetic poles in the rotor.

f = frequency of the induced emf.

ϕ = magnetic flux pole.

N = speed of the rotor in rpm.

$\therefore$ Time for N revolution of the rotor is equal to (=) 60s

" 1 " " " " " (=) $\frac{60}{N}$ s.

Each stator conductor is cut by a flux of ϕP webers.

We know,

$$\text{Average emf induced per conductor} = \frac{d\phi}{dt} = \frac{\phi P}{\frac{60}{N}} \text{ volt.}$$

Again, we know that,

$$f = \frac{PN}{120}$$

$$\therefore N = \frac{120f}{P}$$

$$\therefore \text{Average emf induced per conductor} = \frac{\phi P}{60} * N.$$

$$= \frac{\phi P}{60} * \frac{120f}{P} = 2f\phi \text{ volt;}$$

$$= 2f\phi\,(2TG)$$

$$= 4f\phi T \text{ volts.}$$

We know that,

$$\text{Form factor for sine wave} = \frac{\text{rms value}}{\text{averge value}} = 1.11$$

$\therefore$ rms value of emf induced per phase = 1.11 * 4fϕT

E_{rms}/Phase = 4.44fϕT volts ...(1)

- Besides the factors indicted by the equation (1), there are some other factors which affects the magnitude of emf induced in the stator windings.
- These factors are pitch factor and distribution factor of the stator windings.

Concentrated winding

Now considering the pitch and distributed factors, emf induced per phase

$E_{rms/phase} = 5.5 + \underbrace{k_P k_D}\, f\phi T$ votls per phase

We know, $N_S = \frac{120f}{P}$ → winding

or, $f = \frac{N_s P}{120}$

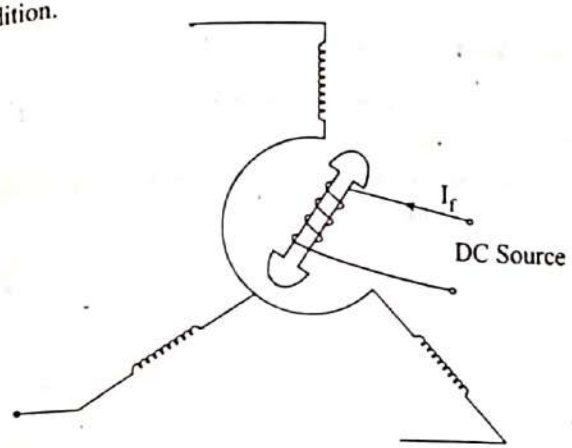
$$E_{rms/phase} = 4.44 * k_w * \frac{N_s P}{120} * \phi * T$$

$\therefore$ $E \propto N_s \phi$

The flux per pole ϕ can be controlled by changing the field current through rotor field winding.

$$\phi \alpha I_f$$

Automatic voltage regulator (AVR) is used to controlled this field excitation so that the alternator generate constant voltage at any load condition.



Advantage of Rotating field alternators:

(i) It is easier to insulate stationary armature winding for high voltage, usually 11 kV or higher rather than rotating armature.

(ii) The output current can be fed to the load directly from the fixed terminals on the stator without slip ring and brushes.

(iii) The field winding deals with low current at low voltage. Therefore, the rotating field winding can be easily insulated. Also, slip ring and brushes do not have to handle large current so that the sparking problem at slip rings minimum.

CONCENTRATED WINDINGS

- If one slot per pole or slots equal to number of poles are employed, then concentrated winding is obtained.

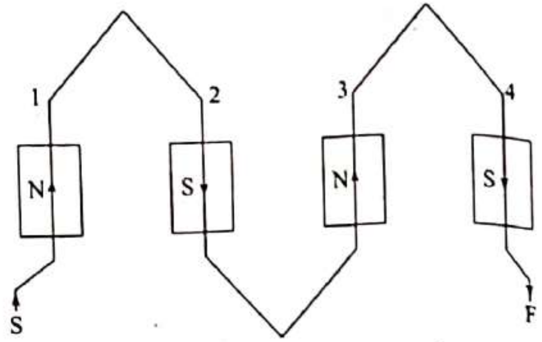


Fig. (a): Skelton wave winding (Concentrated winding).

- In this winding the number of conductors or coil sides is equal to the number of poles.

Alternators with load: (or Alternator on load)

- The stator of the synchronous generator has three sets of winding on which emfs are induced.
- Usually these three windings are 'star' connected and the neutral is earthed as shown in Fig.

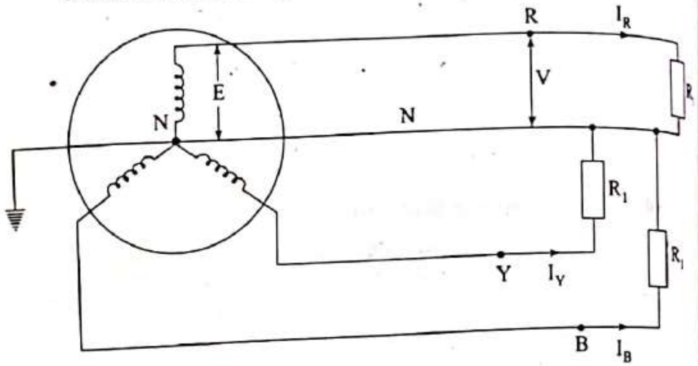


Fig. Alternator with load.

- When the generator is loaded current will flow through the stator winding and some voltage drop will take place in the stator winding.
- Let, E = emf induced per phase in the stator winding.
- At no-load operation, the terminal voltage V will be equal to the emf induced (E).

But at loaded operation, the terminal V will be equal to the emf induced (E) due to following three reasons:

(i) Voltage drop due to armature winding (R_a).

(ii) Voltage drop due to leakage reactance of armature winding (X_L)

(iii) Armature reaction.

If the effect of armature reaction is neglected, the terminal voltage is given by

$$\vec{V} = \vec{E} - \vec{I}_a R_a - j\vec{I}_a X_L$$

or, $\vec{E} = \vec{V} + \vec{I}_a + j\vec{I}_a X_L$

or, $\vec{E} = \vec{V} + \vec{I}_a + (R_a + jX_L)$

$\therefore$ $\vec{E} = \vec{V} + \vec{I}_a Z_s$

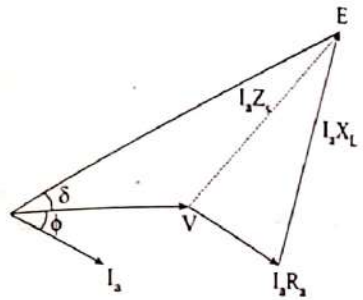


Fig. Phase diagram.

Armature Reaction:

- The effect of armature (stator) flux on the fluxed produced by the rotor field poles is called armature reaction.
- When the synchronous generator is loaded with external load, current will flow through the armature windings.
- The current carrying armature winding produces its own magnetic field which is also rotating in nature.
- The effect of this armature field on the field produced by the rotor is known as armature reaction.
- The nature of armature reaction depends on the power factor of the load.

(1) When the load is resistive: (Unity power factor):

- If the load is purely resistive i.e. power factor is equal to 1, the[re] is no phase difference between the terminal voltage (v) and th[e] armature current.
- Since the nature of the armature flux will be in phase w[ith] armature current, the magnitude flux produced by three pha[se] windings will have similar wave form as that of the termin[al] voltage as shown in Fig. 1(a) & 1(b)

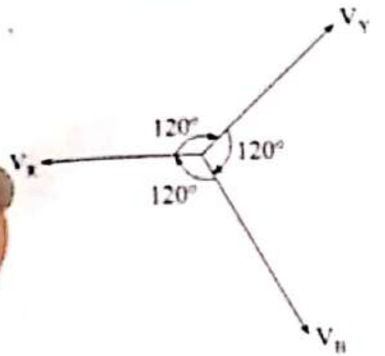
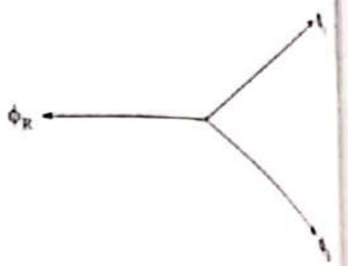


Fig. 1(a) Phasor diagram of generated voltage



1(b) Phasor diagram of armature flux.

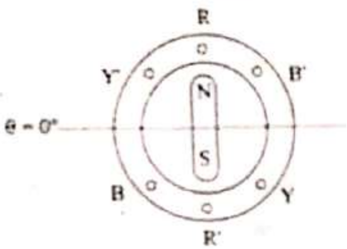


Fig. 1(c): Position after 90° rotation

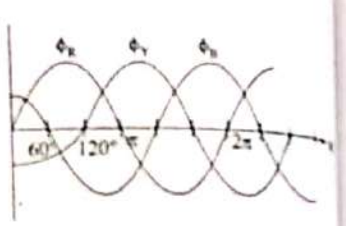


Fig. 1(d): Wave form armature flux

At $\omega t = 90°$,

$\phi_R = \phi_m \sin\omega t = \phi_m \sin 90° = \phi_m$

$\phi_Y = \phi_m \sin(\omega t - 120°) = -\frac{1}{2}\phi_m$

$\phi_B = \phi_m \sin(\omega t - 240°) = -\frac{1}{2}\phi_m$

- When the magnet rotates 90° from its zero position, voltage and current in the R-coil will be positive maximum and voltage and current in the Y-coil and B-coil will be negative.
- Then the net magnetic flux set up by armature is given by the vector sum of ϕ_R, ϕ_Y and ϕ_B.

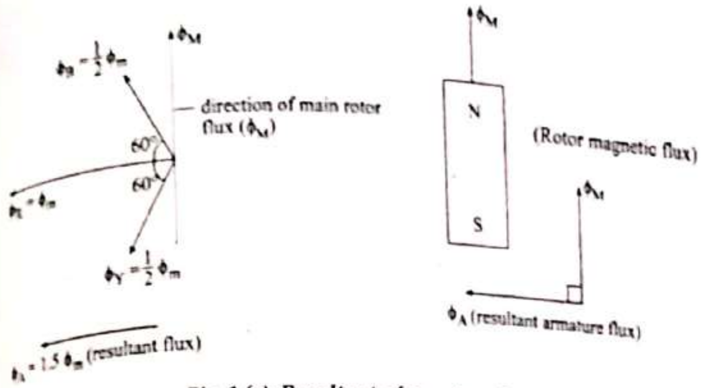


Fig. 1 (e): Resultant of armature flux.

- According to Fig. 1(e), the resultant flux, $\phi_A = 1.5\,\phi_m$ whose direction lags by an angel of 90° with the direction of main flux ϕ_M produced by the rotor.
- Both of these flux rotates with the same speed in the same direction.
- Therefore, at every instant, the armature reaction flux (ϕ_A) try to distort the main flux ϕ_M. This type of flux is called cross-magnetizing flux.

(2) When the load is inductive (Lagging power factor)

- The load current logs the voltage 'V' by an angel of 'α' in the case of the inductive load.
- Hence, the resultant armature flux (ϕ_A) lags the main flux (ϕ_M) by an angle of (90° + α) as showing in Fig. 2.

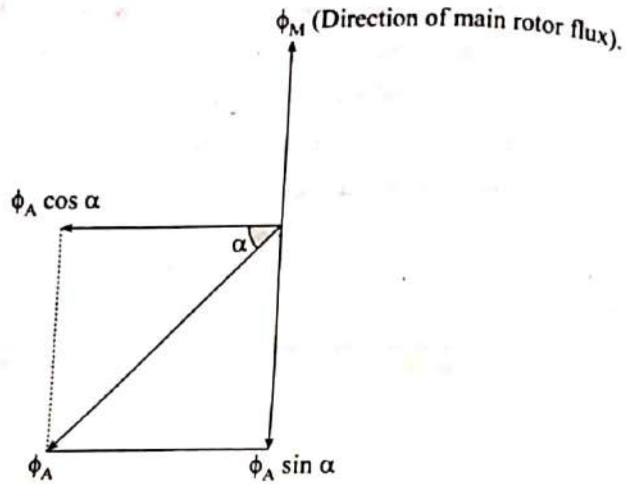
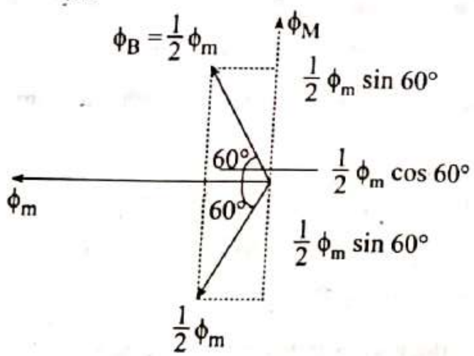


Fig. 2. Phasor diagram of main flux and armature flux fo inductive load.

- The armature flux ϕ_A has two components.

(i) $\phi_A \sin\alpha$ - component along with the direction opposite to ϕ_M.
  - This component is known as demagnetizing component.
  - It opposes ϕ_M.

(ii) $\phi_A \cos\alpha$ - component along the direction perpendicular to ϕ_M.
  - This component is known as cross-magnetizing component.
  - It distorts ϕ_M.



for resistive load

$$\phi_n = -\phi_m - \frac{1}{2}\phi_m \cos 60° - \frac{1}{2}\phi_m \cos 60°$$

$$= -\phi_m - \frac{1}{2}\phi_m \cdot \frac{1}{2} - \frac{1}{2}\phi_m = -1.5\,\phi_m$$

$$\phi_V = \frac{1}{2}\phi_m \sin 60° - 1/2\,\phi_m \sin 60° = 0$$

$$\phi_r = \sqrt{\phi_n^2 + \phi_v^2} = 1.5\,\phi_m.$$

(3) **When the load is capactive: (Leading Power factor)**

- The load current leads the voltage 'V' by an angle of 'α' in the case of the capacitive load.
- Then the waveforms of armature flux will also lead by an angel of 'α' with respect to that in the case of resistive load.
- Hence, the resultant armature flux (ϕ_A) lags the main flux (ϕ_m) by an angel of (90° - α) as shown in Fig. 36.

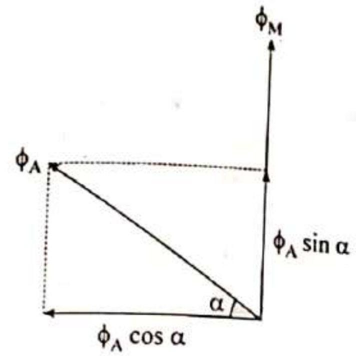


Fig. 3 Phasor diagram of main flux and armature flux for capacitive load.

- Here, the armature flux (ϕ_A) has two components.

(i) $\phi_A \sin\alpha$- component along the direction of ϕ_M.
  - This component is known as magnetizing copmponent
  - It supports ϕ_M.

(ii) $\phi_A \cos\alpha$ -0 component along the direction perpendicular to ϕ_M.
  - This component is known as cross - magnetizing component
  - It distorts ϕ_M.

- Thus, the armature flux distorts the main flux and tries to change the magnitude depending on the power factor of the load.
- This causes change in the voltage obtained at the terminate of the generator.
- The $I_{aq}X_a$ represents the voltage drop due to armature reaction.

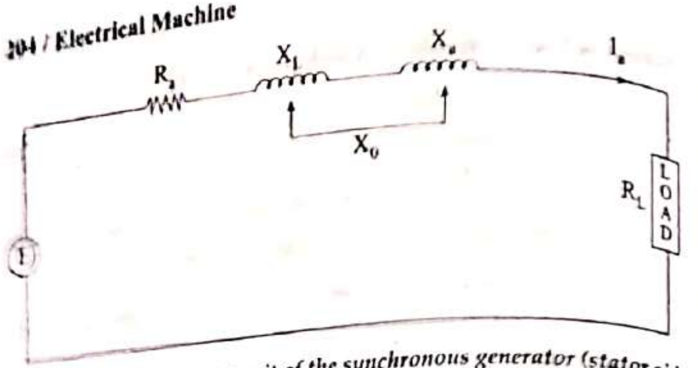


Fig. 4 Equivalent circuit of the synchronous generator (stator side)

Where, E = per phase no-load voltage.

R = armature resistance.

X_L = leakage reactance of armature.

X_a = reactance corresponding to armature reaction.

- X_L and X_a can be combined and represented by

$X_S = X_L + X_a$

Where, X_s is known as synchromous reactance.

Then, total impedance of the circuit is given by

$Z_s = R_a + j(X_L = V_a)$

$\boxed{Z_s = Ra + jX_s}$

Where, Z_s is also called synchromous impedance.

Here,

$E = V + I_aR_a + jI_aX_L + jI_aX_a$

$E = V + I_a(R_a + jX_s)$

$\therefore \boxed{E = V + I_aZ_s}$

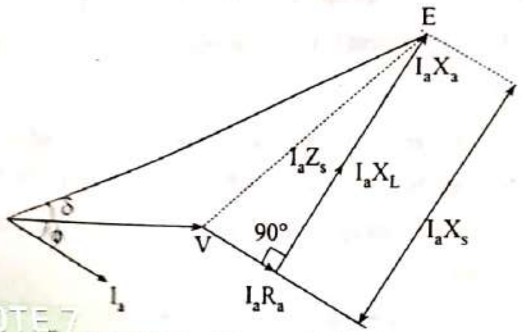


Figure. 5. Phasor diagram for logging current.

I_aR_a - voltage drop due to armature winding resistance.

I_aX_L = voltage drop due to leakage reactance of armature winding.

I_aX_a = voltage drop due to armature reaction.

Summary of nature of armature reaction.

i) The armature reaction flux is constant in magnitude and rotates at synchronous speed.

ii) The armature reaction is cross-magnetizing when the generator supplies a load at unity power factor.

iii) When the generator supplies a load at logging power factor, the armature reaction is partly demagnetizing and partly cross magnetizing.

iv) When the generator supplies a load at leading power factor, the armature reaction is partly magnetizing and partly cross magnetizing.

v) IN all cases, if the armature reaction flux is assumed to act independently of the main flux, it induces voltage in each phase which lags the respective phase currents by 90°.

Voltage Regulation:-

- When the load on the generator change: from no-load to full load, assuming that the generator running constant speed and constant excitation, the terminal voltage across the load will change due to voltage drops in internal resistance and reactance of the stator winding.
- The magnitude and the nature of these voltage depends on the power factor of the load.
- As the effect of armature reaction could be cross magnetizing, demagnetizing or magnetizing according to the resistive, inductive or captive loads respectively, the terminal voltage may increase or decrease with increase in load.

(a) Unity power factor:

- The generated emf 'E' is the phasor sum of terminal voltage 'V', IR_a drop and IX_s drop.
- Here, the terminal voltage 'V' is less than the no-load emf 'E'.

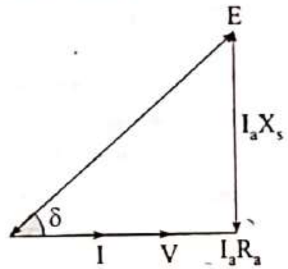


Fig: 1(a): Phasor diagram for unity power factor.

(b) **Lagging power factor:**

- In this case, I lags V by an angle of 'ϕ' an in Fig 1(b).
- Here also the terminal voltage 'V' is less than load emf 'E'.

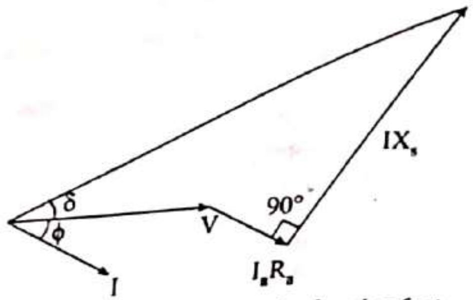


Fig. 1(b) Phasor diagram for lagging factor.

(c) **Leading power factor:**

- In this case, the terminal voltage could be greater than emf 'E' as shown in Fig.. 1 (c).

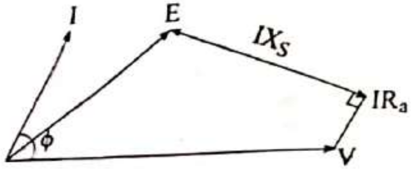


Fig: 1. (c) Phasor diagram for leading power

E - magnitude of generated voltage per phase.

V - magnitude of rated terminal voltage per phase.

The voltage regulation of a synchronous generator is defined as the percentage rise in voltage at the terminals when the load is reduced from full-load rated value to zero, the speed and field current (excitation) remaining constant.

$$\text{Voltage regulation\%} = \frac{E - V}{V} \times 100$$

Where, E = magnitude of no-load voltage per phase.

V = magnitude of full load voltage per phase.

- The voltage regulation depends on the power factor of the load.
- For unity and lagging power factors, there is always a voltage drop with the increase of load, but for a certain leading power factor the full-load voltage regulation is zero.

- Fig. 1(d) shows voltage regulation curves for lagging power factor, unity power factor and leading power factor.

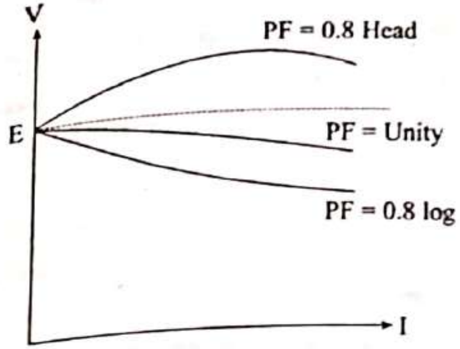


Fig. 1(d): Voltage regulation curve

PARALLEL OPERATION OF ALTERNATORS:

- Electric power system are interconnected for economy and reliable operation.
- In an actual power system, there are two or more than two alternators running in parallel.
- So that required number of alternators can be connected to the system according to consumers demand.
- The process of connecting two alternators in parallel is known as "synchronization".
- In an interconnected power system, many number of alternators at various stations will be connected in parallel through bus bars at station and transmission lines.
- In such a system an alternator will be synchronized to an infinite bus bar on which any number of alternators had been already connected.
- An infinite bus bar is the bus bar whose voltage and frequency is independent and constant with the load.
- They are connected in parallel by means of transformers and transmission lines.

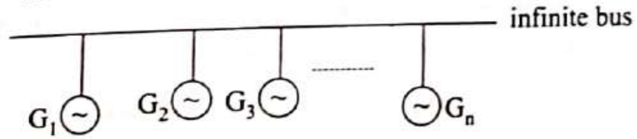


Fig.

REASONS OF PARALLEL OPERATION

- Alternators are operated in parallel for the following reasons:
- Several alternators can supply a bigger load than a single alternator.

(1) During period of light load, one or more alternators may be shut down, and those remaining operate at or near full load, and thus more efficiently.

(2) When one machine is taken out of service for its scheduled maintenance and inspection, the remaining machines maintain the continuity of supply.

(3) If there is a breakdown of a generator, there is no interruption of the power supply.

(4) In order to meet the increasing future demand of load more machines can be added without disturbing the original installation.

(5) The operating cast and cost of energy generated are reduced when several generators operate in parallel.

NECESSARY CONDITIONS FOR PARALLELING ALTERNATORS

- For proper synchronization of two alternators or synchronizing an alternator to the infinite bus bar, the following conditions should be satisfied.

(i) The terminal voltage of both alternators should be equal.

(ii) The frequency of both alternators must be equal.

(iii) The waveforms of emf generated by both alternate should be in phase.

(iv) The percentage impedance of both alternators should be same.

(v) The phase sequence of both alternators must be same.

- When two alternators are operating so that all the above requirements are fulfilled, they are said to be in synchnorism.
- The process of connecting them in synchnosim is called as synchronization.

- The current shared by two alternators running in parallel should be proportional to their MVA ratings.
- The current carried by these alternators are inversely proportional to their internal impedance.
- From the above tow statements it can be said that impedance of alternators running in parallel are inversely proportional to this MVA ratings. In other words percentage impedance should be identical for all the alternators run in parallel.
- Before an alternator is synchronized with other generators for the first time, its phase sequence must be checked to determine that it has same phase sequence as that of the other alternators.
- The phase sequence can be checked by a phase sequence indicator as showing in Fig. 1
- It is a small three phase induction motor that rotates in one direction for one phase sequence and in opposite direction for the other phase sequence.
- If the motor rotates is the same direction with both voltage of the running alternator (G1) and incoming generator (G_2) when connected separately, then it is clear that the both alternators have same phase sequence.
- Fig. 1 shows the connection diagram for synchronizing two alternators.
- G_1 is the alternator which already running and supplying current to the load.
- G_2 is the second alternator which is to be connected in parallel with G_1.
- Voltammeter V_1 measures the main bus bar voltage and voltmeter V_2 measures the output voltage of generator G_2.

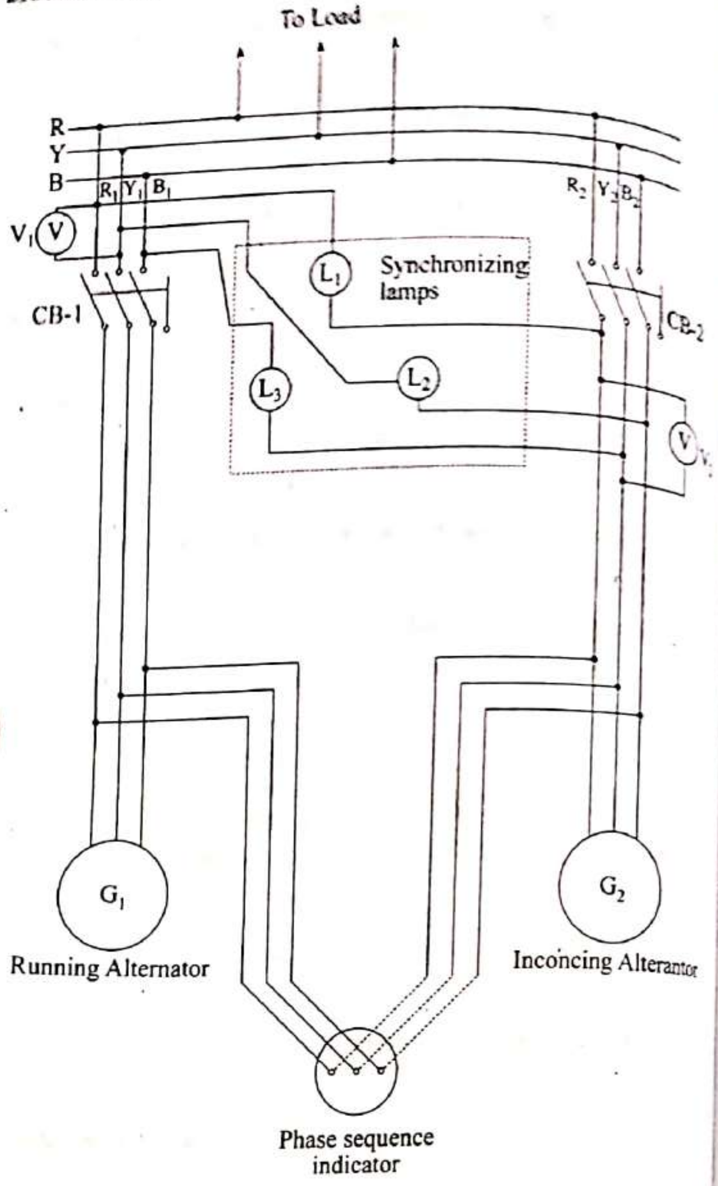


Fig. 1: Connection diagram for synchronization of two alternators.

- L_1, L_2 and L_3 are three lamps placed physically in triangular form.
- These lamps are known as synchronizing lamps.

- L_1 is connected across R_1 and R_2.
- L_2 is connected across Y_1 and B_2.
- L_3 is connected across B_1 and Y_2.
- The incoming generator G_2 is rotated by its prime mover approximately up to its synchronous speed keeping the CB-2 open.
- The excitation of G_2 is adjusted so that the voltage generated by the incoming generator, as measured by V_2, is to match the main bus bar voltage, as measured by V_1.
- The synchronizing lamps are used to make sure that the voltage generated by G_2 is in phase with bus bar voltage and the frequency of incoming generator is same as that of the bus bar frequency.
- Voltage stars (phasor diagram) of two machines are shown superimposed on each other in Fig.1 2(a).
- If the frequencies of the both voltage stars are equal, both vectors rotated with the same speed and the difference between R_1 and R_2, Y_1 and B_2, B_1 and Y_2 remains constant.
- Hence at this condition, L_1 remain dark and L_2 and L_3 will glow with equal brightness, then in such situation the CB-2 of the incoming generator can be closed so that both generators operates in parallel.
- If the frequency of the increasing generator G_2 is greater than that of the running generator G_1, then R_2 - Y_2 - B_2 vectors rotates faster than the R_1- V_1 - B_1 vectors as shown in Fig. 2(b).
- In such a situation, voltage across the L_1 goes on increasing, voltage across the L_2 goes on decreasing and the voltage across the L_3 goes in increasing.
- After some time, the vectors B_2 and Y_1 will get coincide resulting in L_2 dark.
- Hence the light gets dark one after another in anti-clockwise direction.
- In such a situation, the speed of the increasing generator G_2 has to be reduced until the situation is as shown in Fig. 2(a), then the CB-2 of the increasing generator can be closed so that both generators operates in parallel.

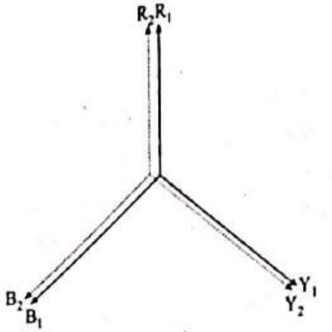


Fig. 2(a)

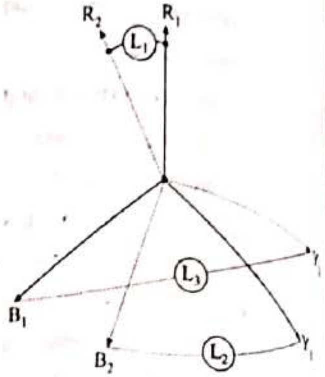


Fig. 2(b)

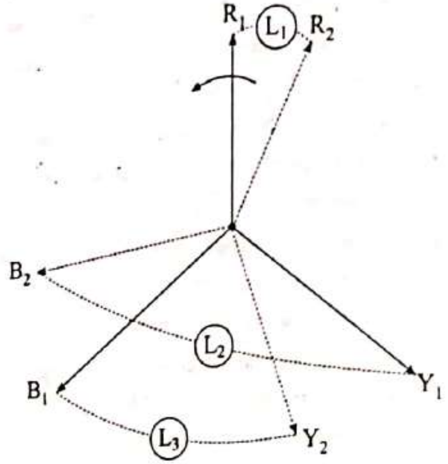


Fig. 2(c)

- If the frequency of the incoming generator G_2 is less than that of the running generator G_1, then R_2 - Y_2 - B_2 vectors rotates slower than the R_1- Y_1 - B_1 vectors as shear in Fig. 2(c).
- In such a situation, voltage across the L_1 goes on increasing, voltage across the L_3 goes on decreasing and voltage across the L_2 goes on increasing.
- After some time, the vectors B_1 and Y_2 will get coincide resulting in L_3 dark.
- Hence the light gets dark one after another in clockwise direction.
- In such a situation, the speed of the incoming generator G_2 has to be increased until the situation is as showing in Fig. 1(a), then the CB-2 of the incoming generator can be closed so that both generators operates in parallel.

INFINITE BUS

- The system behaves like a large generator having virtually zero internal impedance and infinite rotational inertia.
- Such a system of constant voltage and constant frequency regardless of the load is called infinite busbar system or simply infinite bus.
- Thus, an infinite bus is a power system so large that its voltage and frequency remain constant regardless of how much real and reactive power is drawn from or supplied to it.
- The characteristics of an infinite bus are as follows:

a) The terminal voltage remains constant, because the incoming machine are two small to increase or decrease it.

b) The frequency remains constant, because the rotational inertia are two large to enable the increasing machine to alter the speed of the system, and

c) the synchronous impedance is very small since the system has a large number of alternators in parallel.

An alternator connected to an infinites bus has the following operating characteristics:

i) The terminal voltage and frequency of the generator controlled by the system to which it is connected.

ii) The governor set paints of the alternator control the real power supplied by the alternator to the infinite bus.

iii) The field current (excitation) in the alternator controlled the reactive power supplied by the alternator to the infinite bus. Increasing the field current in the alternator operation in parallel with an infinite bus increases the reactive power output of the alternator.

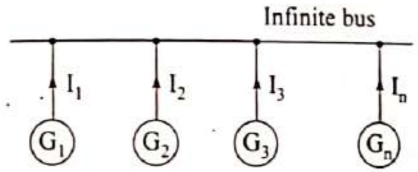
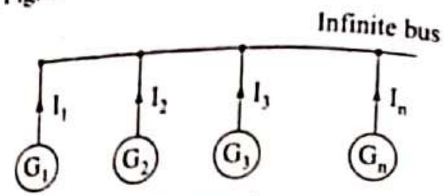


Fig. Infinite bus system.

Obtaining an infinite bus:

Consider n generators G_1, G_2,.....G_n connected to an infinite b... shown in Fig. 1.



(a) Proof of voltage remaining constant

Let,

V = terminal voltage of the bus

E = induced emf of each generator

Z_s = synchronous impedance of each generator

n = number of generators in parallel.

$V = E - IZeq$

where, $Z_{seq} = \frac{Z_s}{n}$

When n is very large, $Z_{seq} \to 0$.

$\therefore$ V = E (constant)

(b) Proof of frequency remaining constant

Let,

J = moment of inertia of each gernator

Total moment of inertia of all n alternators

$= J + J + J + ... + J + (\text{times}) = nJ.$

$$\text{Acceleration of alternator} = \frac{\text{accelerating torque}}{\text{momnet of inertia}}$$

$$= \frac{T_a}{\Sigma J} = \frac{T_a}{nJ}$$

If n is very large, nJ is very large.

and speed is constant.

- Consequently, frequency is constant.
- Therefore, in order to obtain a constant-voltage, constan... frequency of a practical busbar system, the number of alternat... connected in parallel should be as large as possible.

EQUIVALENT CIRCUIT OF A SYNCHROMOUS GENERATOR.

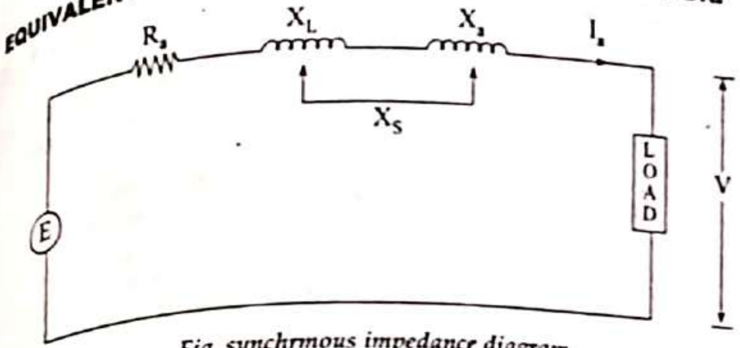


Fig. synchrmous impedance diagram.

$E = V + I_aR_a + jI_aX_L + JI_aX_a$

$E = V + I_a(R + jX_s)$

$\therefore E = V + I_aZ_s$

$\therefore V = E - I_aZ_s$

3-ϕ SYNCHRONOUS MOTOR

- A synchronous motor is a machine that converts ac electric power to mechanical power at a constant speed called synchronous speed.
- A synchronous motor is a "doubly-excited machine"
- Its rotor poles are excited by direct current (dc) and its stator windings are connected to the ac supply.
- The air gap flux is, therefore, the resultant of the fluxes due to both rotor current and stator current.
- In fact, a given synchronous generator can also be used as a synchronous motors.
- Some characteristic features of a synchronous motor are as follows:
  - i) It runs either at synchronous speed or not all that is while running it maintains a constant speed equal to the synchronous speed.
  - ii) It is not self-starting. It has to be run upto synchronous speed by some means before it can be synchronized to the supply.
  - iii) It can be operated under wide range of power factors both lagging and leading.

OPERATING PRINCIPLE:

- Synchronous motor is not self starting.
- When the stator windings are supplied by three phase voltage, the rotating magnetic field is produced in the air gap.

- The stator field rotates at synchronous speed.
- At the same time if the rotor field windings are excited by current, the rotor poles will get magnetized.
- But the interaction between stator magnetic field and rotor magnetic field will not be able to produce a continuous rotation.
- This facts can be explained as follow.
- At starting the position of rotor poles could have many alternative positions relative to the stator poles as shown in Fig.
- If the relative position between rotor poles and stator poles at the starting is as shown in Fig. 1(a), the like poles will get repel and the tendency of the rotor will be to rotate in anti-clockwise direction.
- This facts can be explained as follow.
- At starting the position of rotor poles could have many alternative positions relative to the stator poles as shown in Fig 1.
- If the relative position between rotor poles and stator poles at the starting is as shown in Fig. 1(a), the like poles will get repel and the tendency of the rotor will be to rotate in anti-clockwise direction.
- But after some time, the N-poles of the stator and s-pole of the rotor comes face to face.
- Then these opposite poles will try to get attract with each other, then the tendency of the rotor will be to rotate in clockwise direction.
- But the heavy mass of the rotor cannot response to such a quick reversal of direction of rotation.
- Hence the rotor remains at rest.

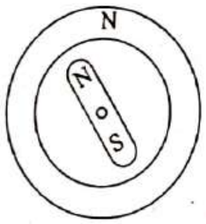


Fig. 1(a)

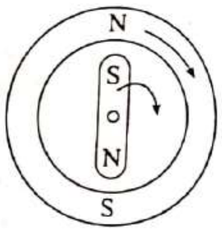


Fig. 1(b)

- If the relative position blow rotor poles and stator poles at the starring is as shown in Fig. 1(b), the unlike poles will et attract and the tendency of the rotor will be to rotate in clockwise direction along with the stators poles.

- But the heavy mass of the rotor cannot pickup the synchronous speed immediately.
- Therefore, after some time, N-pole of the stator and N-pole of the rotor comes face to face.
- Now the like poles repels each other and the tendency of the rotor will be to rotate in anti-clockwise direction.
- But the heavy mass of the rotor cannot response to such a quick reversal of direction of rotation.
- Hence the rotor remains at rest.
- If the relative position between rotor poles and stator poles at the starting is as shown in Fig. 1(c), the like poles will get repel and the tendency of the rotors will be to rotate in anti-clockwise direction.
- But after some time, the N-pole of the stator and s-pole of the rotor comes face to face.

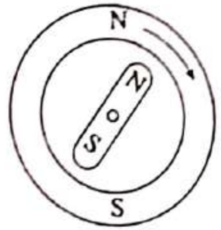


Fig. 1(c)

- Then these opposite poles will try to get attract with each other, then the tendency of the rotor will be to rotate in clockwise direction.
- But the heavy mass of the rotor cannot response to such a quick reversal of direction of rotation.
- Hence the rotor remains at rest.
- Hence, at any position, the motor is not self-starting.
- If the rotor is rotated upto or near to the synchronous speed, before supplying voltage to the stator, by some auxiliary means without exacting the rotor field winding and then stator and field are excited by their respective supply,. the rotor poles will get magnetically locked up into synchronous with the stator poles, then the rotor rotates continuously even the auxiliary means is removed.

STARTING METHODS:

- A synchronous motor is not self-starting.
- It can be started by the following methods.

i) A dc motor coupled to the shaft of synchronous motor.
ii) Using field exciter of synchronous motor as dc motor.
iii) A small induction motor of at least one part of poles less than the synchronous motor. (pony motor).
iv) Using damper winding as a squirrel cage induction motor.

- In the first method, the unexcited rotor is rotated by means of a dc motor coupled to the shaft of the synchronous motor.
  - The speed of the dc motor is adjusted by its field regulator.
  - As the speed reaches near to synchronous speed, the field winding of the synchronous motor is excited y the dc current and the dc motor is switched off.
  - Then the motor continuously rotates with synchronous speed.
- The second method is similar to the first method except that the exciter of the synchronous motor (i.e. a dc shunt generator) is operated as dc motor for the time being and as the speed reaches close to the synchronous speed, the dc machine is again used as exciter.
- The third method, using an auxiliary induction motor with at least one pair of pole less involves the same synchronizing process as that of the first method.
- Most of the modern synchronous motors are started with the help of the damper windings.
- Fig. 2 shows the constructional detail of a rotor pole having damper winding.

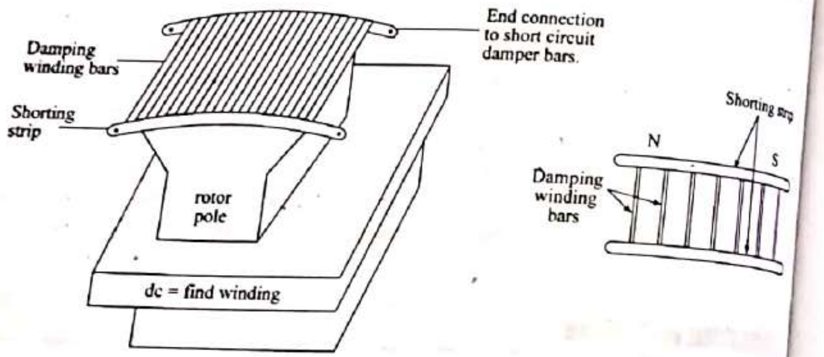


Fig. 2: Rotor pole with damper winding.

- It should be noted that the shorting strip, which short circuit the rotor bars, contains holes for bolting to the most set of damper winding on the next pole.
- In this way, a complete squirrel cage winding is formed.
- Although the bars are not of the capacity to carry the rated synchronous motor load, they are sufficient.

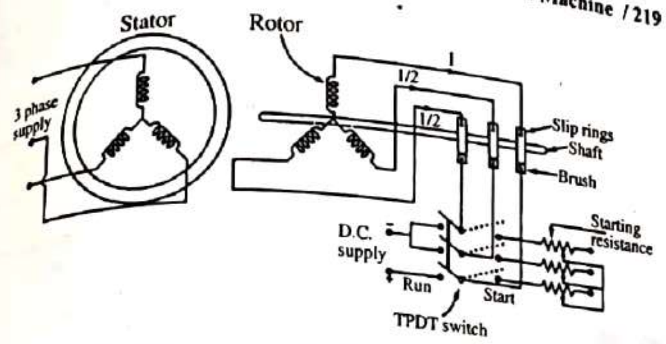


Fig. 3: Synchronous motor starting with phase wound damper winding to start the motor as induction motor.

- Start-Delta or auto transformer methods are used to reduce the starting current drawn by the motor.
- It is particularly impossible to start a synchronous motor its field excited.
- Even with unexcited condition, the rapidly rotating magnetic field of the stator will induce extremely high collage in many turns of the field winding.
- Therefore, it is better to short circuit dc field widening during the starring period, whatever voltage and current are induced in it may then aid in producing induction motor action.
- All the above method shall be used with the synchromesh without load.
- In order to start the synchronous motor with load, phase wound damper winding shall be used that external resistance can be inserted to produce high starting torque.
- Fig. 3 shows the schematic diagram of phase would damper winding for starting synchronous motor.
- Such motor will have rotor with five slip rings.
- Two for the dc field excitation and three for a star connected wound damper winding.
- the motor is started with full external resistance per phase and dc field circuit open.
- As the motor approaches synchronous speed, the starting resistance is reduced and, when the field voltage is applied, the motor pulls into synchronism.
- Today the most widely used method of starting a synchronous motor is to use damper windings.

- A damper winding consists of heavy copper bars inserted in slots of the pole faces of the rotor as shown in Fig.1 2. These bars are short, circuited by end rings at both ends of the rotor.
- Thus, these short-circuited bars form a squirrel cage winding.
- When a 3-ϕ supply is connected to the stator, the synchronous motor with damper winding will start as a 3-ϕ induction motor.
- As the motor approaches synchronous speed, the dc excitation is applied to the field windings.
- The rotor will then pull into step with the stator magnetic field and then the synchronous motor runs as synchronous speed.

NO-LOAD AND LOADED OPERATION

- A synchronous motor is not self-starting.
- It has to be speeded up to synchronizes spord by some auxiliary means.
- The supply to the dc winding of the rotor has to be switched on, then the rotor poles will get magnetically locked up with stator poles.
- However, the engagement between the stator and rotor poles is not absolutely rigid one.
- As the load on the motor increases, the rotor progressively tends to fall back in phase (but not in speed) by some angle, but the motor still continuous to run with the synchronous sped.
- At no-load, if there is no power loss in the motor, the stator poles and rotor poles will be along the same axis and phase difference between the applied voltage 'V' and the back emf 'E_b' (developed in the armature winding) will be exactly 180° sec Fig. 1(a).
- But this is not possible in practice, because some power loss takes place due to iron loss and friction loss.
- Hence, the rotor pole lags by some angel 'α' with the stator pole and the phasor diagram will be as shown in Fig. 1(b).
- The angular displacement between the rotor and stator place 'α' with the stator pole and the phasor diagram will be as showing in Fig. 1(b).
- The current drawn by armature at no-load is given by

$$I_a = \frac{\vec{V} - \vec{E_0}}{Z_s} - \frac{E_R}{Z_s}$$

Where, E_R = Net voltage across the armature.

Z_s = synchronous impedance per phase.

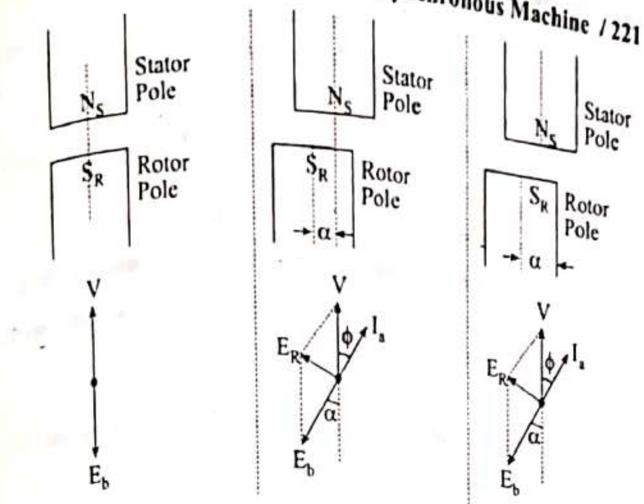


Fig. 1(a) (No-load, No-loss) Fig. 1(b) (No-load) Fig. 1(c) With-load

- In the case of dc motor, the speed of the armature decreases with increase in load, due to which the back emf will decrease and then the armature current will increase to overcome the increased load.
- But in the case of synchronous motor, the speed does not change with load.
- When the load on a synchronous motor increase, the rotor poles lags the stator poles by larger angle 'α' and the phase angle between V and E_b will increase < not that magnitude of E_b will-remain constant) so that the net voltage E_R will increase and the armature current will increase.

EFFECT OF EXCITATION:

- The dc current supply to the rotor field winding is known as excitation in synchronous motor.
- As the speed of synchronous motor is constant, the magnitude of back emf remains constant provided the flux per pole produced by the rotor does not change.
- So the magnitude of back emf can be changed by field excitation.
- By changing the excitation, the motor can be operated at both lagging and leading power factor.
- This fact can be explained by following analysis:
- The value of excitation for which the magnitude of back emf σ_b is equal to applied voltage V is known as 100% excitation.

- If the excitation is more than 100%, then the motor is said to be over excited and if the excitation is less than 100%, then the motor is said to be under excited.
- Consider a synchronous motor operating with a constant load.
- Fig. 1(a) shows the phasor diagram of the case of 100% excitation that is when E_b= V (in magnitude)
- The armature current I_a lags behind V by a small angle 'ϕ'.
- 'θ' is the phase angle between I_a and E_R whose magnitude is given by, $\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$.
- Since X_s and R_a are constant, angle θ also remains constant.
- if the motor is under excited, the magnitude of E_b will be less than V.
- Therefore, the resultant of E_b and V(i.e. E_R) will shift upward by some angle, then the direction of I_a will also shift by same angle so that angle 'θ' again remain constant as shown in Fig. 1(b).
- Here the magnitude of I_a has increased and I_a lags V by grater angle so that power factor is decreased, but the active component $I_a \cos\phi$ remains same so that output power also remains constant.
- Fig.1(c) represents the condition for overexcited motor (i.e. when E_b>V).
- Therefore, the resultant voltage vector E_R is pulled in the anti-clockwise and I_a is also shifted in anti-clockwise and I_a is also shifted in anti-clockwise direction.
- It is seen that now motor is drawing a leading current.
- It may also happen for same value of excitation, that I_a may be in phase with V i.e. power factor is unity as shown in Fig. 1(d).
- At this instant the current drawn by motor is minimum.

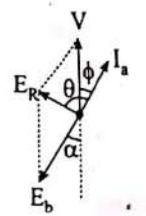


Fig. 1(a) 100% excitation

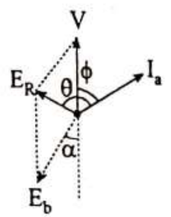


Fig. 1(b) under excitation

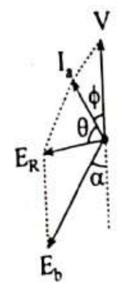


Fig. 1(c) over excitation

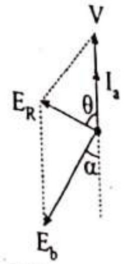


Fig. 1(d) Unity power factor

The following two important points shall be understand clearly form the above discussion:

i) The magnitude of armature current varies with excitation. The current has larger values at both low and high values of excitation.

In between, it has minimum value corresponding to a certain excitation for which power factor is unity. The variation of I_a with excitation are shown in Fig. 2 which are known as 'V' curve.

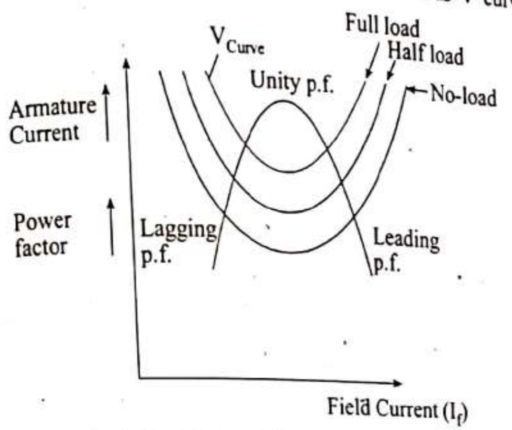


Fig. 2: V and inverted V-curves.

ii) For the same input, armature current varies between a wide range and power factor also vary accordingly with excitation.

When over excited, motor runs with leading power factor and the motor runs with lagging power factor when under excited.

The variation of power factor with excitation is also shown in Fig. 2 and known as inverted V curves. it would be noted that minimum armature current corresponds to unity power factor.

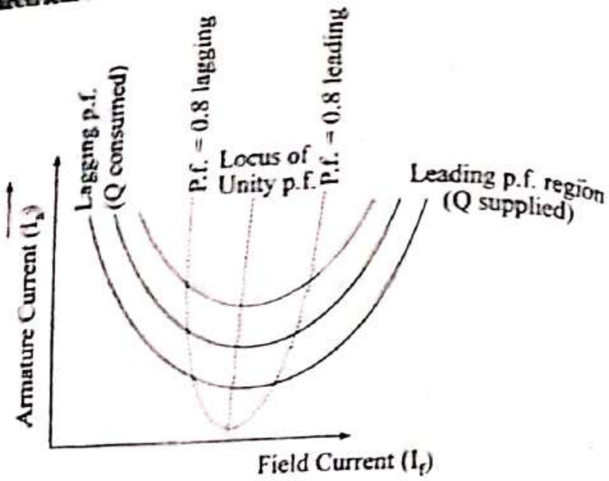


Fig. V-curves of a synchronous motor.

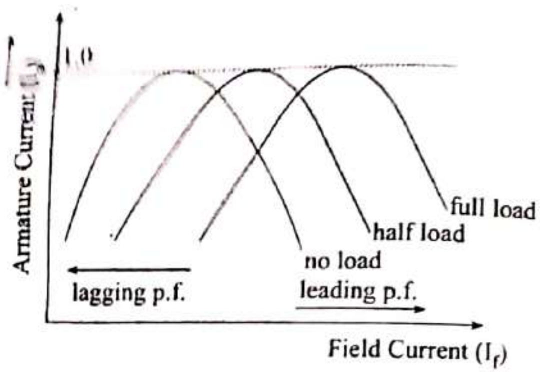


Fig. Pf versus field current at different loads (Inverted V-curves).

Comparison of Various Excitations

Type of Excitation	Comparison of E and V	Nature of P.F.	Armature Cuttente I
Normal excitation	E = V	lagging	Increased I
Under "	E<V	"	"
Over "	E>V	leading	"
Critical "	E>V	Unity	Minimum I

...TING OR PHASE SWINGING

- A steady-state operation of a synchronous motor is a condition of equilibrium in which the electromagnetic torque is equal and opposite to the load torque.
- In the steady sate, the rotor runs at synchronous speed, thereby maintaining a constant value of the torque.
- If there is a sudden change in the load torque, the equilibrium is disturbed , and there is a resulting torque which changes the speed of the motor. It is given by

$$T_e - T_{load} = J\frac{d\omega_m}{dt} \quad ...(i)$$

Where,

J = moment of inertia

ω_m = angular velocity of the rotor in mechanical units.

- When there is a sudden increase in the load torque, the motor slows down temporarily and the torque angle δ is sufficiently increased to restore the torque equilibrium and the synchronous speed.
- The electromagnetic torque is given by

$$T_e = \frac{3VE_f}{\omega_s X}\sin\delta \quad ...(2)$$

- Since δ is increased, the electromagnetic torque increases. consequently, the motor is accelerated.
- When the rotor reaches synchronous sped, the torque angle δ is larger than the required value δ_1 for the new state of equilibrium.
- Hence, the rotor sped continuous increase beyond the synchronous speed.
- As a result of rotor acceleration above synchronous speed, the torque angle δ decreases.
- At the point where motor torque becomes equal to the load torque, the equilibrium is not restored, because now the speed of the rotor is greater than the synchronous speed.
- Therefore, the rotor continues to swing backwards. The torque angle goes on decreasing.
- When the load angle δ becomes less than the required values δ_1, the mechanical load becomes grater than the developed power.
- Therefore, the motor starts to slow down.
- The load angle is increased again. Thus, the rotor swings or oscillates around synchronous sped and the required value δ_1 of the torque angel before reaching the new steady state.

- Similarly, the motor responds to a decreasing load torque by a temporary increase in sped, and thereby, a reduction of the torque angle δ.
- The rotor swings or oscillates around synchronous sped and the new required value δ_2 of the torque angle before reaching the new equilibrium position (steady state).
- The phenomenon of oscillation of the rotor about its final equilibrium position is called hunting.
- Since during rotor oscillations, the phase of the phasor E changes relative to phasor V., hunting is also known as phase swinging.
- The term hunting is used to signify that after sudden application of load, the rotor attempts to search for or hunt for its new equilibrium space position.

Causes of hunting

i) Sudden changes of load.
ii) faults occurring in the system which the generator supplies.
iii) sudden changes in the field currents
iv) cyclic variations of the load torque.

Effect of hunting

i) It can lead to loss of synchronism.
ii) It can cause variations of the supply voltage producing undesirable lamp flicker.
iii) It increases the possibility of resonance. If the frequency of the torque component becomes equal to that of the transient oscillations of the synchronous machine, resonance may take place.
iv) Large mechanical stresses may develop in the rotor shaft.
v) The machine losses increase and the temperature of the machine rises.

Reduction of hunting

- The following are some of the techniques used to reduce hunting
  (a) damper winding.
  (b) Use of flywheels.
- The prime mover is provided with a large and heavy flywheel. This increases the inertia of the prime mover and helps in maintaining the rotor sped constant.
  (c) By designing synchronous machines with suitable synchronizing power coefficients.

Tutorial

1. **A 4-pole alternator has an armature with 25 slots and 8 conductors per slot and rotates at 1500 rpm and flux per pole is 0.05 Wb.**
Calculate the emf generated if winding factor is 0.96 and all conductors are in series.

Solution:

Flux per pole = 0.05 Wb.

Frequency $f = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50$ Hz.

Number of conducted in series,

Z_p = number of slots * number of conductor per slot

= 25*8 = 200

Number of turns, $T = \frac{Z_P}{2} = 100$

Winding factor, $kw = k_d\, k_p = 0.9r$

Generated emf, $E = 4.44\ kw\ \phi f T$ votls.

$= 4.44 * 0.96 * 0.05 \times 50 * 100$

$= 1065.6$v

2. **15.8 A 3-ϕ, 50Hz, 20 pole salient pole alternator with star connected stator winding has 180 slots on the stator. Each slot consists of 8 conductors. The flux per pole is 25 mWb and sinusoidally distributed. The coils are full-pitched. Calculate**
   i) **The speed of the alternator**
   ii) **Winding factor**
   iii) **Generated emf per phase and**
   iv) **Line voltage.**

Solution:

Flux per pole, ϕ = 25 mWb = 0.025 Wb.

Frequency = 50 Hz.

Number of armature conductors,

Z = No. of slots * no. of conductors per slot.

= 180 * 8 = 1,440.

No. of armature conductors per phase, $= \frac{1,440}{3} = 480$.

No. of turns per phase, $T = \frac{480}{3} = 240$

No. of poles, P = 20.

i) Sped, $N = \frac{120f}{P} = \frac{120*50}{20} = 300$ rpm.

(no.of slots)

ii) Number of slots per pole, $n = \frac{180}{20}$ (no. of poles)

No. of slots per pole per phase,

$$m = \frac{n}{\text{no. of phases}} = \frac{9}{3} = 3$$

Angular displacement between the slots,

$$\beta = \frac{180°}{n} = 20° \text{ (electrical)}.$$

Distribution factor, $k_d = \frac{\frac{\sin m\beta}{2}}{m \sin \beta/2}$

$$= \frac{\sin \frac{3*20°}{2}}{3 \sin 20°/2} = \frac{\sin 30°}{3\sin 10°} = 0.96$$

Pitch factor, $k_p = 1$ for coils are full pitched.

ii) Winding factor, $k_w = k_d k_p = 0.96 \times 1 = 0.96$ Ans.

iii) Generated emf per phaews = 4.44 k_d kpϕfT volts.

= 4.44*0.96×1 0.02J × 50 × 240

= 1.280 V ans.

iv) Line voltage, $V_L = \sqrt{3}$ *1,280 = 2215 V. Ans.

3. What type of rotor of a synchronous generator would you expe to find in (i) a 2-pole machine (ii), a 23 -pole machine?

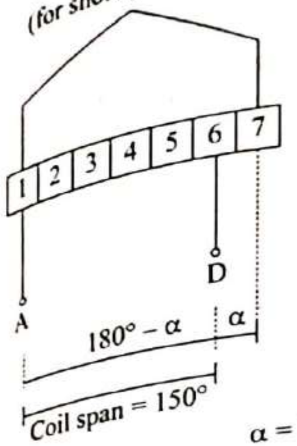
Solution:

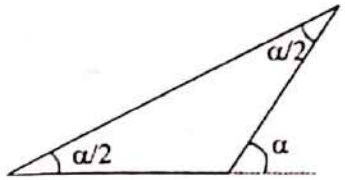
We know, $N_S = \frac{120f}{P}$

i) $N_S = \frac{120\times50}{2} = 2000$ rpm: ⇒ cylindrical rotor (high sped)

ii) $N_S = \frac{120 \times 50}{12} = 500$ rpm; salient rotor. (1000 speed)

In pitch factor, α = phase angel/chording angel.
(for short-pitched winding)





$$\alpha = 180° - 150° = 30°$$

- Firstly, draw full-pitched winding & then short-pitched winding.

4. A 3-ϕ, star-connected a alternator is rated at 1600 kVA, 13500V. The armature effective resistance and synchronous reactance are 1-5Ω and 30Ω respectively per phase. Calculate the percentage regulation for a load of 1280 kW at power factor of (a) 0.8 leading (b) unity (c) 0.8 logging.

Solution:

(a) $P_3\phi = \sqrt{3}\, V_L\, I_L \cos\phi$

$1280 \times 10^3 = \sqrt{3} \times 1350\, I_L*0.8 \Rightarrow I_L = 68.43A = I_a$

$R_a = 1.5\ \Omega$

X+s = 30 Ω

$V_{Ph} = \frac{V_L}{\sqrt{3}}$ = f(13500,$\sqrt{3}$) = 7794.5v.

cosϕ = 0.8; sinϕ = 0.6

For reading power factor,

$E_P^2 = (V_{ph} \cos\phi + I_aR_a)^2 + (V_p \sin\phi - I_aX_s)^2$

$= (7794*0.8 + 68.43*1.5)^2 + (7794*0.6\text{-}68.43*30)^2$

∴ $E_P = 6859.6$ V

Voltage regulation $= \frac{E_P - V_{ph}}{V_{ph}} \times 100 = \frac{6859.6 - 7794.5}{7797.5} \times 100$

= – 11.99%

(b) Unity power factor : $\cos\phi = 1$, $\sin\phi = 0$

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

$1280 \times 10^3 = \sqrt{3} * 13500 I_L \times 1 \Rightarrow I_L = 54.74A = I_a$

$E_P^2 = (V_p\cos\phi + I_aR_a)^2 + (V_p\sin\phi + I_aX_a)^2$

$= (V_P + I_aR_a)^2 + (I_a X_3)^2$

$\therefore \quad E_P = 8046V.$

$$\text{Voltage regulation} = \frac{E_P - V_{Ph}}{V_{ph}} = \frac{8044 - 7794.5}{7754.5} = 3.227\%$$

(c) Power factor 0.8 lagging

Magnitude of I_a will be the same as calculated in first case.

$E_P^2 = (V_{ph}\cos\phi + I_aR_a)^2 + (V_p \sin\phi + I_aX_s)^2$

$= (7794.5*0.8 + 68.43\times1.5)^2 + (7794.5*0.6+65.4330)^2$

$= 6338^2 + 6729.6^2$

$\therefore \quad E_P = 9244.4$

$$\text{Voltage regulation} = \frac{E_P - V_{Ph}}{V_{ph}} \times 100 = \frac{9244.4 - 7794}{7794.5} = 18.6\%$$

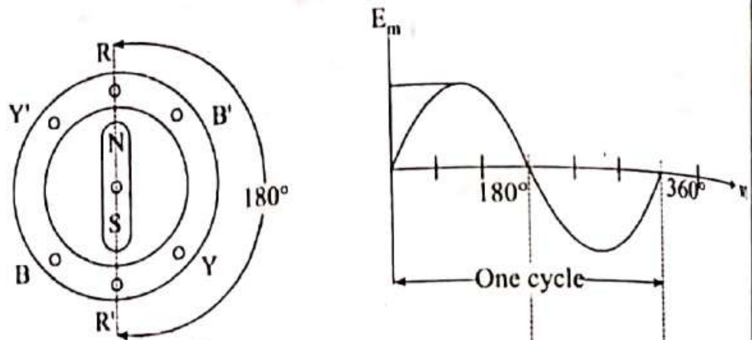


Fig. 2-pole machine

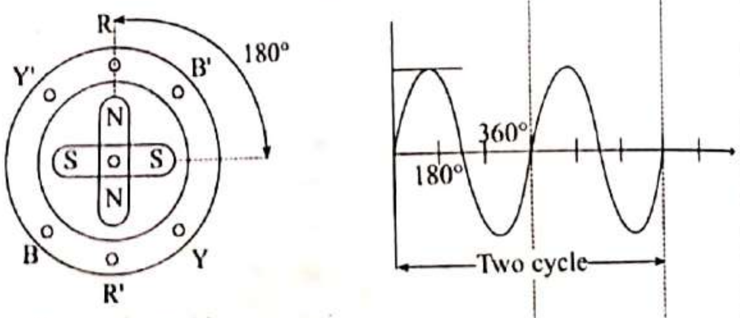


Fig. 4-pole machine

5. A 3000V, 3-ϕ synchronous motor running at 1500 rpm has its excitation kept constant corresponding to no load terminal voltage of 3000V. Determine the power input, power factor and torque developed for an armature current of 250 A if the synchronous reactance is 5Ω per phase and armature resistance is neglected.

Solutions: Given, $I_n = 250$, $R_a = 0$, $X_s = 5\Omega$

Supply voltage per phase, $V = \dfrac{3000}{\sqrt{3}} = 1732V.$

Induced emf per phase, $E_f = \dfrac{3000}{\sqrt{3}} = 1732V.$

Synchronous impedance $Z_0 = R_a + jX_s = 0 + j5 = 5 < 90°\Omega$

We know, $\vec{E_f} = \vec{V} - \vec{I_a}Z_s$

If V is taken as reference phasor, then for lagging power factor,

$\vec{I_a} = I_a < -\phi$

$\therefore \quad \vec{E_f} = \vec{V} - (\vec{I_a} < -\phi)\,(5 < 90°)$

or, $\vec{E_f} = \vec{V} - 5 * 250 < 90° - \phi$

or, $\vec{E_f} = \vec{V} - 1250\,[\cos(90° - \phi) + j\sin(90° - \phi)]$

or, $\vec{E_f} = (\vec{V} - 1250\sin\phi) - j1250\cos\phi$

$\therefore \quad E_f^2 = (v - 1250\sin f)^2 + (1250\cos\phi$

or, $E_f^2 = v^2 - 2v*1250\sin\phi + (1250\sin\phi)^2 + (1250\cos\phi)^2$

or, $1732^2 = 1732^2 - 2*1732 + 1250\sin\phi + (1250)^2$

or, $2*1732 * 1250\sin\phi = (1250)^2$

or, $\sin\phi = \dfrac{1250}{2\times1732} = 0.3608$

$\cos\phi = 0.9326$ (logging)

Input power, $P_i = \sqrt{3}V_1 I_a\cos\phi$

$= \sqrt{3}*3000*250*0.9326 = 1211483W$

For logging P.f. $= E_f^2 = (v\cos\phi - I_aR_a)^2 + (v\sin\phi - I_aX_S)^2$

$E_f^2 = v^2\cos\phi + V^2\sin^2\phi - 2v\sin\phi\, I_aX_s + I_a^2X_s^2$

$\because \; E_f^2 = V^2 - 2\sin\phi * InX_S + I_a^2 * S^2$

Also, $P_i = 2\pi \dfrac{NS}{60} T$

Torque, $T = \dfrac{P_i \times 60}{2\pi N_s} = \dfrac{1211453 \times 60}{2\pi \times 1500} = 7712.5$ NM

6. **A 20MVA, 3-phase, star-connected, 11nV, 12-pole, 50Hz salien pole synchronous motor has reactance of $X_d = 5\Omega$ $X_q = 3\Omega$. At full-load, unity power factor and rated voltag determine**

(a) The excitation voltage

(b) The active power

(c) Maximum value of the power angel and the correspondin power.

Solution: $S = \sqrt{3}\, V_L I_a$

or, $20\times10^6 = \sqrt{3} * (11\times10^3 * I_A \Rightarrow I_a = \dfrac{20\times10^6}{\sqrt{3}\times 11\times 10^3}$

$= 1049.72A$

We know (from the phasor diagram a + unity p.f.)

$V\sin\delta \;\; I_qX_q$

$I_q = I_q \cos\delta \;:\; I_d = I_a\sin\delta$

$\therefore$ $V\sin\delta = (I_a\cos\delta)\, X_q$

or, $\tan\delta = \dfrac{I_aX_q}{V} = \dfrac{1049.72*3}{\left(\dfrac{11\times10^3}{\sqrt{3}}\right)} = 0.49585$

$\therefore$ $\delta = 26.4°$

$\therefore$ $I_q = I_{acos}\delta = 1049.72 \cos 26.4° = 940.3A$

$I_d = I_a\sin\delta = 1049.72 \sin26.4° = 466.7A$

(a) Excitation voltage per phase.

$E = V\cos\delta + I_dX_d$

$= \dfrac{11\times10^3}{\sqrt{3}}\cos26.4 + 466.7*5 = 5688+2333.5$

$= 8021.5V$

(b) Active power for 3-phase

$P_{3\phi} = \dfrac{eVE}{X_d}\sin\delta + \dfrac{3V^2}{2}\dfrac{(X_d - X_q)}{X_dX_q}\sin2\delta$

or, $P_{3\phi} = \dfrac{3\times11\times10^3\times 8021.5}{\sqrt{3}*5}\sin26.4° + \dfrac{3}{2}\left(\dfrac{11\times10^3}{\sqrt{3}}\right)^2\left(\dfrac{5-3}{5*3}\right)\sin2*26.4$

or, $P_{3\phi} = 13590728 + 6425341$

or, $P_{3\phi} = 20016069W$

$P_{3\phi} = 2001.61\ kW.$

(e) $P_{3\phi} = \dfrac{3VE}{X_d}\sin\delta + \dfrac{3V^2}{2}\left(\dfrac{X_d - D_q}{X_dX_q}\right)\sin2\delta$

At maximum power angle, maximum power willoccur. For maximum power $\dfrac{dP_{3}\phi}{d\delta} = 0$

or, $\dfrac{3VE}{X_d}\cos\delta + \dfrac{V}{X_dX_q}(X_d - X_q)\cos2\delta = 0$

or, $2\cos^2\delta + 1.895\cos\delta - 1 = 0$

Thus, $\cos\delta = \dfrac{-1.895 \pm \sqrt{(1.895)^2 + 8}}{4}$

or, $\cos\delta = 0.3775$ (neglecting - ve value).

$\therefore$ $\delta = \cos^{-1}(0.3775) = 67.82$

This is the maximum value of power (torque) angles.

→ Power corresponding to maximum power angle.

$= \dfrac{3VE\sin\delta}{Xd^n}\;\dfrac{3V^2}{2}\left(\dfrac{X_d - X_q}{X_dX_q}\right)\sin2\delta$

$= \dfrac{3\times11\times10^3\times8021.5}{\sqrt{3}*5} * \sin67.82° + \dfrac{3}{2} * \left(\dfrac{11\times10^3}{\sqrt{3}}\right)^2$

$\left(\dfrac{5-3}{5\times3}\right)\sin(2*67.82)$

$= 39.95$ MW.

→ For lagging power factor [Synchronous motor).

$E_f^2 = (V\cos\phi - I_aR_a)^2 + (V\sin\phi - I_aX_S)^2$

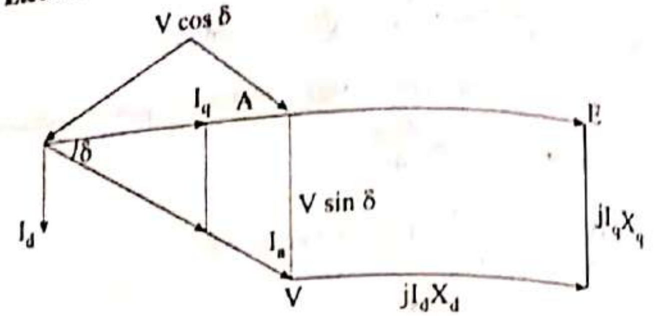
For Unity power factor

$E_f^2 = (V - I_aR_a)^2 + ((I_a X_S)^2$

For leading power factor

$E_f^2 = (V\cos\phi - I_aR_a)^2 + (V\sin\phi + I_aX_S)^2$

$\because$ $\boxed{\vec{E}_f = \vec{V} - \vec{I}_a Z_s}$



∵ $V\sin\delta = I_aX_q$

∵ $V\cos\delta + I_dX_q = 1$

Fig. Phasor diagram for For Unity power factor.

7. A 3-phase 50Hz, 8-pole alternator has a star-connected winding with 120 slots and 8 conductors per slot. The flux per pole is 0.05 Wb, sinusoidally distributed. Determine the phase and line voltages. [2066]

Solution:

Let us take the full-pitch coil.

∴ For full-pitch, pitch factor $K_c = 1$

Slots per pole per phase, $m = \dfrac{\text{Slots}}{\text{Poles} \times \text{phases}}$

$$m = \frac{120}{8 \times 3} = 5$$

Angular displacement between adjacent slots in electrical degrees (β)

$$= \frac{180^\circ}{\text{slots/pole}} = \frac{180^\circ \times \text{poles}}{\text{slots}} = \frac{180^\circ + 8}{120} = 12^\circ$$

$$\text{Distribution factor, } k_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin\frac{5 \times 12^\circ}{2}}{5\sin\frac{12^\circ}{2}} = 0.9567$$

Total number of conductors = Conductor per slot × Number of slots = 8 ×5 120 = 960.

$$\text{Conductors per phase, } Z_p = \frac{960}{3} = 320$$

Generated voltage per phase,

$$E_P = 2.22\, K_cK_df\phi Z_p = 1699\text{ V}$$

Generated voltage per line

$$E_L = \sqrt{3}\, E_P = 2942.8\text{ V}$$

8. **A 3-phase, 16-pole synchronous generator has a requirement: air-gap flux of 0.06 Wb per pole. The flux is distributed sinusoidally over the pole. The stator has 2 slots per pole per phase and 4 conductors per slot are accommodated in two layers. The coil span is 150°. electrical. Calculate the phase and the induced voltages when the machine runs at 375 rpm.** [2073]

Solution:

$$\text{Frequency, } f = \frac{PN_s}{120} = \frac{16 \times 375}{120} = 50\text{ Hz}$$

$$\alpha = 180^\circ - 150^\circ = 30^\circ$$

$$\text{Pitch factor, } K_C = \cos\frac{\alpha}{2} = \cos\frac{30^\circ}{2} = 0.9659.$$

$$m = \text{Slots per pole per phase} = \frac{\text{slots}}{\text{poles} \times \text{phases}}$$

$$\text{Slots} = m \times \text{poles} \times \text{phases} = 2 \times 16 \times 3 = 96$$

Total number of conductors = slots × conductors per slot = 96 × 4 = 384

$$\text{Number of conductors per phase } Z_P = \frac{384}{3} = 128.$$

Angular displacement between adjacent slots

$$\beta = \frac{180^\circ \times \text{poles}}{\text{slots}} = \frac{180^\circ \times 16}{96} = 30^\circ$$

Distribution factor,

$$K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin 2\pi\frac{30^\circ}{2}}{2\sin\frac{36^\circ}{2}} = 0.9659.$$

Since the flux is sinusodially distributed, form factor, $K_f = 1.11$.

The generated voltage per phase is given by

$$E_P = 2\, K_f K_C K_d f \phi Z_p \text{ or } 2.22\, K_CK_df\phi Z_p.$$

$$= 2.22 \times 0.9659 \times 0.9659 \times 50 \,\forall\, 0.06 \times 128$$

$$= 795.3\text{ V}$$

$$\text{Generated line voltage, } E_l = \sqrt{3}\, E_p = \sqrt{3} \times 795.3 = 1377.5\text{ V}$$

$E_P^2 = (V_P + I_a R_a)^2 + (I_a X_s)^2$

$= (7794.5 + 54.74 \times 1.5)^2 + (54.74430)^2$

$E_P = 8046 \text{ V}$

$\text{Voltage regulation} = \frac{E_P - V_P}{V_P} \times 100 = \frac{8046 - 7794.5}{7794.5} \times 100 = 3.22\%$

(c) Power factor 0.5 lagging

Magnitude of I_a will be the same as calculated in first case

$E_P^2 = (V_p \cos\phi + I_a R_a)^2 + (V_P \sin\phi + I_a X_s)^2$

$= (7794.5 \times 0.8 + 68.43 \times 1.5)^2 + (7794.5 \times 0.6 + 68.43 \times 30)^2$

$E_P = 9244.4\text{V}$

$\text{Voltage regulation} = \frac{E_P - V_P}{V_P} \times 100\% = \frac{9244.4 - 7794.5}{7794.5} \times 100\%$

$= 18.6\%$

12. A straight line law connects terminal voltage and load of a 3-phase star connected alternator delivering current at 0.8 power factor lagging. At no load, the terminal voltage when delivering current to a 3-phase, star connected load having a resistance of 8Ω and reactance of 6Ω per phase. Assume constant speed and field excitation. **[2071]**

Solution:

$\text{Power, } P_{3\phi} = 3V_P I_P \cos\phi$

$2280 \times 10^3 = 3 \times \frac{3300}{\sqrt{3}} I_P \times 0.8$

$I_P = 498.6\text{A}$

$\text{No. load phase voltage} = \frac{3500}{\sqrt{3}} = 2020.7\text{V}$

$\text{Full load phase voltage} = \frac{3300}{\sqrt{3}} = 1205.3 \text{ V}$

Voltage drop per phase for a current of 498.6 A

$= 2020.7 - 1905.3 = 115.4 \text{ V}$

$\text{Voltage drop per phase for 1 A current} = \frac{115.4}{438.6} \text{ V}$

Let, I be the current supplied by the alternator,

Therefore, the voltage drop per phase for supplying a current I at 0.8

$\text{power factor lagging} = \frac{115.4}{498.6} I = 0.2315I \text{ Volts.}$

Terminal voltage per phase for supplying a current I at 0.8 power factor lagging = 20207 – 0.2315 I

$\text{Load impedance, } Z_L = \sqrt{R_L^2 + XL^2} = \sqrt{8^2 + 6^2} = 10\Omega$

$\text{Load terminal voltage} = IZ_L = I \times 10\text{V}$

$10I = 2020.7 - 0.2315 I$

or, $I = \frac{2020.7}{10.2315} = 197.5 \text{ A}$

$\therefore$ Terminal voltage per phase $= IZ_L = 197.5 \times 10 = 1975 \text{ V}$

Line value of terminal voltage $= \sqrt{3} \times 1975 = 3 \times 20.8 \text{ V}$

13. **A 3-phase, 10 kVA, 400 V, 50 Hz star connected alternator. Supplier the rated load at 0.8 power factor lagging. If the armature resistance is 0.5Ω and synchronous reactance is 10Ω, find the torque angle and voltage regulation.** **[2069]**

Solution:

$\text{Apparent power, } S_{3\phi} = \sqrt{3}\, V_L I_L$

$10 \times 10^3 = \sqrt{3} \times 400\, I_L \Rightarrow I_L = \frac{10 \times 10^3}{\sqrt{3} \times 400} = 14.4 \text{ A}$

$\text{Impedance, } Z_S = R_a + jX_s = 0.5 + j10 = 10.012 < 87°\Omega$

$\text{Phase current, } I_{ap} = I_L = 14.4 \text{ A}$

$\text{Rated phase voltage, } V_P = \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.9\text{V}$

Let, V_P be taken as reference phasor,

$V_P = V_P < 0° = 230.3 < 0° \text{ V} = (230.9 + j0) \text{ V}$

At a lagging power factor of 0.8

$I_{ap} = I_{ap} < -\cos^{-1} 0.8° = 14.4 < -36.87°\text{A}$

$E_{ap} = V_P + I_{ap} Z_s = 230.9 + j0 + (14.4 < -36.87°)(10.021 < 87°)$

$= 230.9 + 144.2 < 50.13°$

$= 230.9 + 92.4 + j110.6$

$= 323.3 + j110.6 = 341.7 < 18.9° \text{ V}$

$E_{ap} = 341.7\text{V}, \delta = < 18.9°$

$\text{Voltage regulation} = \frac{E_{ap} - V_P}{V_P} \times 100\% = \frac{341.7 - 230.9}{230.9} \times 700\%$

$= 47.98\%$

14. **A 550V, 55 kVA, single-phase alternator has an effective resistance of 0.2Ω. A field current of 10A produces an armature current of 200 A on short-circuit and an emf of 450 V on open circuit.**

Calculate the synchronous reactance and voltage regulation at full load with power factor 0.8 lagging. [2070]

Solution:

Apparent power, $S_{1\phi} = VI_a$

$$55 \times 10^3 = 550 I_a$$

$$I_a = \frac{55 \times 10^3}{550} = 10A$$

P.F. $(\cos\phi) = 0.8$, $\sin\phi = 0.6$

$$\text{Synchronous impedance } Z_S = \frac{\text{Open – Circuit phase voltage}}{\text{Short – circuit armature current}}$$

$$= \frac{450}{200} = 2.25\ \Omega$$

Synchronous resistance,

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{(2.25)^2 - (0.2)^2} = 2.24\Omega$$

Generated armature voltage per phase for lagging p.f.

$$E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_S)^2}$$

$$= \sqrt{(550 \times 0.8 + 100 \times 0.2)^2 + (550 \times 0.6 + 100 \times 2.24)^2}$$

$$= \sqrt{460^2 + 554^2}$$

$$= 720\text{ V}$$

$$\text{Voltage regulation} = \frac{E_a - V}{V} \times 100\% = \frac{720 - 550}{550} \times 100\% = 30.91\%$$

15. **In a 50 kVA, star-connected, 440 V 3-phase. 50 Hz alternator, the effective armature resistance is 0.25Ω per phase. The synchronous resistance is 3.2Ω per phase and leakage reactance is 0.5Ω power factor.**

(a) internal emf, (b) no-load emf, (c) percentage voltage regulation at full load (d) value of the synchronous reactance which replaces armature reaction [2065]

Solution:

Apparent power, $S_{3\phi} = \sqrt{3}\, V_L I_L$

$$50 \times 10^3 = \sqrt{3} \times 440 I_L$$

$$\Rightarrow I_L = \frac{50 \times 10^3}{\sqrt{3} \times 440} = 65.6A = I_a$$

Let, V_P be taken as reference phasor

$$V_P = V_P < 0° = \frac{440}{\sqrt{3}} < 0° = 254 < 0°\text{ V}$$

At unity power factor, $I_a = I_a < 0° = 65.6 < 0° = 65.6 + j0.$

(a) Leakage impedance

$$Z_L = R_a + jX_L = 0.25 + j0.5 = 0.559 < 63.4°\Omega$$

$$= 0.559 < 63.4°\Omega$$

Internal emf,

$$E_{P,\,int} = V_P + I_aZ_L$$

$$= 254 < 0° + (65.6 < 0°)(0.559 < 63.4°)$$

$$= 254 + j0 + 36.67 < 63.4°$$

$$= 254 + 16.42 + j32.79$$

$$= 272.4 < 6.91°\text{ V}$$

Line value of internal emf

$$E_{L,\,int} = \sqrt{3} \times 272.4 = 472.8\text{ U}$$

(b) Synchronous impedance

$$Z_S = R_a + jX_S = 0.25 + j3.2 = 3.21 < 85.53°\ \Omega$$

No-load emf, E_a

$$E_{ap} = V_P + I_aZ_S$$

$$= 254 < 0° + (65.6 < 0°)(3.21 < 85.53°)$$

$$= 254 + j0° + 210.6 < 85.53°$$

$$= 254 + 16.4 + j210$$

$$= 342.37 < 37.83°\text{ V}$$

Line value of no-load emf

$$E_{aL} = \sqrt{3}\, E_{ap} = \sqrt{3} \times 342.37 = 593\text{ V}$$

(c) Voltage regulation $= \dfrac{E_{ap} - V_{ap}}{V_{ap}} \times 100\%$

$$= \frac{432.37 - 254}{254} \times 100\%$$

$$= 34.79\%$$

(d) Synchronous reactance, $X_S = X_L + X_{AR}$

$$\therefore\ X_{AR} = X_S - X_L = 3.2 - 0.5 = 2.7\ \Omega$$

16. **A 1500 kVA, star-connected, 2300 V, 3-pahse, salient-pole synchronous generator has reactance $X_d = 1.95\ \Omega$ and $X_q = 1.40\ \Omega$ per phase. All losses may be neglected. Find the excitation voltage for operation at rated kVA and power factor of 0.85 lagging.** [206..]

Solution:

Voltage per phase, $V_P = \dfrac{2300}{\sqrt{3}} = 1328$ V

$$(kVA)_{3\phi} = \frac{3V_P I_a}{1000}$$

$$1500 = \frac{3 \times 1328\ I_a}{1000} \Rightarrow I_a = 376.5A$$

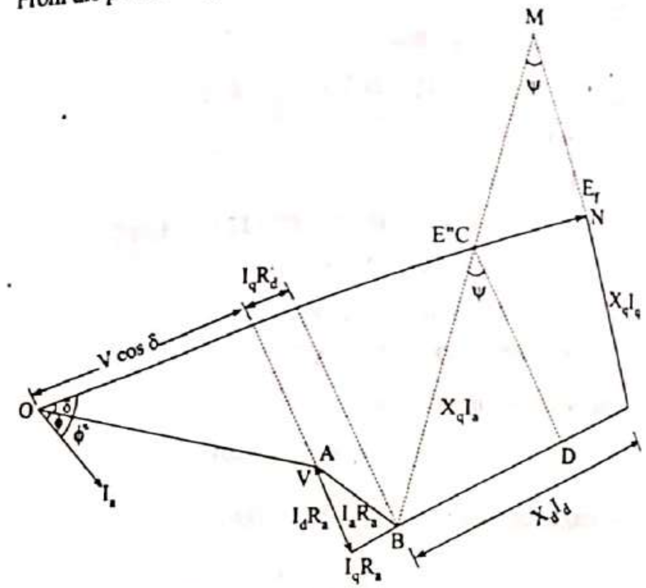
Let, V_P be the reference phasor.

$V_P = V_P < 0° = 1328 < 0°$

$\cos\phi = 0.85, \phi = 31.8°$

$I_a = I_a < -\phi = 376.5 < -31.8°$ A $= 320 - j198.4$ A

From the phasor diagram.



$E'' = OC = OA + AB + BC$

$= V_P + 0 + jX_qI_a = (1328 + j0°) + j(1.40)(320 - j198.4)$

$= 1328 + 277.8 + j448 = 1605.8 + j448$

$= 1667 < 15.6°$V

The phase difference between E" and I_a is angle ψ

$\psi = \delta + \phi = 15.6° + 31.8° = 47.4°$

$I_d = I_a \sin\phi = 376.5 \sin 47.4° = 277.14$ A

$(X_d - X_q)I_d = (1.95 - 1.40) \times 277.14$

Since, E_f, E" and $j(X_d - X_q)\ I_d$ are in phase we add the magnitudes

$E_f = E + (X_d - X_q)I_d = 1667 + 152.4 = 1819.4$ V

17. **A 3.75 mVA, 10 kV, 3-phase, 50 Hz, 10 pole alternative has 144 slots containing a two-layer diamond winding with 5 conductors per coil side in each slot. The coil span is 12 slot pitches. The flux per pole is 0.116 Wb.** [2061]

Solution:

Flux per pole, $\phi = 0.116$ Wb

Supply frequency, f = 50 Hz

Slots per pole, $n = \dfrac{\text{No. of slots}}{\text{No. of poles}} = \dfrac{144}{10} = 14.4$

Slots per pole per phase, $m = \dfrac{\text{(Slots per pole)}}{\text{No. of phases}} = \dfrac{14.4}{3} = 4.8$

Angular displacement between slots $\beta = \dfrac{180°}{n} = \dfrac{180°}{14.4} = 12.5°$

Coil span $= 12 \times 12.5 = 150°$

Chording angle, $\alpha = 180° - 150° = 30°$

Pitch factor, $K_p = \cos\dfrac{\alpha}{2} = \cos\dfrac{30°}{2} = 0.3659$

$$\text{Distribution factor, } K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{m\beta}{2}} = \frac{\sin\frac{4.8 \times 12.5°}{2}}{4.8\sin\frac{12.5°}{2}} = 0.9568$$

Number of turns per phase,

$$T = \frac{14.4 \times 5 \times 2}{2 \times 3} = 240$$

Phase voltage, $E_P = 4.44\ K_dK_P\ \phi\ fT$.

$= 4.44 \times 0.9568 \times 0.9659 \times 0.116 \times 50 \times 240$

$= 5.712$ V

18. **A 3-phase star connected synchronous generator supply current of 10 A having phase angle of 20° lagging at 400 V. Find the load angle and the components of armature current I_d and I_q if $X_d = 10\Omega$ and $X_q = 6.5\Omega$. Assume armature resistance to be negligible.** [2062]

Solution:

Direct axis synchronous reactance per phase $X_d = 10\Omega$.

Quadrature axis synchronous reactance per phase $X_q = 6.5\Omega$

Assume current, I = 10A.

Power factor angle, $\phi = 20°$ (Lagging)

Terminal voltage per phase,

$$V = \frac{400}{\sqrt{3}} = 230.94 \text{ V}$$

$$\tan\delta = \frac{I \times X_q \cos\phi}{V + I X_q \sin\phi} = \frac{10 \times 6.5 \times \cos 20°}{230.94 + 10 \times 6.5 \times \sin 20°}$$

$$= \frac{61.08}{253.17} = 0.24126$$

Load angle, $\delta = \tan^{-1}(0.24 + 26) = 13.564°$

Angle $\theta = \delta + \phi = 13.564° + 20° = 33.564°$

Direct axis component of armature current

$$I_d = I \sin\theta = 10 \sin 33.564° = 5.53 \text{ A}$$

Quadrature axis component of armature current

$$I_q = I \cos\theta' = 10 \cos 33.564° = 8.33 \text{ A}$$

19. **A 3-phase synchronous generator produces an open-circuit line voltage of 6928 V when the de excitation current is 50A. The ac terminals are then short circuited, and the three line currents are found to be 800 A.**

a. **Calculate the synchronous reactance per phase.**

b. **Calculate the terminal voltage if three 12W resistance connected in Wye across the terminals.** [2063]

Solution:

The induced voltage per phase $E_P = \frac{E_L}{\sqrt{3}} = \frac{6928}{\sqrt{3}} = 4000$ V

(a) When the terminals are short-circuited, the any impedance limiting the current flow is that due to the synchronous reactance. Consequently.

$$X_S = \frac{E_P}{I} = \frac{4000}{800} = 5\Omega$$

$\therefore$ The synchronous reactance per phase is 5Ω.

(b) The impedance of the circuit is

$$Z = \sqrt{R^2 + X_S^2} = \sqrt{12^2 + 5^2} = 13\Omega$$

The current is $I = \frac{E_P}{Z} = \frac{4000}{13} = 308$ A.

The voltage across the load resistor is

$$E = IR = 308 \times 12 = 3696 \text{ V}$$

The line voltage under load is

$$E_L = \sqrt{3}\,E = \sqrt{3} \times 3696 = 6402 \text{ V}$$

20. **A 30 MVA, 15 kV, 60 HZ 3-pahse alternator has a synchronous reactance of 1.2 pu and a resistance of 0.02 pu. Calculate**

a. **The base voltage, base power and base impedance of the generator.**

b. **The actual value of the synchronous reactance.**

c. **The actual winding resistance per phase.**

d. **The total full-load copper losses.** [2072]

Solution:

(a) The base voltage is $E_B = \frac{E_L}{\sqrt{3}} = \frac{15000}{\sqrt{3}} = 8660$ V

The base power is $S_B = \frac{30 \text{ MVA}}{3} = 10 \text{ MVA} = 10^7$ VA

The base impedance is $Z_B = \frac{E^2_B}{S_B} = \frac{8660^2}{10^7} = 7.5\Omega$

(b) The synchronous reactance is

$$X_S = X_S(PU) * Z_B = 1.2 \times 7.5$$

$$\therefore X_S = 9\Omega$$

(c) The resistance per phase is

$$R = R(PU) \times Z_B = 0.02 Z_B$$

$$R = 0.02 \times 7.5 = 0.15\ \Omega$$

(d) The per unit copper losses at full load are

$$P_{(Pu)} = I^2(Pu)\, R\,(Pu) = 1^2 \times 0.02 = 0.02$$

Note that at full-load the per unit value of I is equal to 1.

The copper losses for all 3 phases are

$$P = 0.02 S_B = 0.02 \times 30 = 0.6 \text{ MW}$$

$$P = 600 \text{ kW}.$$

21. **A 36 MVA, 21 kV, 1800 rpm, 3-phase alternator. Conect to power grid has a synchronous reactance of 9Ω per phase. If the existing voltage is 12 kV (line to neutral), and the system voltage is 17.3 kV (Line to line), calculate the following:**

a. **The active power which the machine delivers when the torque angle δ is 30° (electrical).**

b. **The peak power that the generator can deliver before it falls out of step (loses synchronism).**

Solution:

(a) Exciting voltage per phase, $E_0 = 12KV$.

System voltage per phase, $E = \frac{17.3\ KV}{\sqrt{3}} = 10\ kV$

Torque angle, $\delta = 30°$

The active power deliver to the power grid is

$$P = \frac{E_0E}{X}\sin\delta = 12 \times \frac{10}{9} \times 0.5 = 6.67\ MW$$

The total power delivered by all three phases is $3 \times 6.67 = 20$ MW

(b) The maximum power per phase is attained when $\delta = 90°$

$$P = \frac{E_0E}{X}\sin 90° = 12 \times \frac{10}{9} \times 1 = 13.3\ MW.$$

Therefore, the peak power output of the alternator

$= 3 \times 13.3 = 40$ MW.

22. **A 3-phase 10 kVA, 100 V, 4-pole, 50 Hz star connected synchronous machine has synchronous reactance of 11 Ω and negligible resistance. The machine is operating as generator on 4900 V bus bars (assumed infinite).**

a. **Determine the excitation emf (phase) and torque angle when the machine is delivering rated kVA at 0.8 pf lagging.**

b. **While supplying the same real power as in part (a), the machine excitation is raised by 20%. Find the stator current, power factor and torque angle.**

c. **With the field current held constant as in part (a), the power (real) load is increased till the steady state power limit is reacted. Calculate the maximum power and kVA delivered and also the stator current and power factor.**

Solution:

Armature Current, $I_a = \frac{S}{\sqrt{3}V} = \frac{10 \times 10^3}{\sqrt{3} \times 400}$

$\therefore \quad I_a = 14.43$ A

p.f. angle, $\phi = \cos^{-1}(0.3) = 36.9°$ log

$$\vec{I}_a = 14.43 < -36.9°$$

Terminal voltage per phase

$$V_t = \frac{400}{\sqrt{3}} = 231V$$

Synchronous reactance, $X_S = 16\ \Omega$

(a) We know,

Generated emf per phase, $\vec{E}_f = \vec{V}_t + j\vec{I}_aX_S$

$= 231 < 0°\ j14.43 < -31.9° \times 16$

$= 231 + 231 < 53.1° = 369.7 + j184.7$

$\therefore \quad E_f = 413.3 < 26.5°$

$\therefore \quad$ Torque angle, $\delta = 26.5°$ E_f leads V_t(generating action)

(b) Power supplied, $P_e = 10 \times 0.85 = 8$ kW (3 phase)

E_f (20% more) $= 413.3 \times 1.2 = 496$ V

$$P_e = \frac{E_fV_t}{X_s} = \text{sing}$$

$$\frac{8 \times 10^3}{3} = \frac{496 \times 231}{16}\sin\delta$$

Torque angle, $\delta = 21.9°$

Again, we know

$$\vec{E}_f = \vec{V}_t + j\vec{I}_aX_S$$

$$\vec{I}_a = \frac{E_f < \delta - V_t < 0°}{jX_S}$$

$$\vec{I}_a = \frac{496 < 21.9° - 231}{j16} = \frac{829 + j185}{j16} = 11.6 - j14.3$$

$\therefore \quad \vec{I}_a = 18.4 < -50.9°$

$\therefore \quad I_a = 18.4$ A, Pf $= \cos 50.9° = 0.63$ lagging.

(c) $E_f = 413$; field current same as in part (a).

$$P_{e(max)} = \frac{E_fV_t}{X_S};\ [\because d = 90°].$$

$$= \frac{4.13 \times 231}{16} \times 10^{-3} = 5.96\ \text{kW/phase or } 5.96 \times 3$$

$= 17.38$ kW 3 phase

Again

$$\vec{I}_a = \frac{413 < 90° - 231}{j16} = 25.8 + j14.43 = 29.56 < 29.2° \text{ A}$$

$I_a = 29.56$ A

$Pf = \cos 29.2° = 0.873$ leading.

kVAR delivered (negative)

$$\frac{Q_e}{P_e} = \tan(-29.2)$$

$\therefore \quad Q_e = 8 \times 0.559 = -4.47$ kVAR.

23. **A 300 MVA, 22 kV, 3 phase salient pole generator is operating at 250 MW power output at a lagging power factor of [illegible] synchronized to 22 kV bus. The generator reactances are $X_d = 1.93$ and $X_q = 1.16$ pu. The generator gives rated open circuit voltage at a field current of 338 A. Calculate the power angle excitation emf and the field current.**

Solution:

Base apparent power $(MVA)_B = 300$

Base voltage $(KV)_B = 22$

Power output, $P_e = \frac{250}{300} = 0.833$ PU

$P_e = V_t I_a \cos\phi$

$0.833 = 1 \times 5\, I_a \times 0.85$

$I_a = 0.98$

$\phi = 31.8°$ log

$\vec{I}_a = 0.98 < -31.8°$

$\vec{E}_f = \vec{V}_t + j\vec{I}_a X_a$

$= 1 + j0.98 < -31.8° \times 1.16$

$= 1 + 1.1368 < 58.2°$

$\vec{E}_f' = 1.91, \delta = 28.2°$

$\psi = \phi + \delta = 31.8° + 28.4° = 60.2°$

$I_d = I_a \sin\phi = 0.98 \sin 60.2° = 0.85$

$I_d (X_d - X_q) = 0.85 (1.93 - 1.16) = 0.654$

$E_f = E_f' + I_d(X_d - X_q) = 1.91 + 0.654 = 2.564$ Pu

$\therefore \quad E_f = 56.4$ kV

And find current,

$$\Sigma_f = \frac{338}{1} \times 2.564 = 866.6 \text{ A}$$

24. **A 3-phase, star connected, round roter synchronous generator rated at 10 kVA, 230 V has an armature resistance of 0.5Ω per phase and a synchronous reactance of 1.2Ω per phase. Calculate the percent voltage regulation at full load at power factor of (a) 0.8 lagging, (b) 0.8 leading (c) Determine the power factor such that the voltage regulation is zero on full load.** **[2071]**

Solution:

Apparent power $S_{3\phi} = \sqrt{3} V_L I_L$

$10 \times 10^3 = \sqrt{3} \times 230\, I_L$

$$I_L = \frac{10 \times 10^3}{\sqrt{3} \times 230} = 25.1 \text{ A} = I_{ap}$$

Rated voltage per phase, $V_P = \frac{V_L}{\sqrt{3}} = \frac{230}{\sqrt{3}} = 132.8$V

Let $\vec{V}_P$ be taken as reference phasor

$\vec{V}_P = V_P < 0° = 132.8 < 0° = 132.8 + j0$

Armature resistance, $R_a = 0.5\ \Omega$

Synchronous reactance, $X_S = 1.2\ \Omega$

$Z_S = R_a\, jX_S = 0.5 + j1.2 = 1.3 < 67.38°\ \Omega$

(a) Power factor 0.8 lagging

$I_{pq} = I_{pq} < -\cos^{-1} 0.8 = 25.1 < -36.87°$ A

$E_P = V_P + I_{pq} Z_S$

$= (132.8 + j0) + (25.1 < -3.87°)(1.3 < 67.38)$

$= 132.8 + 32.63 < 30.51°$

$= 132.8 + 28.1 + j16.56$

$= 160.9 + j16.56 = 161.75 < 5.87°$ V

Voltage regulation

$$= \frac{E_P - V_P}{V_P} \times 100 = \frac{161.75 - 132.8}{132.8} \times 100\% = 21.8\%$$

(b) Power factor 0.8 lending

$I_{ap} = I_{ap} < \cos^{-1} 0.8 = 25.1 < 36.87° < 36.87°$ A

$E_P = V_P + I_{ap} Z_S$

$= 132.8 + (25.1 < 36.87°)(1.3 < 67.38°)$

$= 132.8 + 32.63 < 104.25°$

$= 132.8 - 8 + j31.62 = 124.8 + j31.62$

$E_P = 128.74 < 14.2°$ V

$$\text{Voltage regulation} = \frac{E_P - V_P}{V_P} \times 100\% = \frac{128.74 - 132.8}{132.8} \times 100$$

$= -3.06\%$

(c) Let ϕ be the required power-factor angle

$I_{ap} = I_{ap} < \phi = 25.1 < \phi$ A

$E_P = V_P + I_{ap} Z_s$

$= 132.8 + (25.1 < \phi)(1.3 < 67.38°)$

$= 132.8 + 32.63 \cos(\phi + 67.38°) + j32.63 \sin(\phi + 67.38°)$

$E_P^2 = [132.8 + 32.63 \cos(\phi + 67.38)]^2 + [32.63 \sin(\phi + 67.38)]^2$

Voltage regulation $= \frac{E_P - V_P}{V_P}$ pu

For zero voltage regulation $E_P = V_P = 132.8$ V

$\therefore \quad 132.8^2 = [132.8 + 32.63 \cos(\phi + 67.38)]^2$

$= [32.63 \sin(\phi + 67.38)^2]$

or, $13.28^2 = (132.8)^2 + 2 \times 132.8 \times 32.63 \cos(\phi + 67.38°)$

$+ 32.63^2 \times \cos^2(\phi + 67.38°) + (32.63)^2 \sin^2(\phi + 67.38°)$

$= 132.8^2 + 2 \times 132.8 \times 32.63 \cos(\phi + 67.38°) + (32.63)^2$

or, $\cos(\phi + 67.38°) = \frac{-32.63}{2 \times 132.8} = -0.122185 = \cos 97°$

$\therefore \quad \phi = 97° - 67.38° = +29.62°$ and $\cos\phi = 0.3$ (leading)

25. A 1000 kVA, 11000 V, 3-phase star-connected synchronous motor has an armature resistance and reactance per phase of 3.5Ω and 40Ω respectively. Determine the induced e.m.f. and angular retardation of the rotor when fully loaded at (a) unity power factor, (b) 0.8 power factor lagging, (c) 0.8 power factor leading. [2073]

Solution:

$V = \frac{11000}{\sqrt{3}} = 6351$ V

$R_a = 3.5\Omega, X_S = 40\Omega$

$(kVA)_{3\phi} = \frac{\sqrt{3}\, V_L I_L}{1000}$

$1000 = \frac{\sqrt{3} \times 11000\, I_L}{1000}, \; I_a = 52.49$ A

(a) Unity power factor: $\cos\phi = 1.0, \phi = 0°, I_a = 52.49 \angle 0°$ A

$E_f = V - I_a Z_S = V - I_a (R_a + jX_S)$

$= 6351 - (52.49 \angle 0°)(3.5 + j40)$

$= 6351 - (183.7 + j2099.6)$

$E_f \angle\delta = 6167.3 - j2099.6 = 6515 \angle -18.8°$V

$\therefore \quad E_f = 6515$ V per phase

$\delta = -18.8°$

Induced line voltage $= \sqrt{3} \times 6515$ V $= 11284$ V

(b) 0.8 power factor lagging: $\cos\phi = 0.8, \sin\phi\; 0.6$

$I_a = I_a \angle -\phi$

$E_f = V - I_a Z_s$

$= V - (I_a \angle -\phi)(R_a + jX_S) = V - (I_a \cos\phi - j I_a \sin\phi)(R_a + jX_s)$

$= (V - I_a R_a \cos\phi - I_a X_s \sin\phi) - j(I_a X_s \cos\phi - I_a R_a \sin\phi)$

$= (6351 - 52.49 \times 3.5 \times 0.8 - 52.49 \times 40 \times 0.6)$

$- j(52.49 \times 40 \times 0.8 - 52.49 \times 3.5 \times 0.6)$

$E_f \angle\delta = 4944 - j\,1569.5 = 5187 \angle -17.6°$ V

$\therefore \quad E_f = 5187$ volts per phase, $\delta = -17.6°$

Induced line voltage $= \sqrt{3} \times 5187 = 8984$ V

$I_a = I_a \angle +\phi$

$E_f \quad = V - I_a Z_S = V - (I_a \angle +\phi)(R_a + jX_S)$

$= (V - I_a R_a \cos\phi + I_a X_s \sin\phi) - j(I_a X_s \cos\phi + I_a R_a \sin\phi)$

$= (6351 - 52.49 \times 3.5 \times 0.8 + 52.49 \times 40 \times 0.6)$

$- j(52.49 \times 40 \times 0.8 + 52.49 \times 3.5 \times 0.6)$

$E_f \angle\delta = 7463.8 - j1790 = 7675 \angle -13.48°$ V

$E_f = 7675$V per phase

$\delta = -13.48°$

Induced line voltage $= \sqrt{3} \times 7675 = 13293$ V

26. A 2000 kVA, 3-phase, star-connected synchronous motor has an effective resistance and synchronous reactance of 0.2Ω and 2.2Ω phase respectively. The input is 800 kW at normal voltage and the induced line e.m.f. is 2500 V. Calculate the line current and power factor. **[2074]**

Solution:

Supply voltage per phase $V = \frac{2000}{\sqrt{3}} = 1154.7$ V

Induced e.m.f. per phase $E_f = \frac{2500}{\sqrt{3}} = 14423.4$ V

Since the induced e.m.f. is greater than the supply voltage, the motor is operating with a leading power factor $\cos\phi$

If V is taken as reference phasor.

$\therefore \quad V = V \angle 0°$ and $I_a = I_a \angle +\phi = I_a \cos\phi + jI_a \sin\phi$

For a star-connected system line current = phase current

$I_L = I_a$

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

$800 \times 10^3 = \sqrt{3} \times 2000\, I_a \cos\phi$

$I_a \cos\phi = \dfrac{800 \times 10^3}{\sqrt{3} \times 2000} = 231$

$R_a = 0.2\ \Omega,\ X_S = 2.2\Omega$

$E_f = V - I_a Z_S$

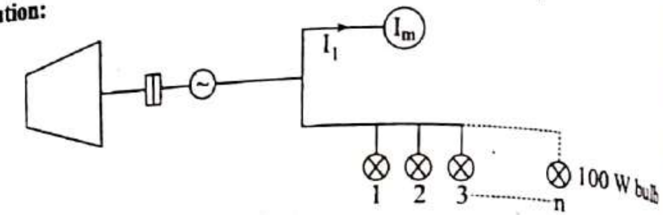
$= V - [(I_a \cos\phi + jI_a \sin\phi)(R_a + jX_a)]$

$= V - [(I_a R_a \cos\phi + I_a X_S \sin\phi) + j(I_a X_S \cos\phi + I_a R_a \sin\phi)]$

$= (V - I_a R_S \cos\phi + I_a X_S \sin\phi) + j(I_a X_S \cos\phi + I_a R_a \sin\phi)$

27. **A 750 kVA, 400V, 50H$_z$, 3-phase alternator delivers 500kw to a 3-phase induction motor at a power factor of 0.8 lagging. Calculate the number of 100w lamps which may be added to the alternator so that the alternator does not overload beyond it's capacity.**

Solution:



Here,

$P = \sqrt{3}\, V\, I \cos\phi$

$500 \times 1000 = \sqrt{3} \times 400 \times I \times 0.8$

$I = \dfrac{500 \times 1000}{\sqrt{3} \times 400 \times 0.8}$

$= 302.136$ Amp.

Volt-amp consumed by IM

$= \sqrt{3} \times VI_1$

$= \sqrt{3} \times 400 \times 902.136$

$= 625$ kVA.

∴ Extra Volt-Amp supplied by synchronous generator

$= (750 - 625) \times 100 = 125$.kVA

Volt-Amp consumed by 100w electric bulb = 100 VA (∵ Pf = 1)

So, no. of lamp that can be added $= \dfrac{125 \times 1000}{100} = 1250$ Nos.

ALTERNATIVELY

Let total no. of lamp = n and have unity Pf then according to question.

$750\ \text{kVA} = \left(\dfrac{500}{\text{P.f.}}\ \text{kw}\right) + \left(\dfrac{n \times 100}{\text{P.f.}}\right)$

$750 \times 19^3 = \dfrac{500 \times 10^3}{0.8} + \dfrac{n \times 100}{1}$

$\Rightarrow\ n = 1250$ nos.

28. **A 3-phase, star-connected, 1500 kVA, 13 kV alternator has armature winding resistance of 0.1 Ω per phase. In each of the following cases if the alternator is supplying rated full load current at rated terminal voltage, calculate emf generated and voltage regulation.** **[2074]**

Case-I Unity power factor

Case - II 0.8 p.f. lagging

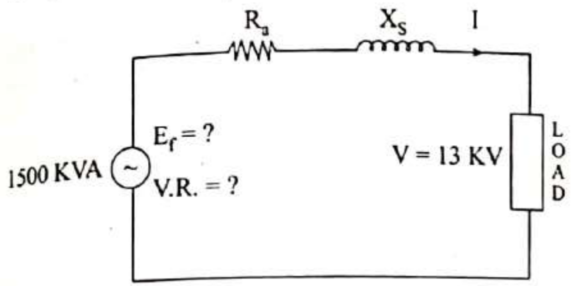
Case-III 0.8 p.f leading

Case I: Fully rated with unity p.f.

$1500\ \text{kvA} = \sqrt{3} \times V \times I$

$\therefore\ I = \dfrac{1500 \times 1000}{\sqrt{3} \times 13 \times 1000} \angle 0° = 66.6192 \angle 0°$ (∵ Pf = 1)

Voltage per phase $= \dfrac{13000}{\sqrt{3}} = 7505.7736 = 7506$ volt.



$\bar{I} = \bar{V} + \bar{I}\,(R_a + jX_s)$

$= 7056 \angle 0° + 66.62 \angle 0° (0.1 + j2.4)$

$= 7512.662 + j159.88$

$= 7514.11 \angle 1.22°$

Voltage regulation (V.R.) $= \dfrac{V_{NL} - V_{FL}}{V_{FL}}$

$= \dfrac{7514.11 - 7506}{7506} \times 100\%$

$= 0.11\%$

Case-II Fully loaded with 0.8 Pf lagging

$\phi = \cos^{-1}(0.8) = 36.87°$

$\therefore \ I = 66.62 \angle -36.87°$

$\bar{V} = \bar{E} - \bar{I}(R_a + jX_s)$

$= 7606\angle 0° - 66.62 \angle -36.87° * (0.1+j2.4)$

$= 7506 \angle 0° - 160.02 \angle 50.74°$

$= 7608.05 \angle 0.93°$

$$\text{Voltage regulation (VR)} = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100\%$$

$$= \frac{7608.06 - 7506}{7506} \times 100\%$$

$= 1.5\%$

Case-III fully loaded with P.f. 0.8 lead

$\therefore \ \bar{I} = 66.62 \angle 36.87°$

$\bar{E} = 7506 - (66.62 \angle 36.87°) * (2.402 \angle 87.61°)$

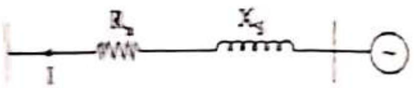
$= 7416.35 \angle 1.02°$

$$V.R = \frac{(7416.35 - 7505.77)}{7505.77} \times 100\%$$

$= -1.1913\%$

29. **A 3-phase, star connected, 1200 kVA, 6.6kV alternator has armature winding resistance of 0.4Ω per phase and synchronous reactance of 6Ω per phase. The alternator delivers full load current at Pf 0.8 lagging at normal rated voltage. Calculate the terminal voltage for the same excitation and load current at 0.8 P.f. leading.** [2073]

Solution:



$V = 6.6\ kv$

$f = 50\ Hz$

$$V_{ph} = \frac{6.6 \times 1000}{\sqrt{3}} = 3810.62v$$

Here,

$$I = \frac{1200}{\sqrt{3} \times 6.6kv} = 104.97\ \text{Amp} \angle -36.87°$$

$\bar{V} = \bar{E} + \bar{I}(R_a + jX_s)$

$= 3810.62 + (104.97 \angle -36.87°) * (6.013 \angle 86.186°)$

$= 3399.28 - j478.497$

$= 343279 \angle -9.01°$

For same excitation voltage,

If $I = 104.97 \angle 36.87°$

$\bar{V} = \bar{E} - \bar{I}(R_a + jX_s)$

$= (34.32.79 \angle -8.01°) + (104.97 \angle 36.87°) * (6.013 \angle 86.186°)$

$= (3399.28 - j478.497) + 631.18 \angle 123.056$

$= 3055.06 + j50.56$

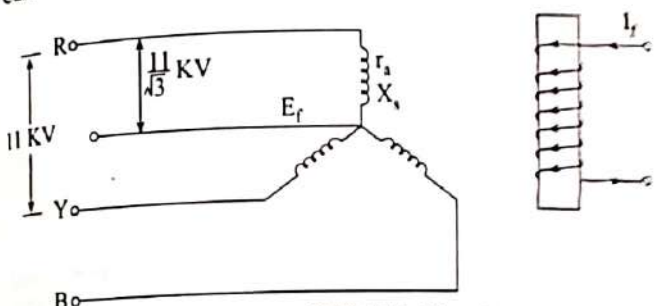
$= 3055.48 \angle 0.948$

30. **A 3-phase, star-connected 1000 kvA, 11kV synchronous motor has armature winding resistance of 0.35Ω per phse and synchronous reactance of 4Ω per phase. Determine the back emf induced and the angular retardation of the rotor when the motor is fully loaded at following three cases.** [2072]

Case - I Unity power factor

Case - II 0.8 P.f. lagging

Case - III 0.8 p.f. leading



1000 KVA (Motor)

Per phase applied voltage

$$V = \frac{11000}{\sqrt{3}} = 6351.04 \angle 0°$$

reference phasor

$Z_s = R_a + jX_s = 0.35 + j4 = 4.015 \angle 84.99°$

Case-I

Fully loaded with unity P.f.

$$\bar{I} = \frac{100 * 1000}{\sqrt{3} \times 11 \times 1000} = 62.48 \angle 0^\circ$$

(as pf is unity)

$$E = V - \bar{I}(Z_s)$$
$$= 6351.04 \angle 0^\circ - (52.48 < 0^\circ)(4.015 \angle 84.9)$$
$$= 6351.04 - (18.4 + j209.9)$$
$$= 6332.64 - j209.9$$
$$= 63361.1 \angle -1.89^\circ \text{ (angular retardation)}$$

Case-II

Fully loaded with 0.8 Pf lagging

$$\bar{I} = 52.48 \angle -36.87$$

$$E_f = \bar{V} - \bar{I}(Z_s)$$
$$= 6351.04 - (52.48 \angle -36.87) * (4.0115) \angle 84.99^\circ)$$
$$= 6351.04 - 138.3 - j158.956$$
$$= 6212.74 - j158.958$$
$$= 6214.77 \angle(-1.46^\circ) \text{ (angular retardation)}$$

Case-III

Fully loaded with 0.8 pf leading

$$\bar{I} = 52.48 \angle 36.86^\circ$$

$$\bar{E}_f = 6351.04 \angle 0^\circ - (52.48 \angle 36.86^\circ) \times (4.015 \angle 84.9)$$
$$= 6351.04 \angle 0^\circ - 210.7 \angle 121.86^\circ$$
$$= 6464.72 \angle -1.580^\circ$$

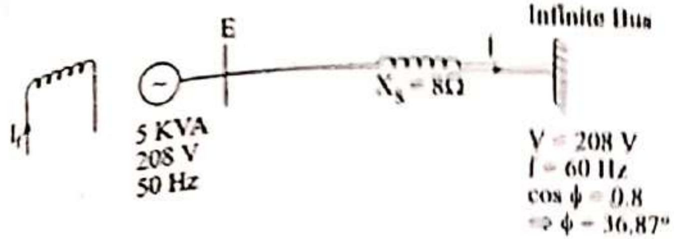
(angular retardation)

31. A 3-phase, 5kVA, 208V, 4-pole, 60Hz star connected synchronous generator had negligible armature winding resitacne and synchronous reactance of 8Ω per phase. The generator is first connected to an infinite bus of 208V, 60Hz.

i) Determine the excitation voltage and the power angle when the generator is delivering rated kVA at 0.8 pf lagging.

ii) If the field excitation is now increased by 20% (keeping turbine power constant), find the stator current, power factor and active and reactive power constant.

iii) With the field current as in case (i) the turbine power is slowly increased. What is the steady state stability limit (Maximum power that can be transfer). What are the corresponding values of stator current power factor and reactive power at this condition.



Solution:

Case-I

$$\bar{I} = \frac{5 \times 1000}{\sqrt{3} \times 208} = 13.88 \angle -36.87^\circ \text{ (w.r.t. } (\bar{V})$$

$$\bar{V} = \frac{208}{\sqrt{3}} = 120.1 \text{ V per phase}$$

$$\bar{E} = \bar{V} + \bar{I}(jX_s)$$
$$= (120.1 \angle 0^\circ) + (13.88 \angle -36.87^\circ) * (j8)$$
$$= 120.1 + 111.04 \angle 53.13$$
$$= 186.72 + j\,88.83$$
$$= 206.78 \angle 25.44^\circ$$

⇒ 358.14 volt line-to-line

Active power supplied = 5kV * cosφ = 4 kW

Case-II

When the field excitation is increased by 20%

$$E_f(\text{new}) = 1.2 * 206.78$$
$$= 248.136 \text{ volt.}$$

But active power remain same

(∵ turbine input is kept same)

$$P = \frac{3|V|\,.\,E_f(\text{new})}{|X_s|} \times \sin\delta \text{ new}$$

$$\sin\delta\text{new} = \frac{4000 \times 8}{3 \times 120.1 \times 248.136} = 0.358$$

$$\therefore \quad \delta_{new} = 21^\circ$$

Then,

$$\bar{I} = \frac{E_f \text{ new} - \bar{V}}{jX_s} = \frac{248.21 \angle 21^\circ - 120.1 \angle 0^\circ}{8 \angle 90^\circ} = 17.86 \angle -51.5^\circ$$

$$\therefore \quad P_F = \cos(-51.5) \text{ lagging} = 0.62 \text{ lag}$$

Reactive Power = 2V.I sinφ = 5.03 kiVAR

Case-III

When power input from turbine increases, the power angel δ increases and more active power will be delivered to infinite.

max power transfer occurs at $\delta = 90°$

$$\therefore \quad P_{max} = \frac{3E_f V.\sin(\delta - 90)}{X_s}$$

$$= \frac{3 * 206.9 * 120.1 \times 1}{8}$$

$$= 9.32 \text{ kw limit}$$

$$\therefore \quad I_a(max) = \frac{E_f - V}{jX_s} = \frac{206.9 \angle 90° - 120.1\angle 0°}{8 \angle 9°}$$

$$= 29.9 \angle 30.1° \text{ Amp}$$

P.f. = cos30.1° = 0.865 (leading)

Reactive power = 3VI sin30.1°

$$= 3 \times 120.1 \times 29.9 \times \sin 30.1°$$

$$= 5.4 \text{ kVAR}$$

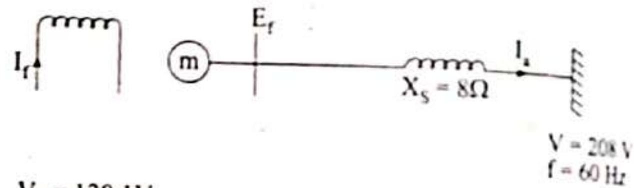
32. The synchronous machine in Q.N.5 is operated as motor form the 3-phase, 208V, 60Hz power supply. The field excitation is adjusted so that the power factor is unity and the motor draw a power of 3kw form the supply.

i) Find the excitation voltage and power angle. Draw the phasor diagram for this condition.

ii) If the excitation is held constant and the shaft load is slowly increased, determine the maximum torque (pull out torque) that the motor on delivered.

Solution:

<u>Case-I</u>



$V_p = 120.1V$

p.f. = unity

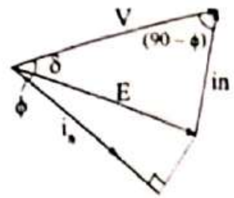
P = 3kW

$$\therefore \quad I_a = \frac{3000}{3 \times 120.1} = 8.36 \angle 0° \text{ w.r.t. } \bar{V}$$

$$E_f = I_a * (jX_s)$$

$$= 120.1 < 0° - 8.33 \angle 0° * 8 \angle 90°$$

$$= 137.35 \angle -29°$$



Here, $\phi = \cos^{-1}(1) = 0°$

<u>Case-II</u>

If I_f = k, its shaft load is increased, maximum power occurs at

$\delta = 90°$

$$P_{max} = \frac{3V * E_f}{X_s}(\sin 90°) = \frac{3 \times 120.1 * 137.35 \times \sin 90°}{8} = 6180.75w$$

Corresponding

$$T_{max} = \frac{P_{max}}{\omega_{syn}}$$

$$N_s = \frac{120}{P} = \frac{120 \times 60}{4} = 800 \text{ rpm}$$

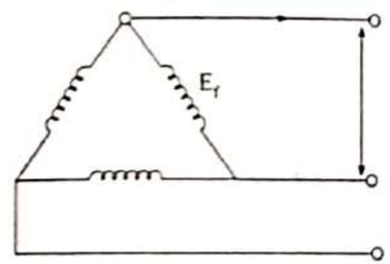
$$\omega_s = \frac{1800}{60} \times 2\pi \text{ rad/sec}$$

$$\therefore \quad T_{max} = \frac{6180.75}{\frac{1800}{60} * 2\pi} = 32.8 \text{ N-m}$$

33. A 50 Hz, 3-phase, 480v, delta connected salient pole synchronous generator has X_d = 0.1Ω and X_q = 0.075Ω. Armature winding resistance is 0.01 Ω per phase the generator supplies a 1200A at 0.8 pf lagging. Calculate the excitation emf. **[2070]**

Solution:

I_L = 1200 A @ 0.8 pf lagging



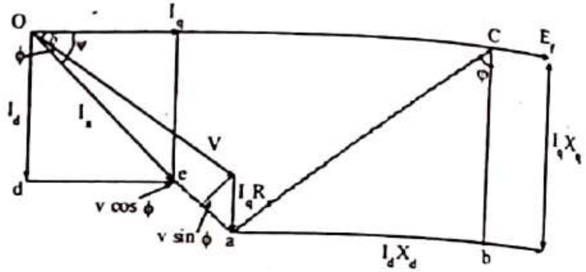
$X_d = 0.1\Omega$
$X_q = 0.075\ \Omega$
$R_A = 0.01\ \Omega$
$V_p = 480V$

$I_a = \frac{12000}{\sqrt{3}} = 692.82°A$

$\cos\phi = 0.8 \qquad \Rightarrow = 36.86°$

$\bar{I}_a = 692.82\ \angle{-36.86°}$

$\sin\phi = 0.6$



$\therefore$ Δoed and Δcab are identical

$\therefore \quad \frac{ac}{oe} = \frac{bc}{de}$

$ac = \frac{bc}{de} \times oe$

or, $\quad oe = \frac{(I_q.X_q) * I_a}{I_q}$

$= I_a.xq$

$\therefore\ \tan\phi = \frac{V.\sin\phi + I_a.r_a}{V.\cos\phi + I_a.R_a} = \frac{480 \times 0.6 + 692.84 \times 0.075}{480 \times 0.8 + 692.84 \times 0.01} = 0.8692$

$\Rightarrow \quad \psi = 41.011°$

$\therefore \quad \delta = 41.011° - 36.87° = 4.14119°$

$I_d = I_a\sin\psi = 692.84 \times \sin 41.011°$

$= 454.543\ \angle{-90°}$

$I_q = I_a.\cos\psi$

$= 692.84 * \cos 41.011°$

$= 522.96\ \angle 0°$

$E_f = \bar{V} + \bar{I} + a\ R_a + \bar{I}_d\,(jX_d) + I_q * (jX_q)$

or, $\quad E = V\cos\delta + I_qR_a + I_d\ X_d$

$= 480 \times \cos(4.14119°) + 522.86 \times 0.01 + (454.643\ \angle{-90°}) \times 0.1$

$= 529.429V$

NOTE

i) When armature resistance is neglected

$\tan\delta = \frac{I_a\ X_q\ \cos\phi}{V \pm I_aX_q\ \sin\phi}$

$I_d = I_a\ \text{isn}\ (\phi+\delta)$

$I_q = I_a\ \cos(\phi + \delta)$

$E = V\cos\delta + I_d.X_d$

$\delta = \psi - \phi$ for generating moe

$\delta = \phi - \psi$ for motoring mode

$\therefore \quad \psi = \phi \pm \delta$

ii) When armature resistance is not neglected.

$\tan\psi = \frac{V\sin\phi \pm I_aX_q}{V\ \cos\phi \pm I_aR_q}$

$\left.\begin{array}{l} I_d = I_a\sin\psi \\ I_q = I_a\ \cos\psi \end{array}\right\} \quad \psi = \phi \pm \delta$

$E = V\cos\delta + I_q\ R_{aq} + I_dX_d$

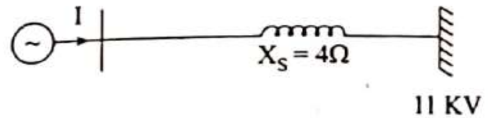
34. **A 3-phase alternator delivers 100A at 0.8 pf lagging to an infinite has of 11kV, 50Hz. The alternator has negligible stator resistance and synchronous reactance of 4Ω per phase.** **[2073]**

i) **Find the openj circuit emf and load angle.**

ii) **When input of the prime mover is increased the power angle is increased by 10°. Find the new stator current and power factor.**

iii) **The excitation is changed now till the power factor becomes 0.8 lagging. Find the new value of stator current.**

Solution:



Phase voltage $V_p = \frac{11000}{\sqrt{3}} = 6350.85V$

$I = 100A$

$\cos\phi = 0.8$ lagging

$\Rightarrow \quad \phi = 36.87°$

$\therefore \quad \bar{I} = 100\ \angle{-36.87°}$

Now,

i) Emf $\bar{E} = \bar{V} + \bar{I}\,(jX_s)$

$= 6350.85 + (100\angle -36.87^\circ) * (j4)$

$= 6598.8\angle 2.7$

$\therefore$ $|E| = 6598.8V$

$\delta = 2.7^\circ$

ii) $\delta' = 10 + 2.7 = 12.7^\circ$

$\therefore$ $E' = 6598.8\angle 12.7^\circ$

$\therefore$ $\bar{E}' = \bar{V} + \bar{I}'\,(jX_s)$

$6598.8\angle 12.7^\circ = 6350.85 + I'(j4)$

$I'(4\angle 90^\circ) = 1453.29\angle 86.58^\circ$

$\bar{I}' = 367.76\angle -3.41539$

$\therefore$ $|I'| = 367.76A$

P.f. $\cos\phi = \cos(8./412539)$ log $= 0.986^\circ$ lag.

35. A 3-phase star connected 50kVA, 440V alternator has effective armature resistance of 0.25 Ω/phase and synchronous reactance of 3.2Ω/phase and leakage reactance of 0.5 Ω/phase. Determine at rated current, voltage regulation in each of the cases. [207..]

i) Unity pf

ii) 0.8 pf lag

iii) 0.8 pf lead.

Solution:

Full load line voltage = 440V

Per phase voltage $v = \frac{440}{\sqrt{3}} = 254.034V$

$R_a = 0.25\ \Omega/ph$

$X_S = 3.2\ \Omega/ph$

Now, current at full load,

$50 \times 10^3 = \sqrt{3} \times V_L \times I_L$

$I_L = \frac{50 \times 10^3}{\sqrt{3} \times 440} = 65.608$ Amp.

<u>Case - I</u>

At unity p.f. $\cos\phi = 1$ $\sin\phi = 0$

$V.R. = \frac{E.V}{V} \times 100\%$

No load voltage,

$E_0 = \sqrt{(V\cos\phi + IR)^2 + (V\sin\phi + IX)^2}$

$= \sqrt{(254.034 + 65.6 * 0.25)^2 + (65.6 * 3.2)^2}$

$= 342.346$ volts

$\therefore$ $VR = \frac{342.346 - 254.034}{254.034} \times 100\% = 34.76\%$

<u>Case - II</u>

At 0.8 pf lag, $\cos\phi = 0.8$, $\sin\phi = 0.6$

$E_0 = \sqrt{(V\cos\phi + IR)^2 + (V\sin\phi + IX)^2}$

$= \sqrt{(254.034 * 0.8 + 65.6 * 0.25)^2 + (254.034 * 0.6 + 65.6 * 3.2)^2}$

$= 423.705$ volts.

$\therefore$ $VR = \frac{E_0 - V}{V} \times 100\%$

$= \frac{423.705 - 254.034}{254.034} * 100\%$

$= 66.79\%$

<u>Case-III</u>

At 0.8 Pf lead.

$E_0 = \sqrt{(V\cos\phi + IR)^2 + (V\sin\phi + IX)^2}$

$= \sqrt{(254.034 * 0.8 + 65.6 * 0.25)^2 + (254.034 * 0.6 - 65.6 * 3.2)^2}$

$= 227.029$ votls.

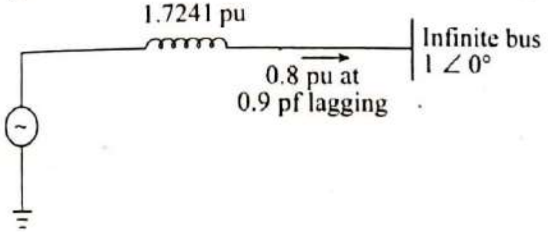
$\therefore$ $V.R. = \frac{E_0 - V}{V} * 100\% = \frac{227.029 - 254 -.034}{254.034} \times 100\% = -10.63\%$

36. A generator has synchronous reactance of 1.7241 pu and is connected to a very large system. The terminal voltage of generator is 1∠0° pu and the generator is supplying a current of 0.18 pu at 0.9 pf lagging, neglecting the resistance calculate.

i) Internal voltage induced

ii) Active and reactive power O/P of generator

iii) The power angel and reactive power output if the excitation of generator is increased by 28% if active power output is constant.



Internal voltage induced,

$E = 1\angle 0° + 0.8 \angle -\cos^{-1}(0.9) * j1.7241$

$= 1\angle 0° + 0.8 \angle -25.84 * j1.7241$

$= 2.026 \angle -37.786$

Complex power, $S_e = V \times I^*$

$= 1\angle 0° \times 0.8 \angle 25.84°$

$= (0.72 + j0.35)$ pu

$\therefore$ $P_e = 0.72$ pu

$Q_3 = 0.35$ pu

OR

$$P_e = \frac{|E|\,|V|}{|X|}\sin\delta$$

$$= \frac{2.026 \times 1}{1.7241}\sin 37.786$$

$= 0.72$ pu

$$Q_e = \frac{|E||V|}{|X|}\cos\delta - \frac{V^2}{X_s}$$

$$= \frac{2.026 \times 1}{1.7241}\cos 37.786 - \frac{1}{1.7241}$$

$= 0.35$

As the excitation is increased, back emf is also increased proportional.
As the electrical power O/P of the bus is constant.

$E' = 1.28 \times E$

$= 1.28 \times 2.026$

$= 2.4312$ pu

$$\therefore \quad P = \frac{|E'|\,|v|}{X}.\sin\delta$$

$\sin\delta = 0.50979$

$\delta = \sin^{-1}(0.50979)$

$\delta = 30.65°$

$\therefore$ Reactive power output

$$= \frac{|E|\,|V|}{X_s}\cos\delta - \frac{V^2}{X_s}$$

$$= \frac{2.4312 \times 1}{1.7241} * \cos 30.65 \ \frac{-1}{1.7241}$$

$= 0.635$ pu

From this we can conclude that as excitation is increased the reactive power O/P to the bus is increased.

37. **A 3-ϕ alternator has a direct axis synchronous resistance of 0.7 pu and quadrature axis synchronous reactance of 0.4 pu. Draw the vector diagram of 0.4 pu. Draw th vector diagram of full load 0.8 pf lagging and obtain.**

i) **load angle**

ii) **components of armature currents (I_d & I_a)**

iii) **no-load pu voltage**

iv) **voltage regulation.**

Solution:

Terminal voltage (V) = i pu

Armature current (I_a) = 1pu

$X_d = 0.7$ pu

$X_q = 0.4$pu

Armature resistance (R_a) = 0

$\cos\phi = 0.8$

$\sin\phi - 0.6$

$\phi = 36.87°$

i) load angle $\tan s = \frac{I_a\, xq \cos\phi}{v + I_a X_q \sin\phi} = \frac{1 * 0.4 * 0.8}{1 + 1 \times 0.4 \times 0/6} \Rightarrow \delta = 14.47°$

ii) $I_d = I_a \sin(\phi + \delta) = 1 \times \sin(36.87° + 14.47°) = 0.781$ pu

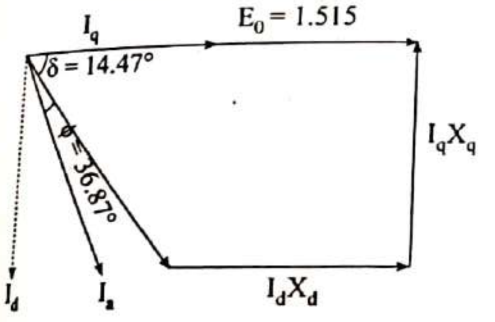
$I_q = I_a \cos(\phi + \delta) = 1 \times \cos(36.87° + 14.47) = 0.625$ pu

iii) $E_0 = v\cos\delta + I_d.X_d = 1 * \cos(14.47) + 0.781 * 0.7 = 1.515$ pu

iv) $V_R = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\%$

$= \frac{1.515 - 1}{1} \times 100\%$

$= 51.,5\%$



38. A 3-ϕ star connected, 50Hz synchronous generator has direct axis synchronous reactance of 0.6 pu and quadrature axis synchronous reactance of 0.45 pu. Draw the phasor diagram at full load 0.8 pf lagging and hence calculate.

i) load angle

ii) I_d circuit voltage.

iii) open circuit voltage.

iv) voltage regulation.

Resistance drop; at full load is 0.015 pu.

Solution:

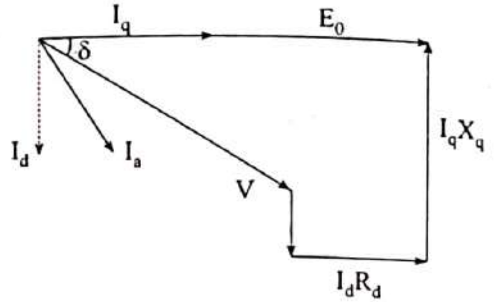


Fig. $\tan\psi = \frac{V\sin\phi + I_a.X_a}{V\cos\phi + I_aR_a} = \frac{1 \times 0.6 + 1\times0.45}{1\times0.8 + 1\times0.015}$

⇒ $\psi = 52.18$

*Armature resistance is not neglected)

i) $\delta = \psi - \phi$ (generating mode)

$\delta = \phi - \psi$ (motoring mode)

∴ $\delta = \psi - \phi = 15.31°$ [$\because \phi = \cos^{-1}(0.8)$]

ii) $E_0 = V\cos\delta + I_q R_a + I_d \times d$

Here,

$I_q = I_q \cos(\phi + \delta)$

$= 1 \times \cos52.18° = 0.614$ pu

$I_d = I_a$ isn $(\phi + \delta)$

$= 1$ □ $\sin 52.18° = 0.7899$ pu

∴ $E_0 = 1.448$

$V_R = \frac{1448 - 1}{1} \times 100\%$

$= 44.8\%$

39. A 3.5 MVA, slow sped, 3-ϕ synchronous generated at 6.6 kV has 32 poles. It's direct and quadrature axis synchronous reactance as measured by the slp test are 9.6Ω and 6Ω respectively. Neglecting armature resistance, determine the regulation and excitation emf needed to maintain 6.6 kV at the terminals when supplying a load of 2.5 MW at 0.89 pf lagging. What maximum power can generator supply at the rated terminal voltage, if the field becomes open circuited?

Solution:

$v = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810.5v$

$\delta = 15.3°$ [$\because \delta = \phi - \phi$]

(same as calculated earlier)

$\left.\begin{array}{l} I_d = 215.94A \\ E_0 = 5748V \\ VR = 50.85\% \end{array}\right\}$ (same on Q.N. 4)

Now,

The total power generated by synchronous generator is

$P_{3-\phi(total)} = \frac{3E_0V}{X_d}\sin\delta + \frac{3v^2}{2}\left\{\frac{1}{X_q} - \frac{1}{X_d}\right\}\sin 2\delta$

When the field get open circuited then power developed is

$P_{(3-\phi,\ total)} = \frac{3v^2}{2}\left\{\frac{1}{x_q} - \frac{-1}{x_2}\right\}\sin2\delta$

And maximum power developed when $\sin 2\delta = 1$

∴ Plaximum power developed

$P_{3-\phi(total,\ max)} = \frac{3v^2}{2}\left\{\frac{1}{x_q} - \frac{-1}{x_2}\right\} = \frac{3}{2}(381.05)^2\left(\frac{1}{6} - \frac{1}{9.6}\right) = 1.361$

OR $X_d = 9.6\Omega$

$X_q = 6\ \Omega$

Power =2.5 MW at 0.8 Pf lagging

$\phi = \cos^{-1}(0.8) = 36.87°$

Per-phase voltage, $V = \frac{6.6 \times 10^{-3}}{\sqrt{3}} = 3810.5$ volt.

Armature current $I_a = \frac{2.5 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3 \times 0.8} = 273.37$ Amp

We know,

$E = V\cos\delta + I_d \times d$

∴ $\tan\delta = \frac{IX_q\cos\phi}{V + IX_q \sin\phi}$

⇒ $\delta = 15.3°$

$\therefore \quad \theta = \phi + \delta = 36.87° + 15.3° = 52.17°$ (or ψ)

$V\sin\delta = I_q X_q$ and $I_q = I\cos\theta = I\cos(\delta + \phi)$

$I_d = I\sin\theta = 273.31 * \sin 52.17°$

$= 215.94$ Amp.

$E = V\cos\delta + I_d X_d$

$= 3801.5 * \cos 15.3° + 215.94 * 9.6$

$= 5748$ Volts

E(line to line) $= \sqrt{3} \times 5748 = 9956$ Volts.

$$\text{Regulation} = \frac{|E| - |V|}{|V|} \times 100\% = \frac{9956 - 6600}{6600} * 100\% = 50.85\%$$

ii) Total power output of machine

$$P = \frac{V_2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta + \frac{|E| - |V|}{X_d}\sin\delta$$

When field is open E = 0 then,

$$P_{1\text{-}\phi} = \frac{V_{Ph}^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta$$

$$= \frac{(3810.5)^2}{2}\left[\frac{1}{6} - \frac{1}{9.6}\right] \times \sin 90°$$

$= 0.45375$ MW.

$P_{3\text{-}\phi} = 3X\, P_{1\text{-}\phi}$

$= 1.361$ MW.

40. A 3000V, 3 - ϕ synchronous motor running at 1500 rpm has its excitation kept constant corresponding terminal voltage of 3000V. Determine the power input, power factor and torque developed for an armature current of 250A if X_s = 5Ω/Ph and R_a is neglected. [2075]

Solution:

$$V = \frac{3000}{\sqrt{3}} = 1732V$$

$$E = \frac{3000}{\sqrt{3}} = 1732V$$

$Z_s = 0 + j5 = 5\angle 90°$

$E_f = V - I_a Z_s$ and $\bar{I}_a = I_a\angle -\phi$

$E_f = V - (I_a \angle -\phi) . (5\angle 90°)$

$= V - 250 \times 5\angle(90 - \phi)$

$= V - 1250(\cos(90 - \phi) + j\sin(90 - \phi))$

$= (V - 1250\sin\phi) - j(1250)\cos\phi$

$E_f^2 = (V - 1250\sin\phi)^2 + (1250\cos\phi)^2$

$1732^2 = V^2 - 2 \times V \times 1250\sin\phi + 1250^2 . \sin^2\phi + 1250^2\cos^2\phi$

$1732^2 = 1732^2 - 2500\sin\phi + 1732 + 1562500$

$$\sin\phi = \frac{1262500}{2500 \times 1732}$$

$= 0.3608$

$\boxed{\cos\phi = 0.9326 \text{ lag}}$

Input power,

$P_{in} = \sqrt{3}\, V_L I_a \cos\phi$

$= \sqrt{3} \times 300 \times 250 \times 0.9326$

$= 1299.51$ kw

$$P_i = T \times \frac{2\pi N_s}{60}$$

$$T = \frac{P_i \times 60}{3\pi N_s} = \frac{1211.51 \times 10^3 \times 60}{2\pi \times 1500} = 7712.7 \text{ N-m}$$

41. A 500V, 50HZ, 3-phase circuit takes 20A at a lagging power factor of 0.84 synchronous motor is used to raise the power factor unity. Calculate the kVA input to the motor, and its power factor when driving a mechanical load of 7.5 kW. The motor has an efficiency of 85%.

Solution:

kVAR drawn by the 3-phase circuit,

$Q = \sqrt{3}\, V_L I_L \sin\phi \times 10^{-3}$

$= \sqrt{3} \times 500 \times 20 \times 0.6 \times 10^{-3} = 10.392$ kVAR

Power supplied by the motor,

$$P = \frac{\text{output in kW}}{\eta} = \frac{7.5}{0.85} = 8.8235 \text{ kW}$$

Power factor will be raised to unity when kVAR (leading) drawn by a 3 phase synchronous motor will become equal to the kVAR drawn by 3-ϕ ac circuit.

i.e. kVAR drawn by synchronous motor, Q = 10.3923 (lagging)

kW drawn synchronous motor, P = 8.8235

kVA input to the motor,

$$\delta = \sqrt{P^2 + Q^2} = \sqrt{8.9235^2 + 10.3923^2} = 13.63 \text{ kvA}$$

$$\text{Power factor, } \cos\phi = \frac{P}{s} = \frac{8.8235}{13.63} = 0.6472 \text{ (leading)}$$

42. The excitation of a 415V, 3-phase, mesh-connected synchronous motor is such that the induced emf is 520V. The impedance per phase is (0.5+j4)Ω. If the friction and iron losses are constant at 1000W, calculate the power output, line current, power factor and efficiency for maximum power output.

Solution:

Supply voltage/phase, V = 415v

∵ motor is mesh connected

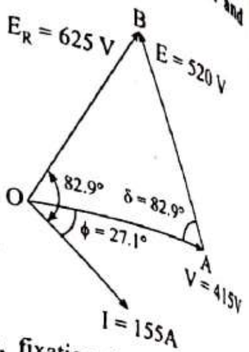
Inducted emf/phase, E = 520V

Synchronous impedance/phase,

$$Z_s = \sqrt{(0.5)^2 + 4^2} = 4.03\Omega$$

Internal angle, $\theta = \tan^{-1}\frac{XS}{Re}$

$$= \tan^{-1}\frac{4}{0.5} = 82.9°$$



For a constant value of supply voltage, fixation (or induced emf), effective resistance Re and synchronous reactance X_s maximum power will be developed when load angle.

$$\delta = \theta = 92.9°$$

Now from phasor diagram ΔOAB we have,

$$F_R = \sqrt{v^2 + F^2 - 2vE\cos\delta}$$

$$= \sqrt{415^2 + 520^2 - 2 \times 415 \times 520 \cos 82.9°}$$

$$= 625 \text{ v/phase}$$

Load current, $I = \frac{E_r}{Z_s} = \frac{625}{4.02} = 155\text{A/phase}$

Line current, $I_L = \sqrt{3}\ I = \sqrt{3} \times 155 = 268.2\text{A}$

Maximum power developed per phase,

$$(P_{mesh})_{max} = \frac{E_y - E^2\cos\theta}{Z_s}$$

$$= \frac{620 \times 415 - 520^2 \times \cos 82.90°}{4.03} = 45255 \text{ W}$$

Maximum power for 3-phase,

$$= 3 \times 45255 = 135765\text{W}$$

Output power = power developed - from and friction losses

$$= 135765 - 1000$$

$$= 134.765 \text{ kW}$$

Total copper losses = $3I^2Re = 3 \times (155)^2 \times 0.5 = 36000\text{W}$

Input to motor = power developed + copper loses

$$= 135765 + 36000 = 171765\text{W}$$

Power factor, $\cos\phi = \frac{\text{Input to motor in watts}}{\sqrt{3}\ I_L V_L}$

$$= \frac{17165}{\sqrt{3} \times 415 \times 268.2} = 0.89$$

Efficiency, $H = \frac{\text{Output}}{\text{input}} \times 100 = \frac{134765}{171765} \times 100$

$$= 78.46\%$$

$$= \sqrt{454^2 - (I'Z_s\cos\phi')^2} = \sqrt{454^2 - (40 \times 2)^2} = 446.9\text{v}$$

$$OC = AC - OA = 4469 - 400 = 46.9\text{v}$$

$$E_R' = \sqrt{BC^2 + OC^2} = \sqrt{(40 \times 2)^2 + (46.9)^2} = 92.73\text{v}$$

Current, $I' = \frac{E'R}{ZS} = \frac{92.732}{2} = 46.366\text{A}$

$$\cos\phi' = \frac{I'\cos\phi'}{I'} = \frac{40}{46.366} = 0.863 \text{ (lead)}$$

43. A salient pole synchronous motor has X_d = 0.85 pu, and X_q = 0.55 pu. It is connected to bus-bars of 1.0 pu voltage, while its excitation is adjusted to 1.2pu. Calculate the maximum power output, the motor can supply without loss of synchronism. Compute the minimum pu excitation that is necessary for the machine to stay is synchronism while supplying the full-load torque (i.e. 1.0 pu power) [2073]

Solution:

For maximum power to be delivered by a salient pole synchronous motor, according to Eq^n:

$$\cos\delta = \frac{-EXq}{4v(Xd - Xq)} + \sqrt{\frac{1}{2} + \left[\frac{Exq}{4v(X_d - X_q)}\right]^2}$$

$$= \frac{-1.2 \times 0.55}{4 \times 1(0.85 - 0.55)} + \sqrt{\frac{1}{2} + \left[\frac{1.2 \times 0.55}{4 \times 1(0.85 - 0.55)}\right]^2} = 0.346$$

or, Load angle $\delta_{(max)} = \cos^{-1}(0.346) = 69.8°$

Now, maximum power is given by:

i.e. $P_{may} \sin\delta + \frac{v^2}{2}\left[\frac{1}{X_d} - \frac{1}{X_d}\right]\sin 2\delta$

$$= \frac{1.2 \times 1}{0.85}\sin 69.8° + \frac{1}{2}\left[\frac{1}{0.55} - \frac{1}{0.85_d}\right]\sin(2 \times 69.8°)$$

$$= 1.533 \text{ pu}$$

The power delivered due to excitation is given as

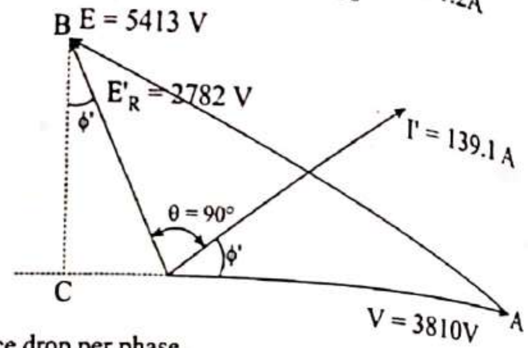
$$P = \frac{EV}{X_d}\sin\delta$$

Since excitation remains constant i.e. 5413V per phase. Supply voltage is also constant i.e. V = 3810 per phase.

Since power input $= \sqrt{3}\, V_L I_L \cos\phi$

So,

$$I_L \cos\phi = \frac{\text{Power input}}{\sqrt{3}\, V_L} = \frac{1500 \times 1000}{\sqrt{3} \times 6600} = 131.2A$$



Impedance drop per phase,

$$E_R' = I'X = 20I'$$

In ΔABC of phasor diagram shown in fig.

$$AB^2 + BC^2 + AC^2$$

or, $AC = \sqrt{AB^2 - BC^2} = \sqrt{E^2 - (E'R \cos\phi')^2}$

$$= \sqrt{(5413)^2 - (20 \times 131.2)^2} = 4734.3v$$

$$OC = AC - AO = 4734.3 - 3910 = 924.3V$$

$$E_R' = \sqrt{BC^2 + OC^2} = \sqrt{(20 \times 131.2)^2 + 924.3^2} = 2782v$$

Line current, $I' = \frac{E'R}{Z_s} = \frac{2782}{20} = 139.1A$

Power factor, $\cos\phi' = \frac{I'\cos\phi'}{I'} = \frac{131.2}{139.1} = 0.9423$ (leading)

46. A 3-phase, Y-connected synchronous motor takes 48kW at 693V (line), the pf being 0.8 lag. The induced emf is now increased by 30%, the power input being the same. Find the new current and Pf. Z_s equal to (0 + j2) ohm/phase. [2070]

Solution:

Supply voltage per phase, $V = \frac{693}{\sqrt{3}} = 400v$

Synchronous impedance per phase, $Z_S = X_s = 2\Omega \quad \because R_e = 0$

Internal angel $\theta = 90°$

At normal excitation

Power factor, $\cos\phi = 0.8$ (lag)

Power factor, $\phi = \cos^{-1} 0.8 = -36.87°$

Armature current/phase

$$I = \frac{kW\ input \times 1000}{\sqrt{3}\, V_L \cos\phi} = \frac{48 \times 1000}{\sqrt{3} \times 693 \times 0.8} = 50A$$

Impedance drop per phase,

$$E_R = IZ_s = 50 \times 2 = 100V$$

Induced emf per phase,

$$E = \sqrt{v^2 + E_R^2 - 2VE_R \cos(\phi + \theta)}$$

$$= \sqrt{400^2 + 100^2 - 2 \times 400 \times 100 \cos[(-36.87°) + 90°]}$$

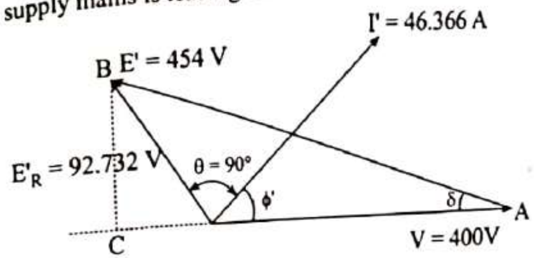
$$= 349.3V$$

When the excitation is increased by 30% the induced emf for phase E' will become $1.3 \times 349.3 = 454V$.

Since power input and supply voltage is constant, active component of current drawn remains unchanged i.e.

$$I'\cos\phi'\ 50 \times 0.8 = 40A.$$

The phasor diagram is shown below, assuming that the current from supply mains is leading one now.



In ΔABCD of the phasor diagram shown above,

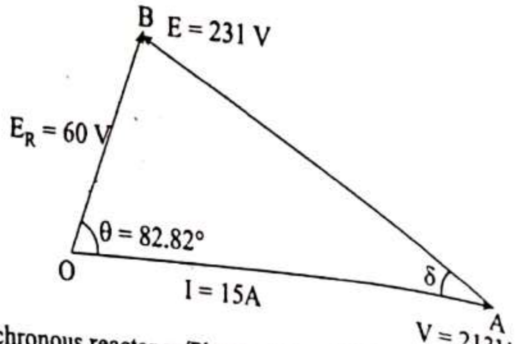
$$AC = \sqrt{AB^2 - BC^2} = \sqrt{E'^2 - (F'R \cos\phi)^2}$$

47. A 400v, 6-pole, 3-ϕ, 50Hz. star-connected synchronous motor has a resistance and synchronous impedance of 0.5Ω and 4Ω per phase respectively. It takes a current of 15A at unity power factor when operating with a certain field current. If the torque load is increased until the line current is increased to 60A, the field current remaining the same determine the gross torque developed and the new power factor.

Solution:

Supply voltage per phase, $V = \frac{400}{\sqrt{3}} = 231V$

Effective resistance/phase $R_e = 0.5\Omega$



Synchronous reactance/Phase = $X_s = \sqrt{4^2 - 0.5^2} = 3.968\Omega$

Synchronous impedance/phase, $Z_s = 4\Omega$

Internal angel, $\theta = \cos^{-1}\frac{R_s}{Z_s} = \cos^{-1}\frac{0.5}{4} = 82.82°$

When input current, $I = 15A$

and $\cos\phi$ = unity

Impedance drop, $F_R = IZ_s = 15\times4 = 60V$

Induced emf/phase,

$$E = \sqrt{V^2 + F_R^2 - 3vE_R\cos\theta}$$

$$= \sqrt{231^2 + 60^2 - 2\times231\times60\ c\ os82.82°}$$

$$= 231V$$

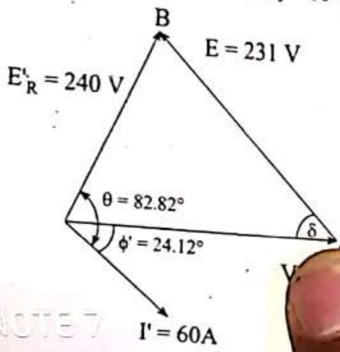
Now when the load on the motor is increased, the angle of retardation δ increases. The phasor diagram is shown fig below input current I' = 60A

Voltage per phase, v = 231V, as before

Induced emf per phase, E = 231V, as before

Since excitation is constant

Impedance drop/phase, $E'R = I'Z_s = 60\times4 = 240V$



Now in ΔOAB of phasor diagram we have

$E^2 = V^2 + E'R^2 - 2VE'R\cos\angle AOB$

or, $231^2 = 231^2 + 240^2 - 2\times231\times240\cos\angle AOB$

or, $\angle AOB = \cos^{-1}0.5195 = 58.7°$

Internal angel, $\theta = 82.82°$

∴ Power factor, $\cos\phi' = \cos24.12° = 0.9127$ (lag)

New motor input $= \sqrt{3}\,V_L I'L\cos\phi'$

$= \sqrt{3}\times400\times60\times0.9127$

$= 38$ kW

Input to synchronous motor, FM = $\frac{\text{Additional load in kw}}{\text{Motor efficienty}}$

$= \frac{1103.25}{0.8} = 1379.0625$ kW

Total land, $P = P_L + P_M = 4000 + 1379.0625 = 5379.0625$ kW

Power factor of combined load,

$\cos\phi = 0.95$ (lagging)

Phase angle, $\phi = \cos^{-1}0.95 = 18.195°$

Combined KUAR, $Q = P\tan\phi = 5379.0625\tan18.195°$

$= 1768$ (leading)

kVAR supplied by the synchronous motor,

$Q_M = Q_L - Q = 3000 - 1768 = 1232$ (leading)

kvA capacity of the motor,

$SM = \sqrt{FM^2 + QM^2} = \sqrt{(1379.0625)^2 + (1232)^2} = 1849.23$ kVA

Power factor of synchronous motor,

$\cos\phi_M = \frac{P_M}{S_M} = \frac{1379.0625}{1049.23} = 0.746$ (leading)

48. A synchronous motor improver the power factor of a load of 500kW from 0.707 lag to 0.95 lag. Simultaneously motor carries a load of 100kW. Find (i) the leading kVA supplied by the motor. (ii) kVA rating of motor (iii) power factor at which the motor operates. [2073]

Solution:

Load supplied, $P_L = 500$kW

Load power fctor, $\cos\phi_L = P_L\tan\phi_L$

$= P_L\tan(\cos^{-1}0.707)$

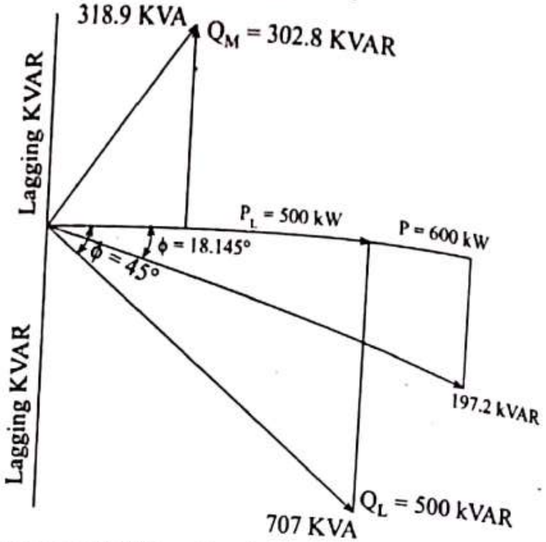
$= 500\tan45° = 500$ kVAR

Synchronous motor load, $P_M = 100$kW

Total load, $P = P_L + P_M = 500 + 100 = 600$ kW

Combined P_f, $\cos\phi = 0.95$ (lagging)

Phase angle, $\phi = \cos(0.95) = 18.95°$



Combined kVAR $= P\tan\phi_L$

$= 600 \tan 18.95°$

$= 600 \times 0.328684 = 197.21$ kVAR

(i) Leading kVAR supplied by motor,

$Q_M = Q_L - Q = 500 - 197.2 = 302.8$

(ii) kVA rating of motor, $S_M = \sqrt{P_M^2 + QM^2}$

$= \sqrt{100^2 + 302.8^2} = 318.9$

Power factor of motor, $\cos\phi_M = \frac{i_m}{S_m} = \frac{100}{318.9} = 0.3136$ (leading)

49. An industrial load of 4,000 kW. is supplied at 111kV, the if being 0.8 lagging. A synchronous motor is required to meet an additional lead of 1500 hp (1103.25 kW) and at the same time to raise the resultant power factor to 0.95 (lagging). Determine the kVA capacity of the motor and the power factor at which it must operate. Take the efficiency of the motor as 80%.

Solution:

Industrial Load, $P_L = 400$ kW

Power factor of load, cas $\phi_L = 0.8$ lagging

Load kVAR, $Q_L = P_L \tan\cos\phi_L$

$= 4000 \tan(\cos^{-1} 0.8) = 3000$ (lagging)

50. A 20 pole, 693V, 50Hz, 3-ϕ, Δ-connected synchronous motor is operated at no load with normal excitation. It has armature reactance per phase of 10Ω and negligible residence. If rotor is retarded by 0.5° mechanical from its synchronous position, compute (i) Rotor displacement in electrical degrees. (ii) armature emf per phase (iii) armature current per phase (iv) power drawn by the motor (v)power developed by the armature. **[2070]**

Solutions:

Supply voltage per phase, V = 693V

(i) Rotor displacement is electrical degrees,

$\delta_{(elec)} = \frac{P}{2}\delta(\text{mech}) = \frac{20}{2} \times 0.5 = 5°$ (elec)

Now from ΔAOB of phasor diagram shown in fig. we have

$E_R = \sqrt{V^2 + E^2 - 2VE\cos\delta}$

$= \sqrt{693^2 + 693^2 - 2 \times 693 \times \cos 5°} = 60.456$V

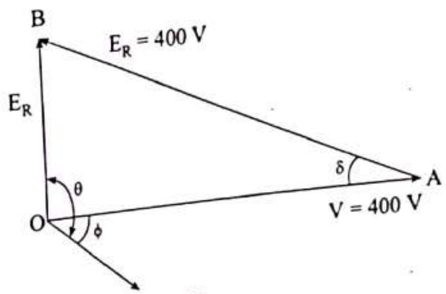
(ii) Armature curmet per phase,

$I = \frac{E_R}{Z} = \frac{60.456}{10} = 6.0456$A

From ΔAOB in fig

$\frac{AB}{\sin\angle AOB} = \frac{OB}{\sin\angle OAB}$ or, $\frac{693}{\sin(\theta - \phi)} = \frac{60.456}{\sin 5°}$ or, $\sin(\theta - \phi) = \frac{693\sin 5°}{60.456}$

$= 0.999$



or, $\theta - \phi = \sin^{-1} 0.999 = 87.44°$

phase angle, $\phi - \theta - 87.44° = 90° - 87.44° = 2.56°$ (lagging)

(iv) Power drawn by the motor,

$P_{in} = \sqrt{3}\, V_L I_L \cos\phi = \sqrt{3} \times 693 \times 6.0456 \times \cos 2.56° = 7249$w

(v) Power developed by the motor,

$i_{mesh} = P_{in} = 72$… $\because R_e$ is negligible

51. A 50Hz, 4- pole, 3-phase, star-connected synchronous motor has a synchronous reactance. The excitation is such as to give on open-circuit voltage of 13.2 kV. The motor is connected to 11.5kV, 50Hz supply. What maximum load can the motor supply before loosing synchronism? What is the corresponding motor torque, line current and power factor? [2071]

Solution:

Supply voltage/phase, $v = \frac{11.5 \times 1000}{\sqrt{3}} = 6640V$

Induced emf/phase, $E = \frac{13.2 \times 1000}{\sqrt{3}} = 7621V$

Internal angle, $\theta = 90°$

$\because$ armature resistance is negligible

Synchronous impedance/phase,

$Z_s = X_s = 12\Omega$

Power developed will be maximum when

Load angle, $\delta = \theta = 90°$

Impedance drop per phase,

$E_R = v^2 + E^2 - 2VE\cos\delta = \sqrt{(6640)^2 + (7621)^2 - 2 \times 6640 \times 7621 \times \cos 90°}$

$= 10108v$

Line current,

I_L = Phase current, $I = \frac{E_R}{Z_s} = \frac{10108}{12} = 842 = 3A$

The maximum load that motor can deliver,

$(P_{mesh})_{max} = 3\left[\frac{E_v}{Z_s} - \frac{E^2}{Z_s}\cos\theta\right]$

$= 3\left[\frac{6640 \times 7621}{12} - \frac{(7621)^2}{12}\cos 90\right] = 12.65MW$

Power supplied to motor,

$P_{in} = P_{mesh}$ + armature copper loss $= i_{mech} = 12.65$ (MW

$\because$ armature resistance is negligible

So, $\sqrt{3}\, V_L I_L \cos\phi = 23.65 \times 10^6$

or, Power factor, $\cos\phi = \frac{12.65 \times 10^6}{\sqrt{3} \times 11500 \times 842.3} = 0.7545$

Synchronous speed, $Ns = \frac{120f}{p} = \frac{120 \times 50}{4} = 1500$ rpm

Torque developed corresponding to maximum power developed,

$(T_{mech})_{max} = \frac{(P_{mech})_{max}}{2\pi n_s/60} = \frac{12.65 \times 10^6}{2\pi \times 1500/60} = 80532$ Nm

52. A 3-ph star-connected synchronous generator supply current of 104 having phase angle of 20° lagging at 400V. Find the load angle and the components of armature current I_d and I_q if X_d= 10Ω and X_q = 6.5Ω. Assume armature resistance to be negligible.

Solution:

Direct axis synchronous reactance per phase $X_d = 10\Omega$

Quadrature axis synchronous reactance per phase, $X_d = 6.5\Omega$

Armature current, I = 10A

Power factor angle, $\phi = 20°$ (lagging)

Terminal voltage per phase,

$V = \frac{400}{\sqrt{3}} = 230.94V$

$\tan\delta = \frac{IX_q\cos\phi}{V + IX_q\sin\phi} = \frac{10 \times 5.5 \times \cos 20°}{230.94 + 10 \times 6.5 \times \sin 20°} = 0.24126$

Load angle, $\delta = \tan^{-1} 0.24128 = 13.564°$

Angle, $\theta = \phi = 13.564° + 20° = 33.564°$

Direct axis component of armature current,

$I_d = I\sin\phi = 10\sin 33.564° = 5.53A$

Quadrature axis component of armature current,

$I_q = I\cos\theta = 10\cos 33.564° = 8.33A$

53. A 44MVA, 10.5 kV, 50Hz, star-connected three-phase salient pole synchronous generator has X_d= 1.83Ω and X_q = 1.21Ω. It delivers total load at 0.8 Pf lagging. The armature resistance is negligible. Determine the powr developed by the generator and the % age voltage regulators.

Solution:

Terminal voltage per phase,

$V = \frac{10.5 \times 1000}{\sqrt{3}} = 6062.17v$

Armature current,

$I = \frac{\text{Rated MVA} \times 10}{\sqrt{3}V} = \frac{44 \times 10^6}{53 \times 10.5 \times 1000} = 2419.37A$

Load phase angle, $\phi = \cos^{-1} 0.8 = 36.87°$

$\sin\phi = \sin 36.87° = 0.6$

Direct-axis synchronous reactance per phase $X_d = 1.83\Omega$

Quadrature - axis synchronous reactance per phase $Xq = 121\Omega$

We know,

$\tan\delta = \frac{IX_q\cos\phi}{v + IX_q\sin\phi} = \frac{2419.37 \times 1.21 \times 0.8}{6062.17 + 2419.37 \times 1.21 \times 0.6} = 0.2995$

Load angle, $\delta = \tan^{-1} 0.2995 = 16.67°$

Angle, $\phi + \delta = 36.87 + 16.67° = 53.545°$

Direct-axis component of current,

$Id = I\sin\phi = 2419.37 \sin 53.545 = 1945.95A$

Excitation voltage per phase

$E_0 = v\cos\delta + IdXd$

$= 6062.17 \cos 16.67 + 1945.95 \times 1.83 = 9368.49v$

$$\% \text{ regulation} = \frac{E_0 - V}{v} \times 100 = \frac{9368.49 - 6062.17}{6062.17} \times 100 = 54.54\%$$

Power developed by generator

$$= \frac{3E_0V}{X_d}\sin\delta + \frac{3V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta$$

$$= \frac{3 \times 9368.49 \times 6063.27}{1.83}\sin 16.67° + \frac{3 \times (6062.17)^2}{2}\left[\frac{1}{1.21} - \frac{1}{1.83}\right] \times \sin 2 \times 16.67$$

$= 35.19 \times 10^6 W$

$= 35.19MW$

54. A 3.5MVA, slow speed, 3-phase synchronous generator rated at 6.6 kv has 32 poles. Its direct and quadrature axis synchronous reactance as measured by the slip test are 9.5 and 6Ω respectively. Neglecting armature resistance, determine the regulation and excitation emf needed to maintain 6.6 kV at the terminate when supplying a load of 2.5MW at 0.8 Pf lagging. What maximum power can generator supply at the rated terminal voltage, ifthe field becomes open circulated?

Solution:

Terminal voltage per phase,

$$V = \frac{6.6 \times 1000}{\sqrt{3}} = 3810.5v$$

$$\text{Armature current, } = \frac{2.5 \times 10^6}{\sqrt{3} \times 6600 \times 0.8} = 273.37A$$

Load phase angle, $\phi = \cos^{-1} 0.8 = 36.87°$

$\sin\phi = \sin 36.87° = 0\text{-}6$

Direct-axis synchronous reactance per phase, $X_d = 9.6\Omega$

Quadrature axis synchronous reactance per phase, $X_d = 6\Omega$

We have,

$$\tan\delta = \frac{IX_q\cos\phi}{V + IX_q\sin\phi} = \frac{273.37 \times 6 \times 0.8}{3810.5 + 273.73 \times 6 \times 0.6} = 0.2737$$

or, $\delta = \tan^{-1} 0.2737 = 15.3°$

Angle $\theta = \phi + \delta = 36.87 + 15.3 = 52.17°$

Direct-axis component of current,

$I_d = I\sin\theta = 273.31 \sin 52.17° = 215.94A$

Excitation voltage per phase,

$E_0 = v\cos\delta + I_dX_d = 3810.5 \times \cos 15.3 + 215.94 \times 9.6 = 5748V$

Excitation voltage (line-to-line) = $53 \times 5748 = 9956v$

$$\text{Percentage regulation} = \frac{9956 - 6600}{6600} \times 100 = 50.85\%$$

When the field get open circuited, the power developed

$$= \frac{V_L^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\theta$$

The power developed will be maximum for $\sin 2\theta = 1$ and so the maximum power, that the generator can supply at the rated terminal voltage, with field open-circuited.

$$= \frac{V_L^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right] = \frac{(6600)^2}{2}\left[\frac{1}{6} - \frac{1}{9.6}\right] = 1.361 MW$$

55. A 10kVA, 380.50HZ, 3-phase, star-connected salient pole alternator has direct-axis and quadrature - axis reactance of 12Ω and 8.2 respectively. The armature has a resistance of 1Ω per phase. The generator delivers rated load at 0.8 Pf lagging with the terminal voltage being maintained at rated value. If the load angle is 16.15°, determine (i) the diet axis and quadrature axis components of armature current, (b) excitation voltage of the generator.

Solution:

Armature resistance, Re = 1Ω

Direct-axis synchronous reactance, $X_d = 12\Omega$

Quadrature-axis synchronous reactance, $X_q = 8\Omega$

Power factor, $\cos\phi = 0.8$

$\phi = \cos^{-1} 0.8 = 36.87°$

Load angle, $\delta = 16.15°$

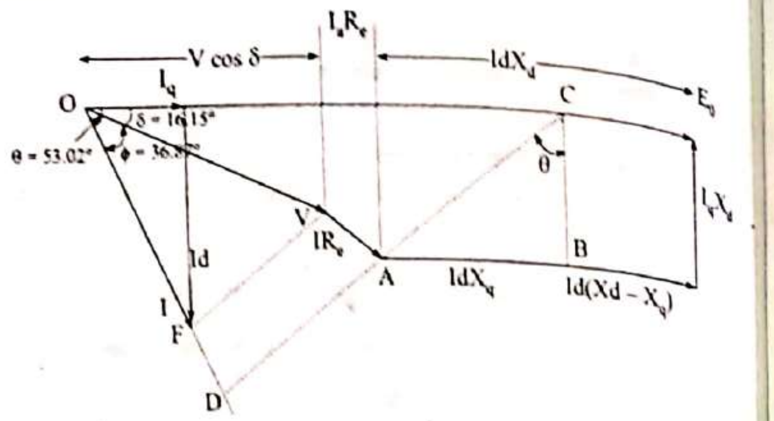
$\theta = \phi + \delta = 36.87° + 16.15° = 53.02°$

$$\text{Terminal voltage per phase, } v = \frac{380}{\sqrt{3}} = 219.4v$$

$$\text{Armature current, } I = \frac{KVA \times 1000}{\sqrt{3}\,V_L} = \frac{10 \times 1000}{\sqrt{3} \times 380} = 15.2A$$

Angle θ can also be determined as follows

$$\tan\theta = \frac{DC}{OD} = \frac{DA + AC}{OF + FD} = \frac{v\sin\phi + IX_q}{v\cos\phi + IRe} = \frac{219.4 \times 0.6 + 14.2 \times 8}{219.4 \times 0.8 + 15.2 \times 1} = 1.3278$$



$\theta = \tan^{-1} 1.3278 = 53.02^\circ$ the same as determined above.

Direct - axis component of armature current,

$Id = I\sin\theta = 15.2 \sin 53.02^\circ\ 12.14A$

Quadrature - axis component of armature current,

$I_q = I\cos\theta = 15.2 \cos 53.02 - 9.14A$

Excitation voltage, $E_0 = v\cos\delta + I_qRe + IdXd$

$= 219.4\cos 16.15 + 9.14 \times 1 + 12.15 \times 12$

$= 210.74 + 9.14 + 145.68 = 365.56v$

Excitation voltage (line-to-line) $= \sqrt{3} \times 365.56 = 633V$

56. A 3-phase, 415V, 6-pole, 50Hz star-connected synchronous motor has emf of 520v (L - L). The stator winding has a synchronous reactance of 2Ω per phazse, and the motor develops a torque of 220Nm. The motor is operating at 415v, 50HZ has (a) calculate the current drawn, form the supply and its power factor draw the phasor diagram shown all the relevant qualities. [2073]

Solution:

Supply voltage per phase, $V = \frac{415}{\sqrt{3}} = 239.6v$

Induced emf per phase, $E = \frac{520}{\sqrt{3}} = 300v$

Synchronous speed of motor,

$N_s = \frac{120f}{p} = \frac{120 \times 50}{6} = 1000$ rpm

Torque developed, T =220Nm

Total power developed,

$3\ imech = \frac{T \times 2\pi Ns}{60} = \frac{220 \times 2\pi \times 1000}{60} = 23038w$

Power developed per pahse $= \frac{23038}{3} = 7679w$

Synchronous impedance/phase,

$Z_s = 2\angle 90^\circ \Omega$

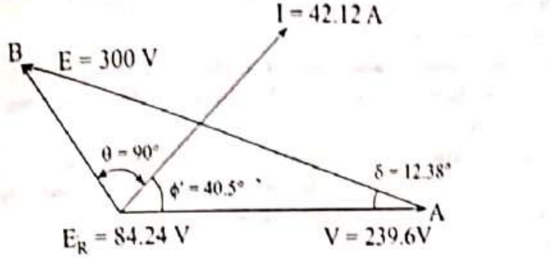
Power developed per phase is given as

$i_{mech} = \frac{Ev}{Z_s} cso(\theta - \delta) \frac{E^2}{Z_s} \cos\theta = \frac{E_s}{Zs} \sin\delta\ (\theta - 90^\circ)$

so $\frac{Ev}{Z_s} \sin\delta = 7.679$

or, $\sin\delta = \frac{7679 \times Z_s}{Ev} = \frac{7679 \times 2}{200 \times 239.6} = 0.2135$

or, $\delta = \sin^{-1}(0.2135) = 12.33^\circ$



From phasor diagram,

$E_R = \sqrt{V^2 + E^2 - 2VE\cos\delta}$

$= \sqrt{(239.6)^2 + (300)^2 - 2 \times 239.6 \times 300 \times \cos 12.33^\circ}$

$= 84.24v$

Current drawn per phase

$I = \frac{E_r}{Z_s} = \frac{84.24}{2} = 42.12A$

Again from phasor diagram

$\sin(\phi + \theta) = \frac{E}{E_R} \sin\delta = \frac{300}{84.24} \sin 12.33^\circ = 0.76$

or, $\phi + \theta = \sin^{-1}(0.76) = 130.5^\circ$

$\phi = 130.5 - 90^\circ = 40.5^\circ$

Power factor $= \cos\phi = \cos 40.5^\circ = 0.76$ (leading)

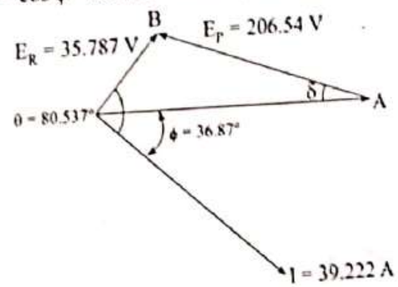


Fig. Phasor diagram

Mechanical power developed = power input = 372Re

$= 21749 - 3 \times (39.222)^2 \times 0.15 = 21.047$ kw

Also, $\dfrac{ER}{\sin\delta} = \dfrac{EP}{\sin(\theta - \phi)}$

or, $\dfrac{35.787}{\sin\delta} = \dfrac{206.54}{\sin(80 - 5377° - 36.87°)}$

$\therefore \quad \sin\delta = \dfrac{35.787 \sin 43.6677°}{206.54} = 0.11964$

Torque angle, $\delta = \sin^{-1} 0.11964 = 6.87°$

57. A 20MVA, 11kv, 3-phase, delta-connected synchronous motor has a synchronous impedance of 15Ω/phase. Windage, friction and iron losses amount to 1200 kw.

(i) Find the value of unity power factor current drawn by the motor a shaft load of 15MW. What is the excitation emf under this condition?

(ii) If the excitation emf is adjusted to 15.5kv (line) and the shaft load is adjusted so that the motor draws unit power factor current. Find the net motor output.

Solution:

(i) Shaft load = 15MW = 15000 kW

Mechanical power developed

P_{mech} = shaft load + windage friction and iron losses

= 15000 + 1200 = 16200 kW

Power input to motor,

$P = P_{mech}$ = 16200 kw neglecting armature resistance

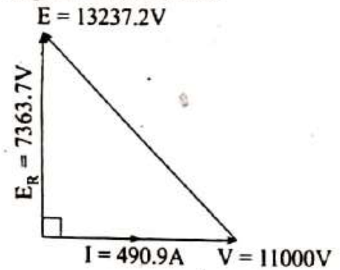
Line current, $I_L = \dfrac{P_{in} \text{ watts}}{\sqrt{3}\, V_L \cos\phi} = \dfrac{16200 \times 1000}{\sqrt{3} \times 11000} = 850.28\text{A}$

Phase current, $I_P = \dfrac{I_L}{\sqrt{3}} = \dfrac{850.28}{\sqrt{3}} = 490.9\text{A}$

Impedance drop per phase, $E_R = I_P X_S = 490.9 \times 145 = 7363.7\text{V}$

Internal angle, $\theta = 90°$ Assuming negligible armature resistance.

From phasor diagram shown below



Excitation emf,

$E = \sqrt{V^2 + E_R^2} = \sqrt{(11000)^2 + (7363.7)^2} = 13237.2\text{v}$

(ii) Impedance drop per phase,

$E_R = \sqrt{E^2 - V^2}$ ∵ Phase angle $\phi = 0°$ and $\theta = 90°$

$= \sqrt{(15500)^2 - (11000)^2}$

= 10920V

Load current per phase,

$I_P = \dfrac{E_R}{Z} = \dfrac{10920}{15} = 728\text{A}$

Line current, $I_L = \sqrt{3}\, I_P = \sqrt{3} \times 728 = 1261\text{A}$

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

$= \sqrt{3} \times 11000 \times 1261 \times 1.0$

= 24006.22kw

Net motor output = 24006.22 – 1200 = 22.80622 MW

58. A 20kw, 400v, 3-phase, star-connected synchronous motor has per phase impedance of (0.15+j0.9)Ω. Determine the induced emf, torque, angle and mechanical power developed for full load at 0.8 Pf lagging. Assume 92% efficiency of the motor. Draw phasor diagram. [2073]

Solution:

Motor input $= \dfrac{\text{Motor output}}{\eta} = \dfrac{20}{0.92} = 21.739\text{kW}$

Armature current, $I = \dfrac{\text{Motor input}}{\sqrt{3}\, V_L \cos\phi} = \dfrac{21739}{\sqrt{3} \times 400 \times 0.8} = 39.22\text{A}$

Supply voltage per phase,

$v = \dfrac{400}{\sqrt{3}} = 230.94\text{V}$

Resultant voltage, $E_R = I \times Z_s = 29.22 \text{ X } \sqrt{0.15^2 + 0.9^2} = 35.787\text{V}$

Internal angel, $\theta = \tan^{-1}\dfrac{X_S}{R_e} = \tan^{-1}\dfrac{0.9}{0.15} = 80.5277°$

Induced emf per phase, $E_p = \sqrt{V^2 + E_R^2 - 2VE_R \cos(\theta - \phi)}$

$= \sqrt{(230.94)^2 + (35.787)^2 - 2 \times 230.94 \times 35.787 \times \cos(80.5377° - 36.87°)}$

$= \sqrt{53333.3 + 1280.7 - 11456.6} = 206.54\text{v}$

$E_L = \sqrt{3}\, E_p = \sqrt{3} \times 206.54 = 357.73\text{v}$

❑❑❑

CHAPTER 7

Fractional Kilowatt Motors

SINGLE PHASE INDUCTION MOTOR

- A single phase induction motor is similar to a 3 - ϕ induction motor in construction except that its stator is provided with a 1-ϕ winding instead of a 3 - ϕ winding.

PRINCIPLE

- When a 1-ϕ ac voltage is supplied to the 1-ϕ stator winding, it will not produce a rotating magnetic field like in the case of 3-ϕ induction motors rather it will produce an alternating magnetic field (pulsating magnetic field) as shown in Fig. 2.

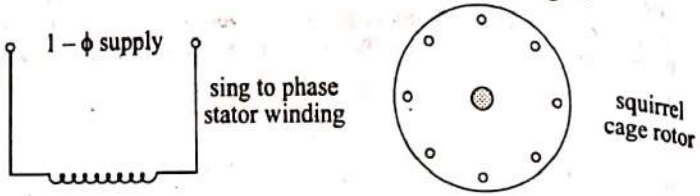


Fig. 1: 1-ϕ induction motor

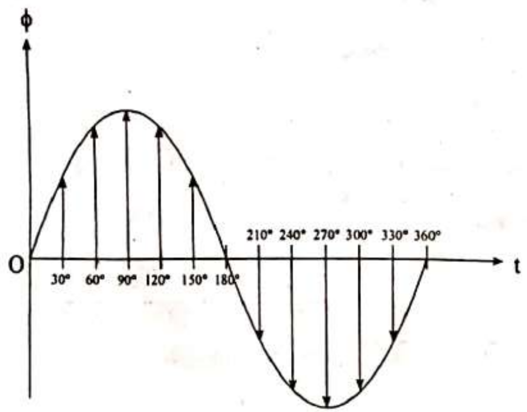


Fig. 2 Pulsating magnetic field in the air gap.

- By pulsating field we mean that the field builds up in one direction, falls to zero, and then builds up in the opposite direction.
- Under these conditions, the rotor does not rotate due to inertia.

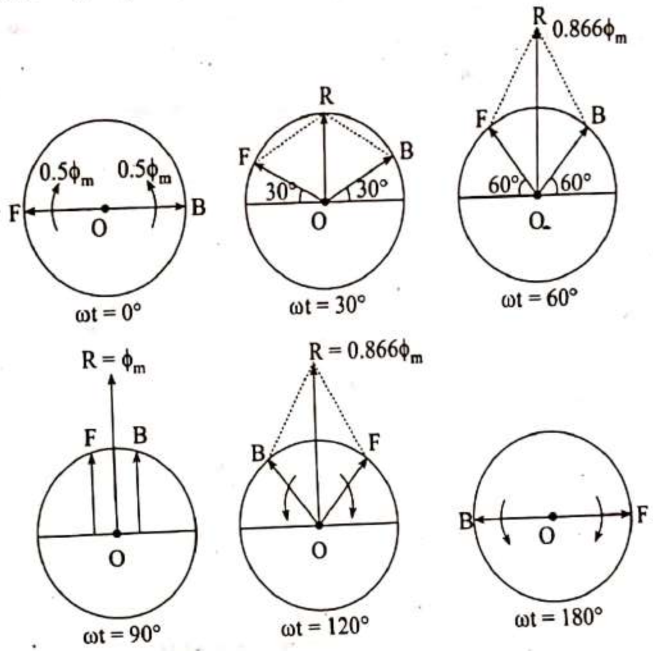
- Therefore, a single phase induction motor is inherently not self-starting, and requires some special starting means.
- However, if the single-phase stator winding is excited and the rotor if the motor is started by an auxiliary means, and the starting device is then removed the motor continuous to rotate in the direction in which it is started.

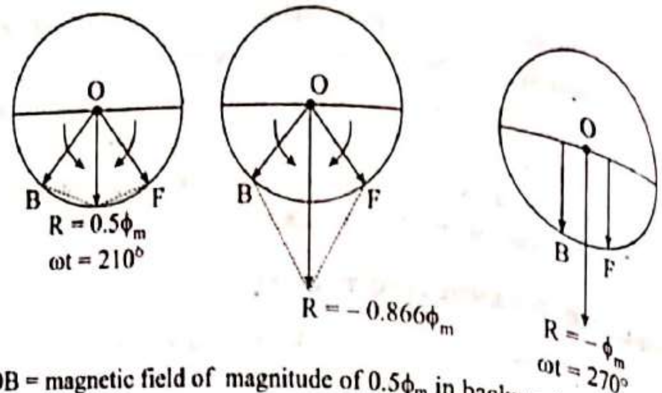
DOUBLE FIELD REVOLVING THEORY

- It states that a stationary pulsating magnetic field can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions.

Fig.: Pulsating Magnetic field.

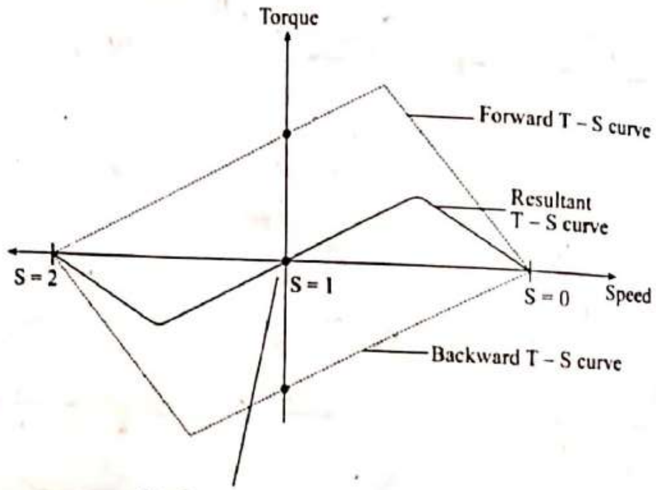
Fig.: Two rotating fields.





OB = magnetic field of magnitude of 0.5ϕ_m in backward direction.
OF = magnetic field of magnitude of 0.5ϕ_m in forward direction

- Hence, it is clear from above graphical analysis, as stated by double revolving field theory, the pulsating magnetic field produced by the single phase winding is equivalent to the phasor sum of two oppositely rotating magnetic fields, each having magnitude of 0.5ϕ_m with a synchronous speed of $N_s = \frac{120f}{P}$.
- The rotating magnetic field "OF" which rotates in clockwise direction is known as forward rotating magnetic field.
- The rotating magnetic field "OB' which rotates in anti-clockwise direction is known as backward rotating magnetic field.
- Based on the double revolving field theory, the torque-speed characteristics of a single phase induction motor can be drawn as shown in Fig. 2.



Net Starting Torque zero.

Fig. 2. Torque - speed curve of 1-ϕ I.M.

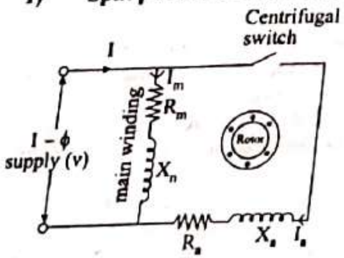
Double Revolving field Theory of single phase I.M.

- The double-revolving-field theory of single-phase I.M.s basically states that a stationary pulsating magnetic field can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions. The induction motor responds to each magnetic field separately, and the net torque in the motor is equal to the sum of the torques due to each of the two magnetic fields.
- When the rotor is stationary (that is, at stand still), the induced voltages are equal and opposite. Consequently, the two torques are also equal and opposite. hence, at stand still the net torque is zero.
- However, if the rotor is given an initial rotation by auxiliary means in either directions the torque due to the rotating field acting in the direction of initial rotation will be more than the torque due to the other rotating field.
- Hence, the motor will develop a net positive torque in the same direction as the initial rotation.
- The motor will, therefore, keep running in the direction of initial rotation.

Starting of Single phase induction motors

- A single phase induction motor with one stator winding inherently does not produce any starting torque.
- In order to make the motor start rotating, some arrangement is required so that the motor produces the rotating torque.
- In running condition, the motor produces the torque with only one winding.
- The method of starting a single phase induction motor is to provide an auxiliary winding on the stator in addition to the main winding and start the motor as a two phase machine.
- The two windings are placed in the stator with their axes displaced '30' electrical degrees.
- This phase difference is enough to produce a rotating magnetic field.
- Since the currents in the two windings are the phase shifted from each other, producing a rotating stator field capable of producing the starting torque.
- However, once the motor is running, it is capable of producing the torque with only main winding.
- So as the motor speeds up the auxiliary winding can be disconnected.
- Based on the various methods used to produce the phase difference between the currents in main and auxiliary windings, the 1-ϕ Induction motors are classified as follows:

1) Split phase induction motors



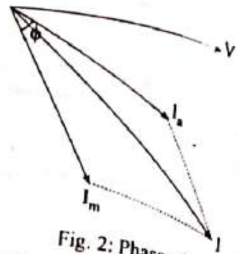


Fig. 1: Split-phase Induction motor Fig. 2: Phasor diagram

Fig. 1 Split-phase Induction Motor Fig. 2 Phasor diagram.

- It is also called a resistances-start motor.
- It has a single-cage rotor and its stator has two windings a main winding and a starting (auxiliary) winding.
- The main field winding and the starting windings are displaced 90° in space like the windings in a two-phase induction motor.
- The main winging has very tow resistance and high inductive reactance.
- Thus, the current I_m in the main winding lags behind the supply voltage V by nearly 90° as shown in Fig. 2.
- The auxiliary winding has a resistor connected in series with it.
- It has a high resistance and low inductive reactance so that the current I_a in the auxiliary winding is nearly in phase with the line voltage.
- Thus, there is time phase difference between the currents in the two windings.
- The time phase difference ϕ is not 90° but usually of the order of 30°.
- This phase difference is enough to produce a rotating magnetic field.
- Since the currents in the two windings are not equal, the rotating field is not uniform, and the starting torque is small of the 1.5 to 2 times the rated running torque.
- the main and auxiliary windings are connected in parallel during starting.
- The starting winding is disconnected from the supply automatically when the motor reaches speed about 70 to 80 per cent of synchronous speed.
- And then the motor runs only on the main windings.
- The torque-speed characteristics of this motor is shown in Fig. 3, which also shows the speed 'n_0' at which the centrifugal operates.

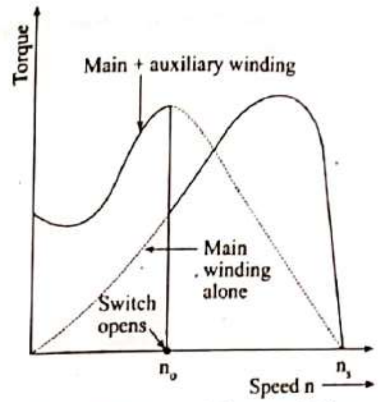
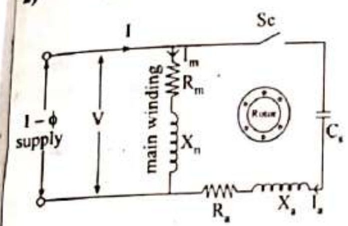


Fig. 3: Torque Speed Characteristics

2) Capacitor start motor



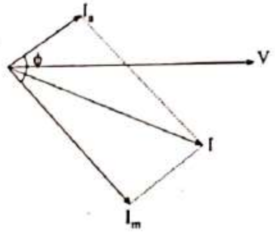


Fig. 1: Split-phase Induction motor Fig. 2: Phasor diagram

- Fig. 1 shows the connection of a capacitor-start motor.
- It has a cage rotor and its stator has two windings namely, the main winding and the auxiliary winding (starting winding).
- The two windings are displaced 90° in space.
- A capacitor C_s is connected in series with the starting winding.
- A centrifugal switch S_c is also connected as shown in Fig. 1.
- By choosing a capacitor of the proper rating the current I_m in the main winding may be made to lag the current I_a in the auxiliary winding by 90° as shown in Fig. 2.
- Thus, a 1 - ϕ supply current in split into two phases to be applied to the stator windings.
- Thus the windings are displaced 90° electrical and their mmf's are equal in magnitude but 90° apart in time phase.
- Therefore the motor acts like a balanced two-phase motor.
- As the motor approaches its rated speed, the auxiliary winding and the starting capacitor C_0 are disconnected automatically by the centrifugal switch S_c mounted on the shaft.

- The motor is so named because it uses the capacitor only for the purpose if starting.

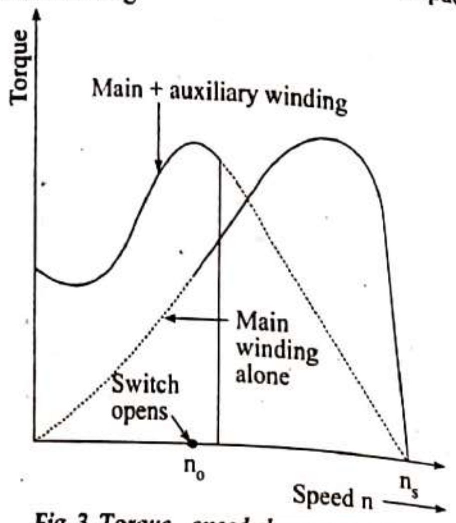


Fig. 3. Torque - speed characteristics

- The capacitor - start motor develops a much higher starting torque (3 to 4.5 times the full-load torque) than does an equally roated split phase induction motor.
- The value of the starting capacitor must be large and the starting-winding resistance to obtain a high starting torque
- The torque-speed characteristic of the motor is shown in Fig. 3, which also shows that the starting torque is high.
- Capacitor start motors are more costly than split-phase motors because of the additional cost of the capacitor.

3) Capacitor-start capacitor-run motor (Two value capacitor motor)

- Fig. 1 shows the schematic diagram of a capacitor-start capacitor run motor. It is also known as two-value capacitor motor.
- It has a cage rotor and its stator has two windings namely the main winding and the auxiliary winding (starting winding).

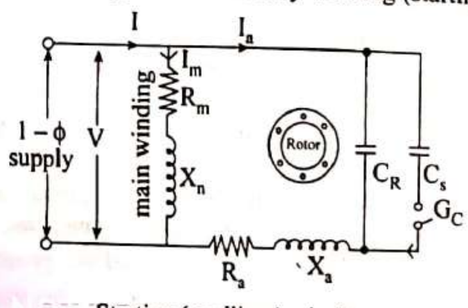


Fig. 1: Capacitor-start capacitor-run motor

- The two windings are displaced 90° in space.
- The motor uses two capacitors C_s and C_R.
- The two capacitors are connected in parallel at starting.
- The capacitor C_s is called the staring capacitor.
- In order to obtain a high starting torque, a large current is required. For this purpose, the capacitive reactance's X in the starting winding should be low.
- Since $X_A = 1/2\pi fC_a$, the value of C_s should be large.
- capacitive reactance in the auxiliary winding.
- During normal operation, the rated line current is smaller than the starting current.
- Hence, the capacitive reactance should be large.
- Since $X_R = 1/2\pi fC_R$, the value of C_R should be small.
- As the motor approaches synchronous speed, the capacitor C_S is disconnected by a centrifugal switch S_C.,
- The capacitor C_R is permanently connected in the circuit.
- It is called the run-capacitor.
- Since are capacitor C_S is used only at starting and the other C_R for continues, running, this motor is also called capacitor-start capacitor-run motor.

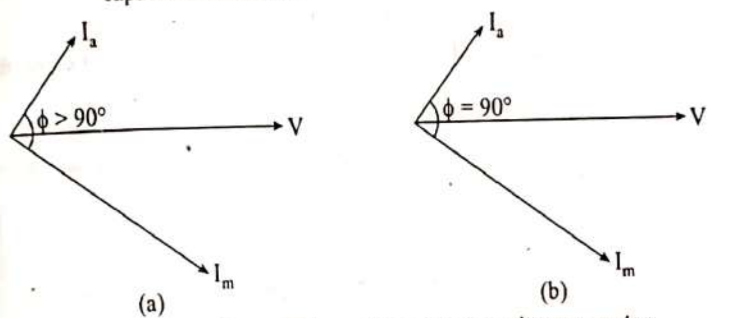


Fig. 2. Phasor diagram of capacitor-start capacitor run motor.

- Figures 2 (a) and (b) show the phasor diagrams of a capacitor-start capacitor-run motor.
- At starting both the capacitor are in the circuit and $\phi > 90°$ as shown in Fig. 2(a).
- When the capacitor C_s is disconnected ϕ becomes 90° (electrical) as shown in Fig. 2(b).
- The torque-speed characteristics of a 2-value capacitor motor is shown in Fig. 3.

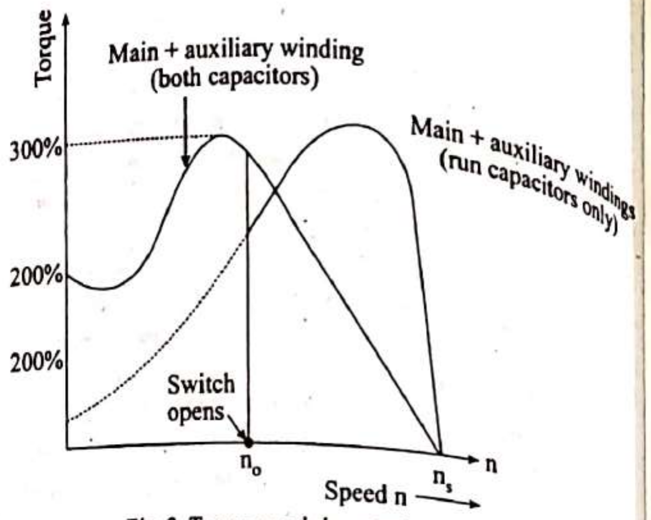


Fig. 3. Torque speed characteristics.

3. Shaded-pole motor

- A shaded - pole motor is a similar type of self-starting 1-ϕ induction motor.
- It consists of a stator and a cage-type rotor.
- The stator is made up of salient poles.
- Each pole is slotted on side and a copper ring is fitted on the smaller part 'a' as shown in Fig. 1.
- This part is called shaded pole.
- The ring is usually a single-turn coil and is known as shading coil.

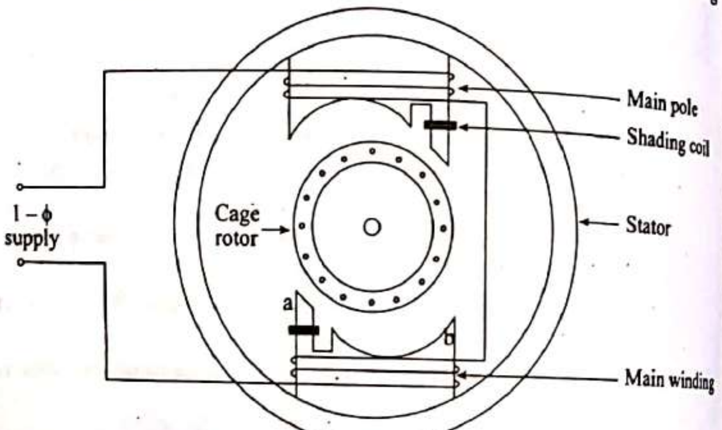


Fig. Shaded-pole motor with two starter poles.

- When alternating current flows in the field winding, an alternating flux is produced in the field core.
- A portion of this flux links with the shading coil, which behaves as a short-circuited secondary of transformer.
- A voltage is induced in the shading coil, and this voltage circulates a current in it.
- The induced current produces a flux called the induced flux which opposes the main core flux.
- Thus, the shading coil causes the flux in the shaded portion 'a' to log behind the flux in the unshaded portion 'b' of the pole.
- At the same time, the main flux and the shaded pole flux are displaced in space.
- This space displacement is less than 90°.
- since there is time and space displacement between the two fluxes, the conditions for setting up a rotating magnetic field are produced.
- Under the action of the rotating flux a starting torque is developed on the cage rotor.
- The direction of this rotating field (flux) is from the unshaded to the shaded portion of the pole.
- In Fig. 1 the direction of rotation is clockwise.
- In a shaded-pole motor the reversal of direction of rotation is not possible.

Equivalent circuit of a single phase I.M.

R_{1M} = resistance of the main stator winding.

X_{1M} = leakage reactance of the main stator winding.

X_M = magnetizing reactance

R_2' = stands-still rotor resistance referred to the main stator winding.

X_2' = standstill rotor leakage reactance referred to the main starts winding.

V_M = applied voltage.

I_m = main winding current.

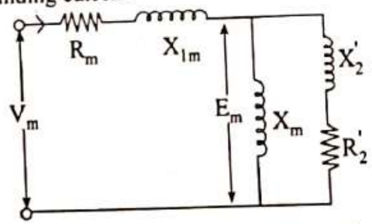


Fig. 1: Equivalent circuit of a single-phase I.M. with only its main winding at standstill.

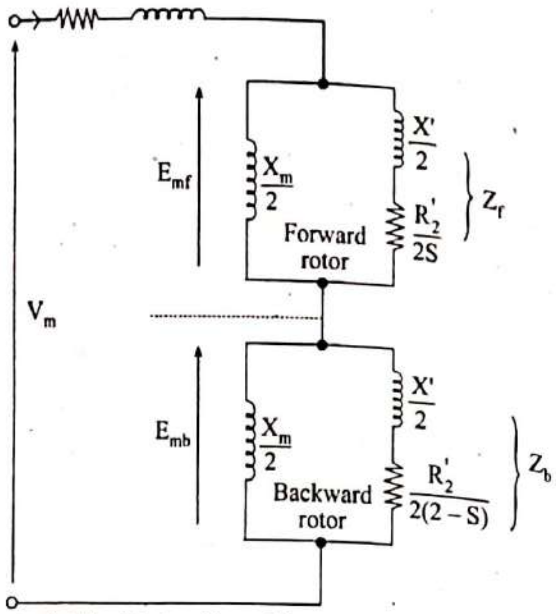


Fig. 1: At standstill with the effects of forward and backward rotating fluxes separated.

- The resultant induced voltage in the main stator winding is E_m, where $E_m = E_{mf} + E_{mb}$

At standstill, $E_{mf} = E_{mb}$

- The effective rotor resistance of an induction motor depends on the slip of the rotor while running.
- S is the slip.
- Thus, the effective rotor resistance in the portion of the circuit associated with the forward rotating flux is $\frac{R_2'}{2S}$.
- The slip of the rotor with respect to the backward rotating flux is (2 – S).
- Therefore, the effective rotor resistance (referred to stator) in the portion of the circuit associated with the backward rotating flux is $\frac{R_2'}{2(2-S)}$.
- When the forward and backward slips are taken into account, the result is the equivalent circuit shown in Fig. 2. Which represents the motor running on the main winding alone.
- Z_f = rotor impedance offered to the forward field.
- Z_b = rotor impedance offered to the forward field.

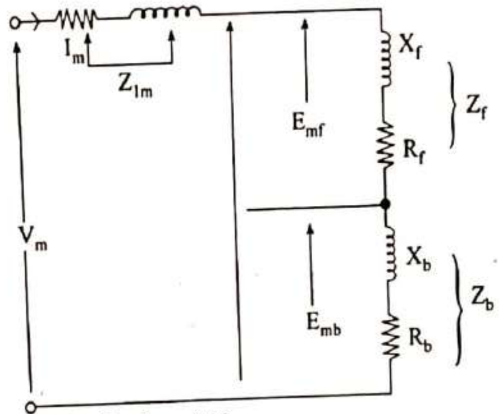
$$Z_f = R_f + jX_f = \left(\frac{R_2'}{2S} + j\frac{X_2'}{2}\right) \parallel \left(j\frac{X_m}{2}\right)$$

$$= \frac{(j\,X_m/2)\left(\frac{R_2'}{2S} + \frac{X_2'}{2}\right)}{\frac{R_2'}{2S} + \frac{jX_2'}{2} + \frac{jX_2'}{2}}$$

$$\text{and } Z_b = R_b + jX_b = \left(\frac{R_2'}{2(2-S)} + j\frac{X_2'}{2}\right) \parallel \left(j\frac{X_m}{2}\right)$$

$$= \frac{(jX_m/2)\left(\frac{R_2'}{2(2-s)} + j\frac{X_2'}{2}\right)}{\frac{R_2'}{2(2-S)} + \frac{jX_2'}{2} + j\frac{X_m}{2}}$$

- The simplified equivalent circuit of a single-phase induction motor with only its main winding energized is shown in Fig. 3.
- The current in the stator winding is $I_m = \frac{V_m}{Z_{1m} + Z_f + Z_b}$



Application of split-phase I.M.

- Split-phase motors are cheap and they are most suitable for easily started loads where frequency of starting is limited. The applications are washing machines, air-conditioning fans, food mixers, grinders, floor polishers, blowers, centrifugal pumps, small drills, lathes, office machinery, dairy machinery, etc. Because of low starting torques, they are seldom used for drives requiring more than 1kW.

Application of capacitor-start motor:

- Capacitor-start motors are used.

SINGLE PHASE SYNCHRONOUS MOTOR

- The 3-ϕ synchronous motors are usually large machines of the order of several hundred kilowatts or megawatts.
- 1 - ϕ synchronous motors are constant - speed machines of small ratings.
- Two types of small synchronous motors are widely used, namely, reluctance motors and hysteresis motors.
- These motors are simple in construction. They do not require dc field excitation nor do they use permanent magnets.

Reluctance Motors

- A single phase synchronous reluctance motor is basically the same as the single phase cage type induction motor.
- The stator has the main winding and an auxiliary (starting) winding.
- The rotor of a reluctance motor is basically a squirrel cage with some rotor teeth removed at the appropriate places such as to provide the desired number of salient rotor poles.
- Fig. 1 Show the 4-pole reluctance type synchronous motor.

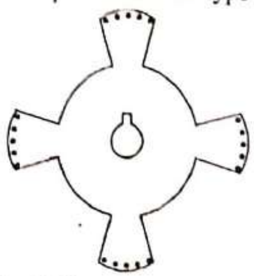


Fig. 1 Reluctance motor rotor.

- When the stator is connected to a single-phase supply, the motor starts as a 1-ϕ induction motor.
- At a sped, of about 75% of the synchronous sped, a centrifugal switch disconnects the auxiliary winding and the motor continues to speed up as a 1-ϕ motor with the main winding in operation.
- The rotor pulls into synchronism.
- For this to happen effectively, the load inertia must be within limits.
- After pulling into synchronism, the induction torque disappears but the rotor remains in synchronism due to the synchronous reluctance torque alone.

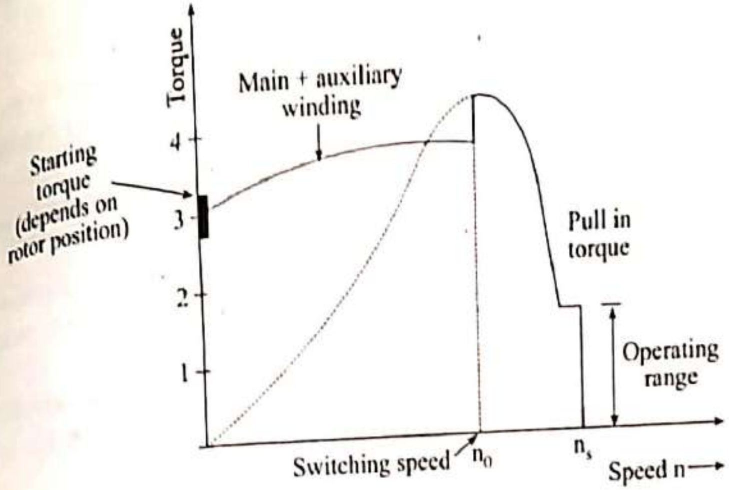


Fig. 2. Torque-speed characteristic of reluctance motor.

- Fig. 2 shows the typical torque-speed characteristic of the 1-ϕ reluctance motor.
- The starting torque is dependent on the rotor position because of the salient pole rotor.
- The value of the starting torque is between 300 to 400% of its full-load torque.
- At about 75% of the synchronous speed, a centrifugal switch disconnects the auxiliary winding and the motor continues to run with the main winding only.
- When the speed is close to synchronous speed, the reluctance torque developed as a synchronous motor pulls the rotor into synchronism and the rotor continues to rotate at synchronous speed.
- The main advantages of a reluctance motor are its simple construction (no slip rings, no bushes, no dc field winding), low cost and easy maintenance.
- The reluctance motor is widely used for many constant sped applications such as electric clocks timers, signallying devices, recoding instruments and photographs etc.

Hysteresis motors:-

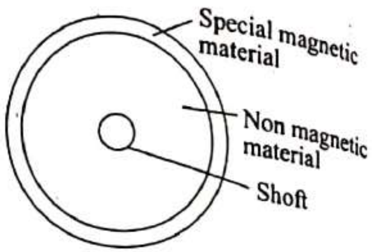
- A hysteresis motor is basically a synchronous motor with uniform air gap and without dc excitation.
- This motor may operate from single phase or 3-ϕ supply.
- In a hysteresis motor torque is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.

Stator construction

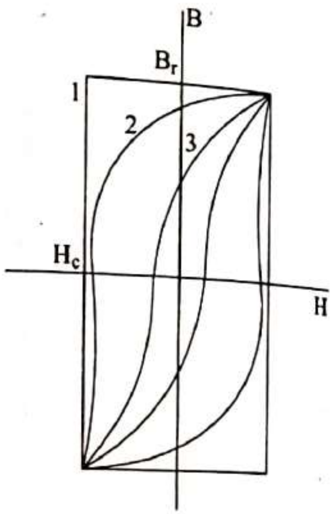
- The stator of a hysteresis motor is similar to that of an induction motor with the basic requirement that it produces a rotating magnetic field.
- Thus the stator of the motor can be connected to either a 1-ϕ or a 3-ϕ supply.
- For a 1 - ϕ hysteresis motor, the stator winding is of permanent split-capacitor type or of the shaded pole type for very small sizes.
- In the case of the permanent split-capacitor type, the capacitor should be used with an auxiliary winding in order to produce as uniform field as possible.

Rotor Construction

- Fig. 1 shows the rotor of a hysteresis motor.

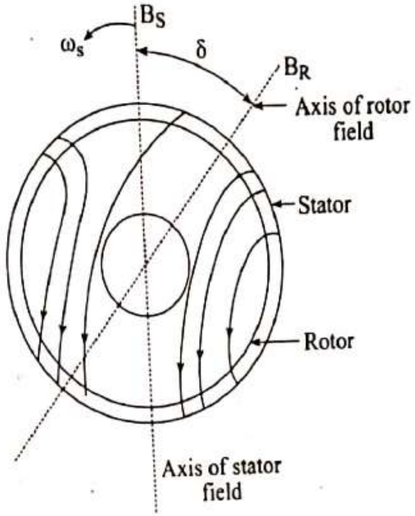


- It consists of core of aluminum or some other nonmagnetic material which carries a layer of special magnetic material.
- The outer layer has a number of thin rings to form the laminated rotor.
- In smaller motors a solid ring may be used.
- Thus, the rotor of a hysteresis motor is a smooth cylinder and it does not carry any windings.
- The ring is made of special magnetic material such as magnetically hard chrome or cobalt steel having very large hysteresis loop as shown in Fig. 2.



Operation

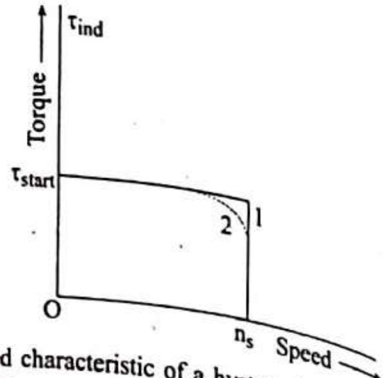
- Fig. 3 shows the basic operation of a hysteresis motor.



- When a 1-ϕ supply is applied to the stator, a rotating magnetic field is produced.
- This rotating magnetic field magnetizes the rotor ring and induces poles within it.
- A uniform cross-section rotor inherently will match the number of stator poles.
- The induced rotor flux lags behind the rotating stator flux because of the hysteresis loss in the rotor.
- The angle δ between the stator magnetic field B_s and the rotor magnetic field B_R is responsible for the production of torque.
- The angle δ depends only on the shape of the hysteresis loop.
- It does not depend on the frequency.
- For this reason, a magnetic material having a wide hysteresis loop should be used.
- Thus, the coercive force H_C and the residual flux density B_r of the magnetic material should be large.
- Ordinary steels are not suitable for a hysteresis motor since their hysteresis loop resemble loop 3 in Fig. 2.
- Cobalt - vanadium type materials are used in hysteresis motors.
- They have the hysteresis loops according to loop 2 in Fig. 2.
- Such a loop approximates the ideal loop 1.

Torque - sped characteristic

The torque-speed characteristic of a practical hysteresis motor is shown by curve 2 in Fig. 9.6. The departure from the ideal characteristic 1 is due to presence of harmonics in the rotating field and other irregularities. The torque-speed characteristic of a hysteresis motor it is constant at all speeds including synchronous speed. Thus, it is seen from the characteristic that locked rotor, starting and pullout torques are all equal. This is a valuable property in that such a motor can pull into synchronism at high inertia loads.



- An ideal torque - sped curve for the hysteresis motor is shown by curve 1 in Fig. 4.
- The torque-sped characteristic of a practical hysteresis motor is shown by curve 2 in Fig. 4.

UNIVERSAL MOTORS

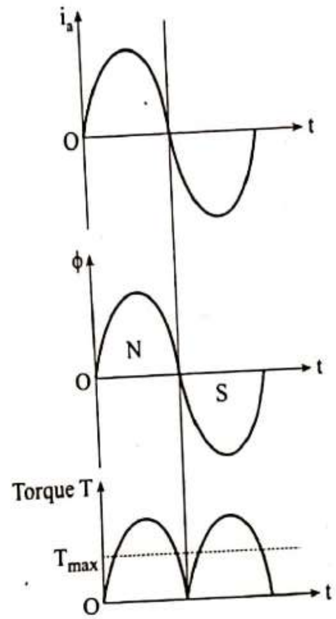
- The universal motor is a specifically designed series around motor that operates at approximately the same sped and output on either dc or ac of approximately same voltage.

Construction:

- Construction of universal motor is very similar to the construction of a DC machine.
- It consists of a stator on which field poles are mounted.
- Field coils are wound on the field poles.
- However, the whole magnetic path (stator field circuit and also armature) is laminated.
- lamination is necessary to minimize the eddy currents which induce while operating on AC.
- the rotary armature is of wound type having straight or skewed slots and commutation with brusher resting on it.
- The commutation on AC is power than that for DC because of the current induced in the armature coils.
- For that reason brushes used are having high resistance.

The single-phase series motor is a commutator-type motor. If the polarity of the line termianls of a dc series motor is reversed, the motor will continue to run in the same direction. Thus, it might be expected that a dc series motor would operate on alternating current also. The direction of the torque developed in a dc series motor is determined by both field polarity and the direction of current through the armature ($T \propto \Phi\, i_a$). Let a dc series motor be connected across a single-phase ac supply. Since the same current flows through the field winding and the armature, it follows that ac reversals from positive to negative, or from negative to positive, will simultaneously affect both teh field flux polarity and the current direction through the armature. This means that the direction of the developed torque will remain positive, and rotation will continue in the same dire;ction. The nature of the torque will be pulsating and frequency will be twice the line frequency as shown in Fig. 8.16. Thus, a series motor can run both on dc and ac. Motors that can be used with a single-phase ac source as well as a dc source of supply voltages are called **universal motors**. However, a series motor which is specifically designed for dc operation suffers from the following drawbacks when it is used on single-phase ac supply:

1. Its efficiency is low due to hysteresis and eddy-current losses.



2. The power factor is low due to the large reactance of the field and the armature windings.

3. The sparking at the brushes is excessive.

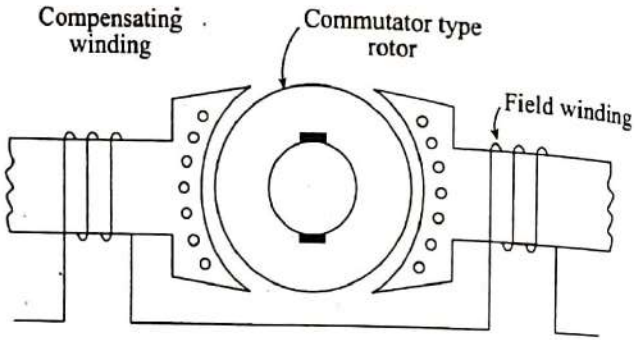
In order to overcome these difficulties, the following modifications are made in a.d.c. series motor that is to operate satisfactory on alternating current :

(a) The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.

(b) The field winding is provided with small number of turns. The field-pole area is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.

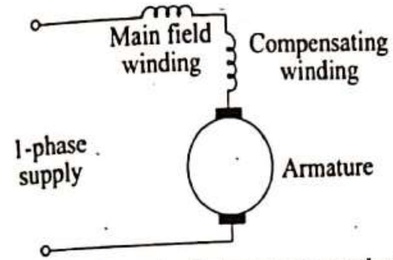
(c) The number of armature conductors is increased in order to get the required torque with the low flux.

(d) In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a **compensating winding** is used. This winding is put in the stator slots as shown in figure.



Series motor with conductively compensated winding.

The axis of the compensating winding is 90 a compensating winding is used. This winding is put in the stator slots as shown in Fig. In such a case the motor is conductively compensated.



Series motor with conductively compensated winding.

The compensating winding may be short circuited on itself, in which case the motor is said to be **inductively compensated.**

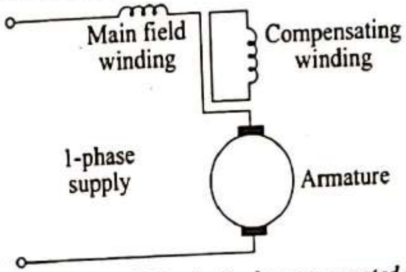


Fig.: Series motor with inductively compensated winding.

The armature of universal motors is of the same construction as ordinary series motor. In order to minimize commutation problems, high resistance brushes with increased brush area are used. The stator core and yoke are laminated to reduce eddy-current loss produced by alternating flux. The machine is generally operated at a lower flux density using very short air gaps.

The universal motor is simple, and cheap. It is used usually for rating not greater than 750 W.

The characteristics of universal motors are very much similar to those of d.c. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent d.c. supply. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in d.c. series motor.

Speed control of universal motors is best obtained by solid-state devices. Science the speed of these motors is not limited by the supply frequency and may be as high as 20,000 r.p.m (greater than the maximum synchronous speed of 3000 r.p.m. at 50 Hz), they are most suitable for applications requiring high speeds.

There are numerous applications where universal motors are used, such as portable drills, hair dryers, grinders, table-fans, blowers, polishers, kitchen appliances etc. They are also used for many other purposes where speed control and high values of speed are necessary. Universal motors of given horse power rating are significantly smaller than other kinds of a.c. motors operating at the same frequency.

SPECIAL PURPOSE MACHINES

- AC or DC machines are used primarily for continuous energy conversion.
- However, there are many special applications where continuous energy conversion is not required.
- For example,

i) robots require position control for the movement of the arm from one position to another.

ii) the printer of a computer requires that the paper move by steps in response to signals received from a computer.

- such application requires special motors of low power rating.

STEPPER MOTORS

- A stepper motor rotates by a specific number of degrees in response to an input electrical pulse.
- Typical step sizes are 2°, 2.5°, 5°, 7.5° and 15° for each electrical pulse.
- It basically converts digital pulse in puts into analog output shaft motion.
- Typical application of stepper motors requiring incremental motion are printers, tape drivers, machine tools, X-Y recorders, robotics etc.
- Fig. 1 shows a simple application of a stepper motor in the paper drive mechanism of a printer.

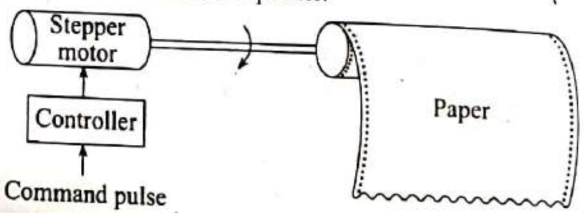


Fig. 1 : Paper driving using stepper motor.

Two types of stepper motors are used:

- Variable reluctance type.

i) Permanent magnet type:

ii) **Variable reluctance type stepper motor**

- A variable reluctance (UR) stepper motor can be of single-stack or the multi-stack type.

Servomotors:

- Servomotors are also called control motors.
- These motors are used in feedback control systems as output actuators.
- The basic principle of operation of these motors is the same as that of other electromagnetic motors.
- However, their design, construction and mode of operation and different.
- Their power rations vary from a fraction of a watt to few hundred watts.
- They have low rotor inertia and, therefore, they have a high speed of response.
- Servo motors are widely used in radars, computers, robots, machine tools, tracking and guidance systems, process controllers
- Both dc and ac (2 - phase and 3-phase) servomotors are being used presently.

DC SERVOMOTORS:

- DC servomotors are separately excited by dc motors or permanent magnet dc motors.
- Fig. 1 (a) shows a schematic diagram of a separately excited dc servomotor.
- The speed of dc servomotors is normally controlled by varying the armature voltage.
- The armature of a dc servomotor has a large resistance so that torque-speed characteristics are linear and have a large resistances that the torque -sped characteristics are linear and have a large negative slope (torque reducing with increasing speed) as shown in Fig. 1.(c).
- The negative slope provides viscous damping for the servo-drive system.
- Fig. 1(b) shows that the armature mmf and the excitation field mmf are in quadrature in a dc machine.

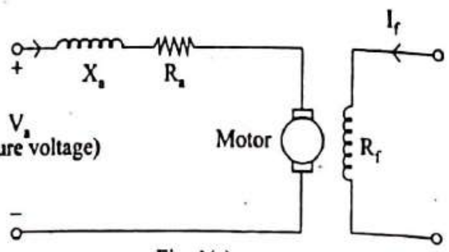


Fig. 1(a)

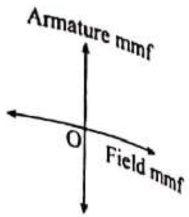


Fig. 1(b)

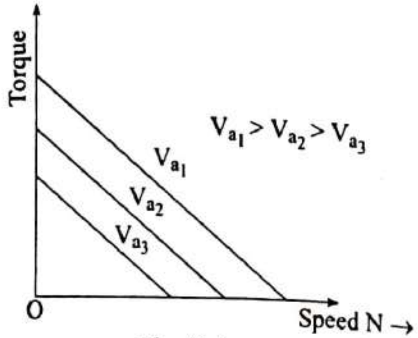


Fig. 1(c)

Fig. 1 DC servomotor (a) schematic diagram: (b) Armature mmf and field mmf; (c) Torque-speed characteristics.

- The provides a fast torque response because torque and flux become decoupled.
- Therefore, a step change in the armature voltage or current produces a quick change in the position or speed of the rotor.
- The power rating of dc servomotors can vary from a few watts to several hundred watts.
- In general, most high-power servomotors are dc servomotor

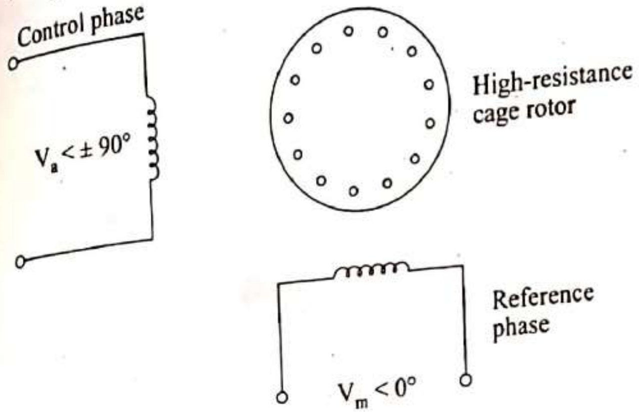
AC SERVOMOTORS

- Most of the ac servomotors are of the two-phase squirrel cage inductions type for low-power applications.-Recently, 3-ϕ squirrel-cage induction motors have been modified for application in high-power servo systems.

Two-phase AC servomotor

- Fig. 1 (a) shows the schematic diagram of a two-phase ac servomotor.
- The stator has two distributed windings of a two-phase ac servomotor.
- The stator has two distributed windings which are displaced from each other by 90 electrical degrees.

- One winding, called the reference of fixed phase, is supplied from a constant voltage source V_m<0.
- The other winding, called the control phase, is supplied with a variable voltage of the same frequency as the reference phase, but is phase displaced by 90 electrical degrees.



(a) Schematic diagram.

Fig. 1 Two-phase ac servomotor

- The control phase is usually supplied from a servo amplifier.
- The speed and torque of the rotor are controlled by the phase difference between the control voltage and the reference phase voltage.
- The direction of rotation of the rotor can be reversed by reversing the phase difference, from leading the lagging (or vice-versa), between the control phase voltage and the reference phase voltage.
- A high rotor resistance ensures a negative slope for the torque-speed characteristics over its entire operating range and thereby furnishes the motor with positive damping for good stability.

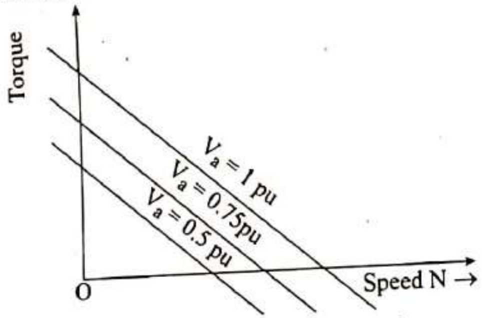
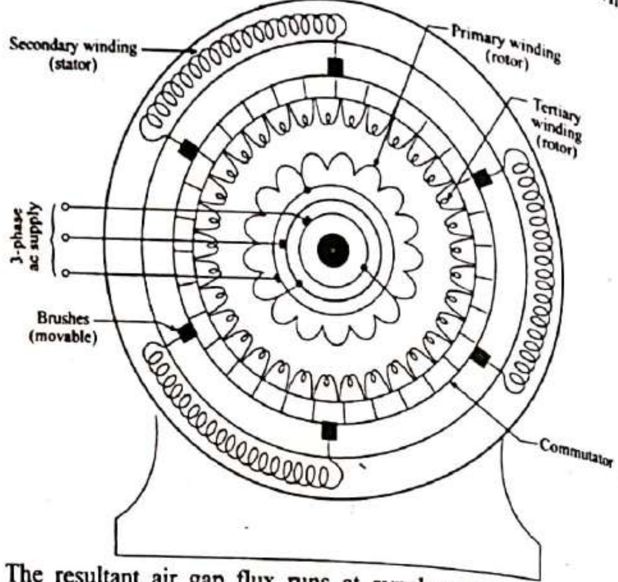


Fig. 1(b) Torque-speed characteristics

Schrage motor

- Schrage motor is basically an inverted 3-ϕ induction motor with primary winding on the rotor and secondary winding on the stator.
- The schematic diagram of a 2-pole Scharge motor is shown in Fig. 1.



- The resultant air gap flux runs at synchronous speed n_s with respect to the rotor and the rotor runs at a sped n in opposite direction with the rotor windings short circuited.
- Consequently, the field runs at slip speed with respect to the stator including slip frequency current in it. This produces torque.
- The rotor also has a a dc winding in the same slots as the primary conductors.
- The dc winding is also known as tertiary or regulating winding.
- It is connected to a commentator on which three sets of moveable brush pairs are placed for a 3-ϕ emf injection into the secondary or stator winding in order to control the sped and power factor of the motor.
- If this emf adds to secondary emf the sped increases.
- If it opposes, the speed decreases.
- The placement of brushes on the same commutator segment nullifies the effect of secondary winding and the machine works as an inverted induction motor.
- Since, the rotating field moves at a slip speed with respect to the brushes, the frequency of the brush emfs is always the slip frequency

Advantages

- A Schrage motor has the following advantages over an induction motor:
  i) Since the external residences are not required for speed control, the overall efficiency is improved.
  ii) Schrage motor provides a constant torque over a wide speed range and the power developed is proportional to speed.
  iii) Speed is easily increased or decreased over a wide range of $0.4n_s$ to $1.4n_s$.
  iv) Speed is independent of load.

Disadvantages

- A Schrage motor is costlier than induction motor of some rating.
- The maintenance cost is also higher.

Two reaction theory:

Two reaction theory was proposed by Andre Blondel.

- The theory proposes to resolve the given armature mms into two mutually perpendicular components, with one located along the axis of the rotor salient pole.
- It is know as the direct-axis (or d-axis) component.
- The other component is located perpendicular to the axis of the rotor salient pole.
- It is known as the quadrature-axis (or q-axis) component by F_d and the q-axis component by F_q.
- The component F_d is either magnetizing or demagnetizing.
- The component F_q results in a cross-magnetizing effect.
- If ψ is the angle between the armature current I_a and the excitation voltage E_f and F_a is the amplitude of the armature mmf, then

$$F_d = F_a \sin\psi \text{ and}$$

$$F_q = F_a \cos\phi$$

What is meant by air gap in synchronous machines?

- Every rotating machine has a stationary stator and a rotating rotor.
- There is a gap of 0.5mm between stator and rotor. This gap is field with air hence called air gap.
- In this air gap rotating magnetic field rotates at a synchronous sped.
- Air gap is more in salient poles machine 1-3 mm, whereas it is 0.3-0.8 mm in round rotor synchronous machine.

Why is the air gap in a synchronous machine larger than in an induction machine?

(1) - In induction machine the emf induced in the rotor winging is mutually is induced emf.

- Induction motor can be treated as a rotating transformer as the emf induced in the rotor is by mutual induction.
- If the air gap is more the leakage flux will be more and the mutual flux gets reduced, reducing rotor emf, current and torque.
- In synchronous machine the magnetic flux is set up separately by field winding. The emf induced in the stator armature wingding is not by mutual induction.
- It is a dynamically induced emf due to relative motion between the field and conductors.
- Hence air gap is not the consideration, particularly for salient pole machines, in the region between poles, the air gap will be much more.

(2) - The main sources of low power factor at which induction motor operates is the air gap between the stator and the rotor.

- This air gap increases the reluctance between the stator and the rotor, which enhances the magnetizing current for production of the given mutual flux between the stator and the rotor for a given supply voltage.
- Therefore, the no-load current of a transformer for a given kVA rating. The air gap in an induction motor should be made small so that the induction motor gives better performance. The small air gap may result mechanical problems in addition to the noise and losses at the slot tooth faces.

Comparison between 3-ϕ synchronous and induction motors

Synchronous motor	Induction motor
i) A synchronous motor is a doubly excited machine. Its armature winding is energized from an ac source, and its field winding from a dc source.	(1) An induction motor is a singly executed machine. Its stator winding is energized from an ac sources.
ii) It always runs at synchronous sped. The speed is independent of load.	(ii) Its sped falls with the increase in load and is always less than the synchronous sped.
iii) It is not self-starting. It has to be run upto synchronous speed by some means before it can be synchronized to ac supply.	iii) An induction motor has got self-starting torque.
iv) A synchronous motor can be operated under wide range of power factors, both lagging and leading by changing its excitation.	(iv) An induction motor operates it only lagging power factor, which becomes very poor at high loads.
(v) It is more efficient than induction motor of the same output and voltage rating	(v) Its efficiency is lesser than that of a synchronous motor of the same output & voltage rating.
(vi) A synchronous motor is costlier than an induction motor of the same output and voltage rating.	(vi) An induction motor is cheaper than a synchronous motor of the same output and voltage rating.

Starting of synchronous motor under load:-

- Synchronous motor with the low resistance type of damper has a relatively low starting torque.
- The starting torque of a synchronous motor may be increased by increasing the resistance of the rotor winding.
- Since in a synchronous motor the squirrel cage windings are not effective during normal condition, because the high resistance starting winding gives at running sped high slip and low effectively in the case of induction motors.
- The motor is required to be started under considerable loads, synchronous motors with phase wound dampers are used.
- Therefore, the resistance of squirrel cage can be made sufficient high to give high starting torque and the motor and be started under considerable load.
- The damper bars are phase connected and brought out to the resistors through slip rings instead of being connected to end rings.
- Thus such motors have five slip rings, two for conducting current to dc field winding and other three to be connected to the terminals of the 3-ϕ rotor winging.
- The resistors are put in the circuit at start and are taken out as the motor attains the nearly synchronous sped, must as done with slip-ring induction motors.
- When the three slip-rings are short circuited, the wining acts as a damper winding.

Tutorial

1. **A $\frac{1}{4}$ HP, split-phase motor draws its starting winding current of 4A lagging the supply voltage by 15° elec. and its running winding current is 6A lagging by 40° electrical calculate.**
   - i) The total current and power factor (at steady state)
   - ii) The component of starting winding current in phase with supply voltage.
   - iii) The phase angle between the starring and running winding currents.
   - iv) The component of running winding current that lags the supply voltage by 90°.

Solution:

Starting winding current,

$I_S = 4 < -15°A = (3.8637 - J1.0353)A$

Running winding current,

$I_m = 6 < -40°A = *4.5963 - j3.8567)A.$

i) Total current

$I_L = (8.46 - j4.892)\ A = 9.77 < -30°$

Total current in magnitude, $I_L = 9.77A$

Power factor, $\cos\phi = \cos(-30°) = 0.866$ (lag).

ii) The component of starting winding current in phase with supply voltage.

= Active component of starting current = 3.8637A

iii) The phase angle between the starting & running winding currents,

$\theta = \phi_m - \phi_s = 40° - 15° = 25°$ Ans.

iv) The component of running winding current that lags behind the supply voltage by 90°

$= \frac{\text{Reactive or j-component of runing winding}}{\text{current} = 3.8567}$ A.

2. **A 250W, 230V, 50HZ capacitor start motor has the following impedances at standstill.**

Main winding, $Z_m =)(7 + j5)\Omega$

Auxiliary ,,, $Z_a = (11.5 + j5)\ \Omega$

- **Find the value of capacitor to be connected in series with auxiliary winding to vive a phase displacement of 90 between the currents in two windings.**
- **Draw the circuit and phasor diagram for motor.**

Solution:

Main winding impedance, $Z_m = (7 + j5) = 8.60 < 35.54°$ Obviously main winding current I_m lags behind the applied voltage V by 35.54°.

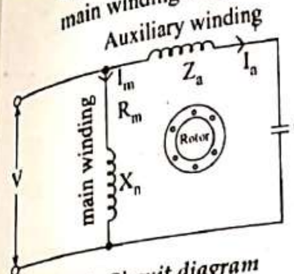


Fig. (a): Circuit diagram

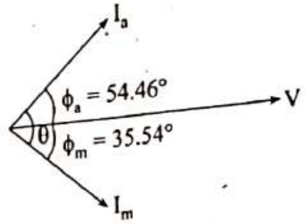


Fig. (b): Phasor diagram

- Auxiliary winding impedance, $Z_a = (11.5 + j5)\ \Omega$
- Since, time phase angle between auxiliary winding current I_a and main winding current I_m is 90°, auxiliary winding current I_a must lead the applied voltage by (90° - 35.54°) or 54.46°.
- If X_C is the capacitive reactance of the capacitor C connected in series with the auxiliary winding, then impedance of the auxiliary winding will be given as

$Z_a' = (11.5 + j5 - jX_C) = 11.5 + j(5 - X_c)$ or

$= 11.5 - j(X_C - 5)$

- For auxiliary winding

$\tan\phi_a = \frac{5 - X_C}{11.5}$

or, $X_C = 5 - 11.5 \tan\phi_a$

or, $X_C = 5 - 11.5 \tan(-54.46°)$

or, $X_C = 5 + 16.1 = 21.1\Omega$

- Capacitance of the capacitor,

$C = \frac{1}{2\pi f X_c} = \frac{1}{2\pi * 50 \times 21.1} = 150.87\ \mu F$

Or

- For auxiliary winding

$\tan\phi_a = \frac{X_c - 5}{11.5}$

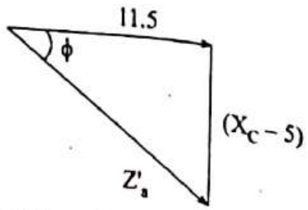
or, $X_C = 5 + 11.5 \tan\phi_a$

or, $X_C = 5 + 11.5 \tan(54.46)$

or, $X_C = 21.1\Omega$

- Capacitance of the capacitor,

$$C = \frac{1}{2\pi f X_c} = \frac{1}{2\pi \times 50 \times 21.1} = 150.87\mu F$$



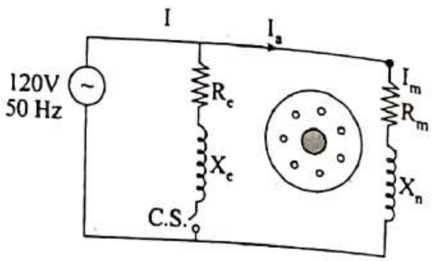
3. **A four-pole single phase, 120V, 50Hz induction motor gave the flowing standstill impedance when tested at rated frequency.**

Main winding $Z_m = (1.5 + j4)$ ohms

Auxiliary winding $Z_a = (3 + j6)\ \Omega$

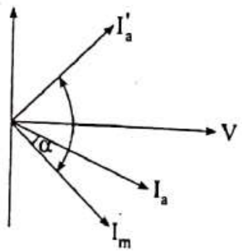
Determine the value of external capacitor and resistor to be inserted in series with the auxiliary winding to obtain maximum starting torque keeping magnitude of auxiliary winding current constant. **[2074]**

Solution:

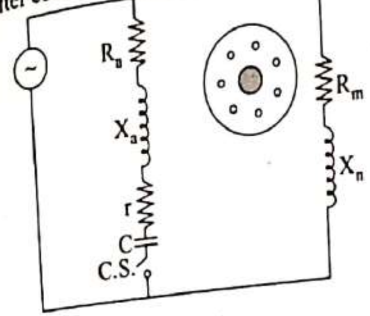


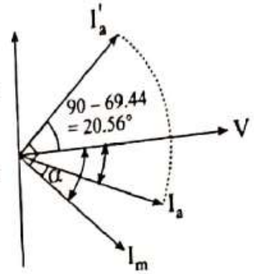
$$i_m = \frac{V\angle 0^\circ}{.1.5 + j4} = \frac{120\ \angle 0^\circ}{1.5 + j4} = 28.08 < -69.44^\circ$$

$$i_a\ \frac{120\ \angle 0^\circ}{(3 + j6)} = 17.88\ \angle -63.43^\circ$$



After connecting capacitor





But from the above circuit,

$$I'_a = \frac{V}{(R_a + r) + j(X_a - X_c)}$$

or, $$17.88\ \angle 20.56 = \frac{120\ \angle 0^\circ}{3 + 4 + j(6 - X_c)}.$$

$\because\ I_a = 17.88\ \angle 20.56^\circ$

By cross multiplication

$(3 + r) + j(6 - X_c) = (120\ \angle 0^\circ) * (17.88\ \angle 20.56)$

Equating real and imaginary part separately we get

$r = 2.2797\ \Omega$

$C = 372\ \mu F$

$\because\ X_c = \frac{1}{2\pi fc}$

$\Rightarrow\ C = \frac{1}{2\pi f.X_c}$

4. **A four pole, single phase, 120v, 50Hz induction motor have the following stand still impedances when tested at rated frequency.**

Main winding : $Z_m = (1.5 + j4)\ \Omega$

Auxiliary winding: $Z_a = (3 + j6)\ \Omega$

If an external capacitor of 1000 μF is inserted in series with the auxiliary winding to obtain higher starting torque. Calculate the percentage increase in starting torque. **[2075]**

Solution:

$V = 120V$

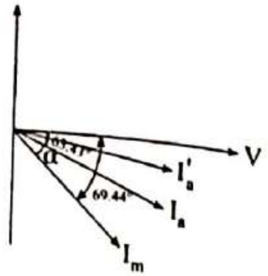
$Zm = (1.5 + j4)\Omega$

$Z_a = (3 + j6)\ \Omega$

$C = 1000\ \mu f$

$$i_m = \frac{V < 0^\circ}{1.5 + j4}$$

$$i_a = \frac{120 < 0^\circ}{3 + j6} = 17.88 < -63.43^\circ$$



After adding capacitor of 1000μF

$$Ia' = \frac{V}{R_a + j(X_a - X_c)} = \frac{120 < 0^\circ}{3 + j\left(6 - \frac{1}{2\pi fc}\right)} = \frac{120 < 0^\circ}{3 + j(6 - 3.183)}$$

$$= 29.19 < -43.12$$

$\therefore \quad \alpha_2 = (69.44 - 43.12) = 26.32$

We know,

Torque $T_i \propto I_{a_1} \sin\alpha_1$

$\therefore \quad T_1 \propto I_{a_1} \sin$ ...(i)

$T_2 \propto Ia_2 \sin\alpha_2$ ...(ii)

$$\therefore \frac{T_2}{T_1} = \frac{Ta_2 \sin\alpha_2}{Ia_1 \sin\alpha_1} = \frac{29.19 \sin(26.32)}{17.88 \sin(6.01)} = \frac{12.94}{1.87} = 6.9121$$

$$\therefore \% \text{ increase in torque} = \left(\frac{T_2 - T_1}{T1}\right) \times 100\%$$

$$= \left(\frac{T_2}{T_1} - 1\right) \times 100\%$$

$$= (6.9121 - 1) \times 100\%$$

$$= 591.21\%$$

Here,

α ⇒ Phase angle between main winding current and auxiliary winding current.

5. **A 2/3 HP, 220v, 50Hz, 6- pole single phase induction motor has following parameters:** [2071]

$R_1 = 3.04\Omega$, $X_1 = 4.2\ \Omega$, $X_0 = 105.6\ \Omega$

$R_0 = 65\Omega$, $R_2' = 6.26\Omega$ $X_2' = 2.12\ \Omega$

Solution:

The motor is operating at 5% slip.

Determine

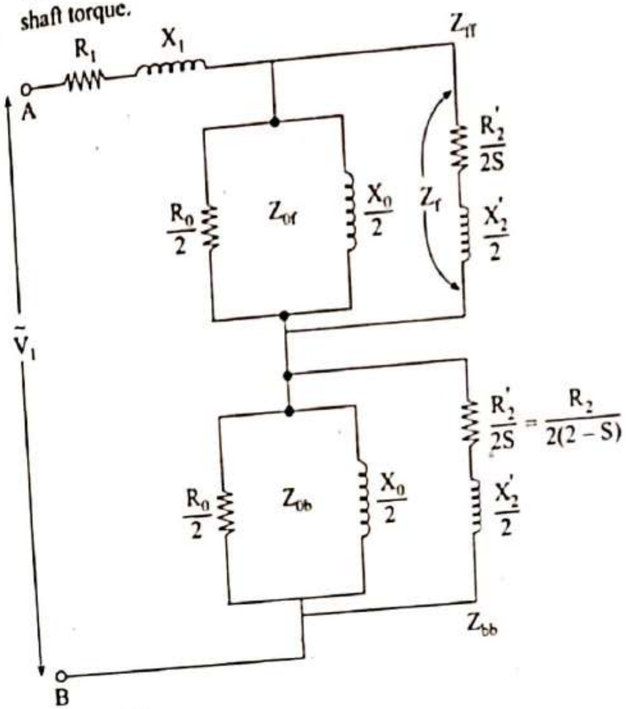
a) motor sped

b) Input current and power factor

c) Air gap power

d) Output power

e) shaft torque.



Slip $S = \frac{N_s - N}{N_s}$

or, $N = N_{sw} - S.N.$

$= 1000 - 0.05 * 1000$

$= 1000 - 50$

$= 950$ rpm.

To calculate input current we should calculate total equivalent impedance Z_{AB} between A & B

$$Z_{AB} = (R_1 + jX_1) + Z_{ff} + Z_{bb}$$

$$Z_f = 62.6 + j1.6$$

$$= 62.62 \angle 1.46^\circ$$

$$Z_b = 1.6 + j1.6 = 2.262 \angle 45^\circ$$

$$Z_0f = z_0b = \frac{65}{.2} * j\frac{\frac{105.6}{2}}{\frac{25}{2} + j\frac{205.6}{2}} = 23.569 + j14.507$$

$Z_{ff} \Rightarrow$ Parallel equivalent of Z_f and Z_of

$$\therefore \quad Z_{ff} = \frac{z_{0f} * z_{ff}}{z_{0f} + z_{ff}} = \frac{(23.56 + j14.5)(62.6 + j1.6)}{(23.56 + j14.5 + 62.6 + j1.6)} = 19.761 \angle 22.49$$

Similarly,

$$Z_{bb} = \frac{z_0b * z_b}{z_0b + z_b} = \frac{(27.66 \angle 31.61) * (1.6 + j1.6)}{(27.66 \angle 31.61) + (1.6 + j2.6)}$$

$$= 2.08498 \angle 42.99$$

$$\therefore \quad Z_{AB} = (R_1 + jX_1) + Z_{ff} + Z_{bb}$$

$$= (3.04 + j4.2) + (19.761 \angle 22.49) + (2.09498 \angle 43.99)$$

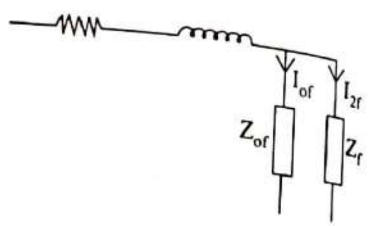
$$= 26.357 \angle 30.089$$

$$\therefore \quad \text{Input current, } I = \frac{V}{Z_{AB}} = \frac{220 \angle 0^\circ}{26.357 \angle 30.089} = 9.3469 \angle -30.089^\circ$$

Input p.f. = cos (30.089) = 0.865 lagging.

To calculate I_{of} and I_{2f}, use current divide rule.

$$\bar{I} = \bar{I}_{of} + \bar{I}_{2f} \ldots \text{(i)}$$



$$\bar{I}_{of} * z_{of} = I_{2f} * Z_f$$

$$\bar{I}_{of} = \frac{I_{2f} * z_f}{Z_{of}}$$

$$= I_{2f} * \frac{62.62 \angle 1.46}{27.66 \angle 31.61}$$

$$= I_{2f} * 2.26 \angle -30.15^\circ$$

from equation.

$$8.3469 \angle -30.089^\circ = I_{2f} * 2.26 \angle -20.15 + I_{2f}$$

or, $\quad I_{2f}[(2.26 \angle -30.15) + 1] = 9.3469 \angle -30.1$

$$I_{2f} = 2.638 \angle -9.09^\circ$$

$$\therefore \quad \bar{E}_{2f} = I_{2f} * 3f = (2.638 \angle 9.09) * 62.69 \angle 1.46 = 165.19 \angle -7.63$$

$$\bar{E}_b = \bar{V} - \bar{E}_f = (8.3469 \angle 20.089^\circ) + (2.04 + j4.2)$$

$$= 220 \angle 0^\circ - (105.19 \angle -7.63) - (8.3469 \angle -30.1) * (3.04 + j4.2)$$

$$= 56.03 \angle -22.138^\circ$$

$$I2_b' = \frac{56.03 \angle -22.138^\circ}{Z_b} = \frac{56.03 \angle -22.138^\circ}{(1.6 + j1.6)} = 24.76 \angle -67.138$$

$$\text{Air gap power of forward field} = (I_{2f})^2 * \left(\frac{R_2'}{2s}\right) = (2.268)^2 * (62.6)$$

$$= 322 \text{ watts.}$$

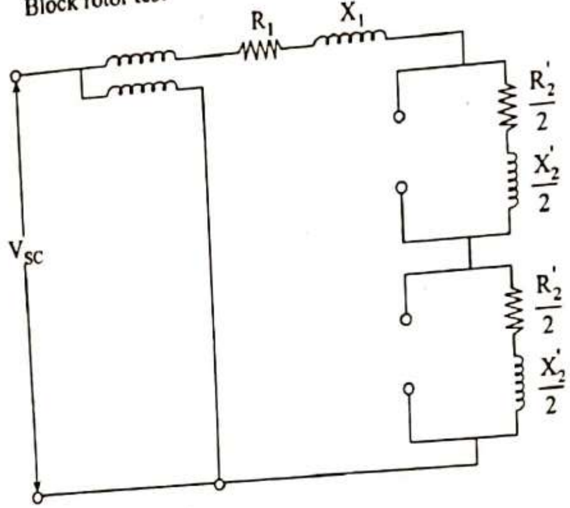
Air gap power of backward field

$$= (I_{2b})^2 * \left(\frac{R_2'}{2(2-s)}\right) = (24.76)^2 * 1.6 = 980.89 \text{ watts.}$$

6. **A 110V single phase induction motor gave the following test results:**
No load test: 110v, 2.8 Amp, 60 watts Block rotor test: 50v, 6.72 Amp, 23.26 watts calculate the equivalent circuit parameters. **[2070]**

Solution:

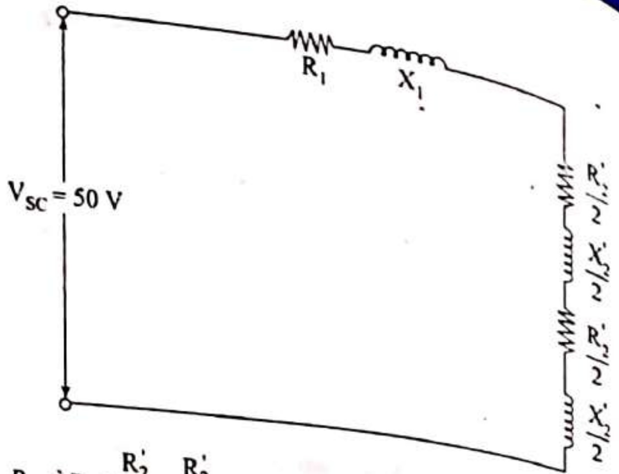
Block rotor test



Block rotor test

N = 0, s = 1

then, equivalent circuit during block rotor test become.



$$R_{sc} = R_1 + \frac{R_2'}{2} + \frac{R_2'}{2}$$

$$R_{sc} = R_1 + R_2'$$

and,

$$X_{sc} = X_1 + \frac{X_2'}{2} + \frac{X_2''}{2} = X_1 + X_2'$$

$$W_{sc} = I_{sc}^{1} * R_{sc}$$

$$R_{sc} = \frac{W_{sc}}{I_{sc}^2} = \frac{232.6}{6.72^2} = 5.15\Omega$$

Again,

$$I_{sc} = \frac{V_{sc}}{I_{sc}} = \frac{50}{6.72} = 7.4404\Omega$$

$$\therefore \quad 2_{sc} = \sqrt{R_{sc}^2 X_{sc}^2}$$

$$\Rightarrow \quad (7.4404)^2 - (5.15)^2 = X_{sc}^2$$

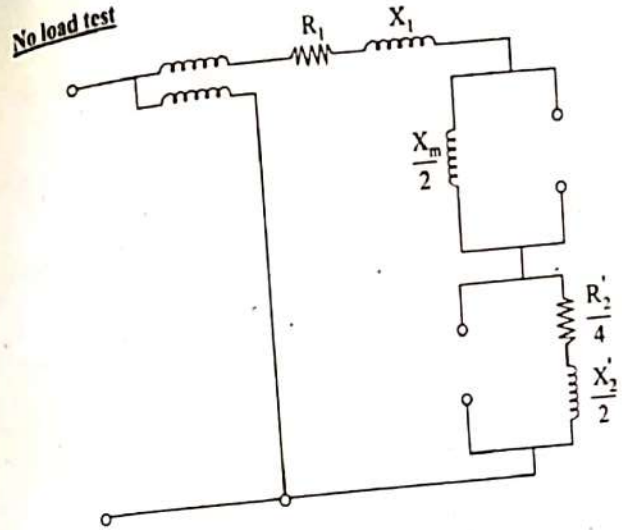
$$X_{sc} = 5.369\Omega$$

Assuming, $R_1 = R_0'$ & $X_1 = X_2'$

$$R_1 = R_2' = \frac{R_{sc}}{2} = \frac{5.15}{2} = 2.575\Omega$$

$$X_1 = X_2' = \frac{X_{sc}}{2} = \frac{5.369}{2} = 2.684\Omega$$

No load test



$P_0 = 60w$

$V_0 = 110V$

$I_0 = 2.8A$

$$\therefore \quad \cos\phi_0 = \frac{60}{110 \times 2.8} = 0.1948$$

$$\Rightarrow \quad \phi_0 = \cos^{-1}(0.1948) = 78.76^\circ$$

No load equivalent impedance

$$Z_0 = \frac{V_0}{I_0} = \frac{110}{2.8} = 39.28\Omega$$

We know that

$$X_0 = X_1 + \frac{X_2'}{2} + \frac{X_m}{2}$$

and $R_0 = R_1 + \frac{R_2'}{4} + \frac{R_m}{2}$

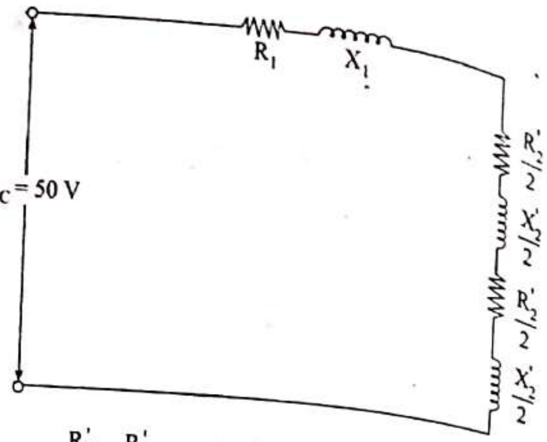
7. **The main winding and starting winding of a 50Hz capacitor start single-phase induction motor have impedances as follows:**

   Main winding (3 + j3) Ω

   Starting winding: (7.5 + j3) Ω

   Calculate the value of capacitor to be connected in series with the starting winding to produce a phase differences of 90° between main winding current and starting winding current at starting.

   [2070]



$$R_{sc} = R_1 + \frac{R_2'}{2} + \frac{R_2'}{2}$$

$$R_{sc} = R_1 + R_2'$$

and,

$$X_{sc} = X_1 + \frac{X_2'}{2} + \frac{X_2''}{2} = X_1 + X_2'$$

$$W_{sc} = I_{sc}^1 * R_{sc}$$

$$R_{sc} = \frac{W_{sc}}{I_{sc}^2} = \frac{232.6}{6.72^2} = 5.15\Omega$$

Again,

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$\therefore \quad 2_{sc} = \sqrt{R_{sc}^2 X_{sc}^2}$

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$$X_{sc} = 5.369\Omega$$

Assuming, $R_1 = R_0'$ & $X_1 = X_2'$

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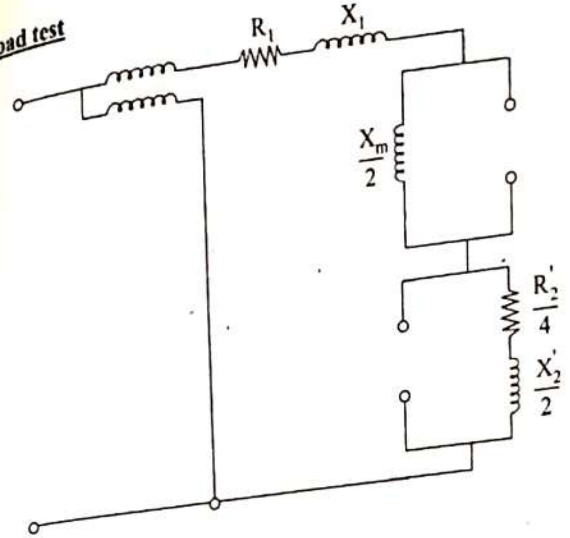
$$X_1 = X_2' = \frac{X_{sc}}{2} = \frac{5.369}{2} = 2.684\Omega$$

<u>No load test</u>



$P_0 = 60$w

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$\therefore \quad \cos\phi_0 = \frac{60}{110 \times 2.8} = 0.1948$

$\Rightarrow \quad \phi_0 = \cos^{-1}(0.1948) = 78.76°$

No load equivalent impedance

$$Z_0 = \frac{V_0}{I_0} = \frac{110}{2.8} = 39.28\Omega$$

We know that

$$X_0 = X_1 + \frac{X_2'}{2} + \frac{X_m}{2}$$

and $R_0 = R_1 + \frac{R_2'}{4} + \frac{R_m}{2}$

7. **The main winding and starting winding of a 50Hz capacitor start single-phase induction motor have impedances as follows:**

Main winding (3 + j3) Ω

Starting winding: (7.5 + j3) Ω

Calculate the value of capacitor to be connected in series with the starting winding to produce a phase differences of 90° between main winding current and starting winding current at starting.

[2070]

9. **A single phase 120V, 60Hz, 4-pole split phase inductin motor has following impedances.**

$Z_m = 5 + j6.25$

$Z_a = 8 + j6$

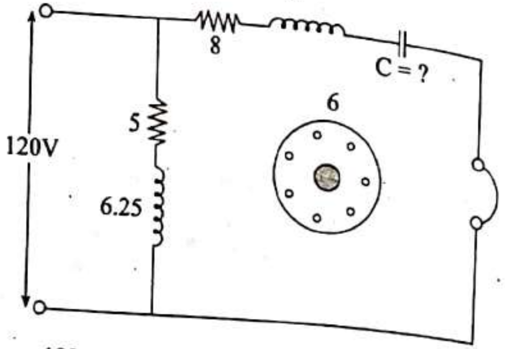
Determine the value of capacitor to be added in series with the auxiliary winding to obtain maximum torque.

Compare the starting torque and starring current with and without the added capacitor in auxiliary winding when operated by 20V, 60 Hz supply. [2074]

Solution:

$T_{st} = kI_aI_m \sin\alpha$

Where α be the angle between I_a and I_m



$$Im = \frac{V}{2m} = \frac{120}{5 + j6.25} = 15 < -51.34°$$

$$In = \frac{V}{2a} = \frac{120}{8 + j6} = 12\ \angle -36.869°$$

- (051.34°)

∴ $\alpha = (-36.869 + 51.34)$

$= 14.47°$

∴ starting torque $\tau_{st} = kI_a\ I_m \sin\alpha$

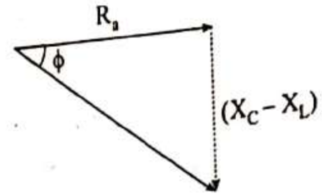
$= k \times 12 \times 15 \times \sin 14.47°$

$= 44.97 \times k$ N-m

For the current to be in quadrature i.e. for maximum starting torque the angel of current in auxiliary winding should be,

$(-51.34° + 90°) = 38.65°$

$$\tan(38.65°) = \frac{X_c - 6}{8} \quad \because \left(\frac{X_c - X_a}{R_a}\right)$$



$0.799 \times 8 + 6 = X_c$

$\Rightarrow X_c = 12.4\ \Omega$

$$C = \frac{1}{2\pi fc} = \frac{1}{2\pi \times 60 \times 12.4}$$

$= 213.9.9\ \mu F$

$T_{st} = kI_aI_m \sin\alpha = kI_aI_m \sin 90°$

I_a after adding capacitor,

$$I_a = \frac{120}{8 + j(6 - 12.4)} = 11.71\ \angle 36.66°$$

Now,

$T_{st} = kI_a\ I_m \sin\alpha = k \times 11.71 \times 15 \times \sin 14.47° = 43.89$ k N-m

10. **A 400V, 6-pole, 3-φ star connected synchronous motor has resistance and synchronous impedance of R_a = 0.5Ω/ph, Z_s = 4Ω/ph. It takes the current of 15A at unity p.f. when operating with a certain field current. if the load torque is increased until the line current becomes 60A, keeping field current constant. Calculate gross torque developed and new p.f.**

Solution:

$R_a = 0.5\Omega/ph$

$Z_z = 4\Omega/ph$

$$V = \frac{400}{\sqrt{3}} = 213V$$

At unity P.f. $\phi = 0°$

Synchronous reactance $X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{4^2 - 0.5^2} = 3.97\Omega$

We have,

$E_b = V - I(R + jX_s)$

$= 231\ \angle 0° - 15\ \angle 0°\ (0.5 + j3.97)$

$= 231.10\ \angle -14.9°$

$|E_b|^2 = |V|^2 + |E_R|^2 - 2|V|.|E_R| \cos(\theta - \phi)$

where,

$E_R = 60 \times 4 = 240V$ (i.e. $I.Z_s$)

$(231.10)^2 - (231)^2 + (240)^2 - 2 \times 231 \times 240 \times \cos(\theta - \phi)$

$\Rightarrow \cos(\theta - \phi) = 0.519$

$\theta - \phi = 58.78°$

Also,

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right) = 82.82$$

$\therefore \quad \phi = 24.04°$

Power input (Pin) $= \sqrt{3} \times V_L.I_a . \cos\phi$

$= 37.96$ kW

Electrical power converted to mechanical power

$P_m = P_{in\ -loss} = 32.50$ kw

$P_m = T \times W_{syn}$

$$\therefore \quad T = \frac{P_m}{\frac{2\pi N_s}{60}} = \frac{32.56 \times 10^3}{\frac{2\pi \times 120 \times 50}{6 \times 60}} = 310.88 \text{ N-m} \qquad \left(\because NS = \frac{120f}{P}\right)$$

11. A 6600V, 3-ϕ star connected synchronous motor draws a full load current of 80 A_{mp} at 0.8 pf leading. The per phase armature resistance in 2.2Ω and synchronous reactance is 22Ω. If the stray losses are 3.2 kW. Calculate induced emf, output power and efficiency. **[2070]**

Solution:

Phase voltage, $V_p = \frac{6600}{\sqrt{3}} = 381.5$ volts.

$\bar{I} = 80 \angle 36.86°$

$R_a = 2.2\Omega$

$X_s = 22\Omega$

Input power, $P_{in} = \sqrt{3} \times V_L \times I \cos\phi$

$= 3\, V_P\, I \cos\phi$

$= 3*3810.51*80*0.8$

$= 731.62$ kW

$P_{out} = P_{in} - P_{loss}$

$= 731.62 - 3.2 - 3 \times 80^2 \times 2.2$

$(3I^2R)$

$= 686.18$kW

$$\eta = \frac{P_{out}}{P_{in}} = \frac{686.18}{731.62} = 93.79\%$$

Induced voltage $= \bar{V}_{ph} - I.z.$

$= 3810.5 \angle 0° - 80 \angle 36.86° * (2.2 + j22)$

$= 4961.988 \angle -17.76°$

Induced line voltage $= \sqrt{3} \times 4961.988 = 8594.4$ volts

$$E_b = \sqrt{V^2 + E_R^2 - 2VE_R\cos(\theta + \phi)}$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) = 84.29°$$

$|E_R| = |I|.|2| = 80 \times 22.11 = 1769$ votls.

$V = \frac{6600}{\sqrt{3}} = 3810.5$ volts.

$E_b = 4962.14$ Votls.

Induced line voltage $= \sqrt{3}\, E_b = 8594.7$ votls.

12. 220V, 4-pole, 50H_z, single phase induction motors. $R_2' = 4.2QW$, $X_2' = 3.2\ \Omega$, $X_{mag} = 74\Omega$ Friction and windage loss = 30 watt. core loss = 98 watt.

If motor is running at a speed of 1425 rpm at rated voltage and frequency, compute stator current, power factor, torque and efficiency. **[2074]**

Solution:

$n_s = \frac{120f}{P} = 1500$ rpm

slip $s = \frac{n_s - n}{n_s} = 0.05$

From equivalent circuit,

$$2f = R_f + jX_f = \left(\frac{R_2'}{2s} + j\frac{x_2'}{2}\right) \| j\frac{X_{mag}}{2}$$

$$= \left(\frac{4.2}{2 \times 0.05} + j\frac{3.2}{2}\right) \| j\frac{74}{2}$$

$= (17.67 + j\,20.76)\Omega$

$$Z_b = R_b + jX_L = \frac{R_2'}{2.(2-5)} + j\frac{X_2'}{2}) \| j\frac{X_{mcr}}{2}$$

$$= \left(\frac{4.2}{2(2-0.05)} + j\frac{3.2}{2}\right) \| j\frac{74}{2}$$

$= (0.99 + j.1.56)\ \Omega$

Input current, $\bar{I} = \frac{\bar{V}}{R_1 + jX_1 + Z_f + Z_b} = 6.96 \angle -50.6°$ Amp

Stator current = 6.96 Amp

Power factor = cos 50.6° = 0.635 lagging

$$\text{Torque} = \frac{I_2\,(R_f - Rb)}{W_{syn}} = 5.149 \text{ Nm} \qquad \left(\because W_{syn} = \frac{2\pi Ns}{60}\right)$$

Input power, $P_{in} = VI\cos\phi = 1016.61$ watt

$P_{mech} = 6.96^2 * (17.67 - 0.99) * (1 - 0.05) = 767.6$ watt

Actual output = P_{mech} - Iron loss - Friction loss

= 767.6 - 98 - 30 = 639.6 watt

$$H = \frac{639.6}{1016.61} \times 100\% = 62.9\%$$

13. A 220v, 50Hz, 6 - pole, 1/6 HP single phase induction motor has r_1 = 11.4Ω, r_2' = 13.8Ω, $x_1 = x_2'$ = 14.3Ω and x_0 = 275Ω. Using double revolving field theory to find **[2074]**

a) Input current and p.f.

b) Torque due to forward and backward field components and gross torque.

c) efficiency when the motor in operating at a slip of 0.06. Neglect R_c constant losses are: 30.2W.

Solution:

Slip (s) = 0.06

$Z_1 = 11.41 + j14.3 = 18.3\angle 51.44$

$Z_f = R_f + jX_f$

$$= \left(\frac{13.2}{2(0.06)} + j\frac{14.3}{2}\right) \| \left(\frac{j275}{2}\right)$$

$= 63.69 + j57.44$

$= 85.734\angle 42.04$

$Z_b = R_b + jX_b$

$$= \left(\frac{13.8}{2(2 - 0.06)} + j\frac{14.3}{2}\right) \| \left(\frac{j275}{2}\right)$$

$= (3.356 + j\,7.15) \| (j137.5)$

$= 3.211 + j6.875$

$= 7.587\angle 64.96°$

∴ Total impedance $Z_{eq} = Z_1 + Z_f + Z_b$

$Z_{eq} = (11.41 + j14.3) + (63.69 + j37.45) + (3.211 + j.6.875)$

$= 78.3011 + j78.625\Omega$

$= 1110.96\angle 45.118$

$$\text{Input current } (I_L) = \frac{V}{Z_\mu} = \frac{220 < 0}{110.96 < 45.118} = 1.98 < -45.118\Omega$$

a) Input current (I_L) = 1.98A

& P.f. ($\cos\phi$) = cos45.118 = 9.705 lagging

b) Torque

$Em(f) = I_1 Z_f = (1.98 < -45.119) \times (85.735 < 42.04)$

$= 169.75 < -3.078$v

$E_m(b) = I_1 Zb$

$= (1.98 < -45.118°) * (7.58 < 64.96°)$

$= 15.02 < 20.84°$

$$\therefore I'_{2f} = \frac{E_m(f)}{\left(\frac{x_2'}{2s} + j\frac{X_2'}{2}\right)} = \frac{169.75\angle -2.078}{\left(\frac{13.8}{2(0.06)} + \varphi\frac{14.3}{2}\right)}$$

$= (1.473\angle -6.636)$ A

and

$$I'_{2b} = \frac{E_m(b)}{\left(\frac{2}{2(2-s)} + j\frac{x_2'}{2}\right)} = \frac{15.02 < 20.84}{\left(\frac{13.8}{2(2.0.06)} + j\left(\frac{14.3}{2}\right)\right)}$$

$= 1.88 < -42.71$ A

∴ Air gap power for forward field

$$P_{gf} = (I_{2f}')^2 * \frac{x_2'}{2s} = (1.473)^2\left(\frac{13.8}{2(0.06)}\right) = 249.52\text{w}$$

Air gap power for backward field

$$P_{gb} = (I_{2b}')^2 * \frac{x_2'}{2(2\text{-}s)} = (1.88)^2 * \frac{13.8}{2(2\text{-}0.06)} = 12.57\text{w}$$

∴ Torque developed for the forward field,

$$T_f = \frac{P_{gf}}{\frac{2\pi Ns}{60}} = \frac{9.55}{Ns} * P_{gf}$$

$$\text{Here, } N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

$$\therefore T_f = \frac{9.55 \times 249.52}{1000} = 2.383 \text{ N - m}$$

and torque developed for the backward field.

$$T_b = \frac{9.55}{Ns} \times P_{gb} = \frac{9.55 \times 12.57}{1000} = 0.12 \text{ N- m}$$

b) Gross torque (net torque)

$= T_f - T_b = 2.383 - 9.12 = 2.263$ N – m

c) Output power,

Mechanical o/p power for the forward field $P_{mf} = (1 - s) P_{gf} = (1 - 0.06) \times 249.52 = 234.5488$ W

and mechanical o/p power for the backward field $P_{mb} = \{1 - 2 - 2)\} P_{gb}$

$= \{1 - (2 - 0.06)\} * 12.57$

$= -11.8158$ w

∴ Mechanical power o/p, $P_n = P_{mf} = P_{mb}$

∴ $P_m = 234.5488$w

∴ Net o/p power = $P_m - P_{loss}$

$= 222.7331 - 30.2$

$= 192.5331$ watt

d) Input power = $VI_1\cos\phi$

$= 220 * 1.96 * \cos 45.118$

$= 307.38$ watt

e) $\eta = \frac{o/p}{I/p} \times 100\% = \frac{192.5331}{307.38} \times 100\% = 62.637\%$

14. The constants of a 1/4 HP, 230v, 4-pole, 60Hz single phase induction motor are as follows. **[2071]**

$R_1 = 10\Omega, X_{q1} = 12.8\ \Omega, R_2' = 11.65\Omega$

$X_2' = 12.8\Omega, X_m = 258\Omega$

The total load is such that the machine runs at 3% slip when applied voltage is at 210V. The iron losses are 35.5 watts at 210V. Calculate.

i) Input current, power factor and input power

ii) Power developed

iii) Shaft power if mechanical losses are of 7 watts.

iv) Efficiency

v) torque due to forward, backward and gross torque.

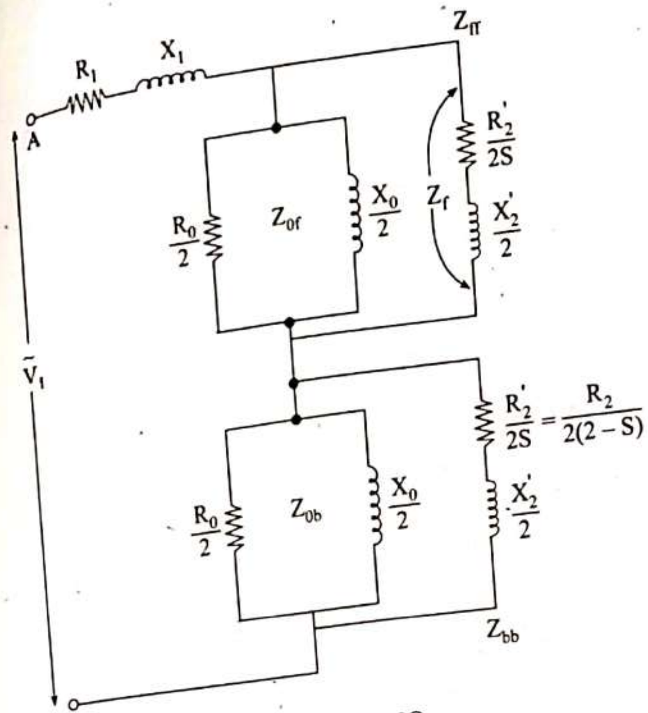
Solution:

slip (s) = 3% = 0.03

Core los s = 25.5w at 210v

$I_m = \frac{335.5}{210} = 0.169A$

and $v_c = \frac{210}{0.169} = 1242\Omega$



∴ $z_1 = (10 + j12.8)\ \Omega = 16.243\ \angle 52°\Omega$

$z_f = (194.166 + j6.4) \| (j129) \| (1242.6)$

$= 100.94 < 52.09\ \Omega$

and

$I_b = (2.957 + j6.4) \| (j129) \| (1242.6)$

$= 6.7\ \angle 66.169°$

∴ Total impedance = $z_{1q} + z_f + z_b$

$= 123.712\ \angle 53.65°$

i) Input current $(I_1) = \frac{V}{Z_{eq}}$

$= \frac{230 < 0°}{123.712 < 53.65} = 1.859 < -53.65$

∴ Input current $(I_1) = 1.859$ A

Power factor $(\cos\phi) = \cos 53.65$

$= 0.5927$ lagging

and input power = $VI_1\cos\phi$

$= 230 \times 1.859 \times 0.5927$

$= 253.42$ watt

ii) $E_{mf} = I_1 Z_f = (1.859 < -53.65) * (100.94 < 53.03)$

$= 87.647 \angle -0.56$ V

$E_{mb} = I_1 Z_b = (1.859 < -53.6) * (6.7 < 66.169)$

$= 12.455 < 12.519$v

$\therefore \quad I'_{2f} = \dfrac{E_{mf}}{(194.166 + j6.4)} = \dfrac{187.64 \angle -0.56}{194.166 + j6.4}$

$= 0.966 < -2.448$A

and

$I'_{2b} = \dfrac{E_{mb}}{(2.957 + j6.4)} = \dfrac{12.955 < 11.519}{(2.957 + j\,6.4)}$

$= 1.757 <-5.2.682°$ A

$\therefore$ Air gap power forforwardfield

$P_{gf} = (I'_{2f})^2 \times 194.166$

$= (0.966)^2 * 194.166$

$= 181.187$ watt.

and Air gap power for backward field

$P_{gb} = (I'_{2b})^2 \times 2.957$

$= (1.767)^2 \times 2.957$

$= 9.233$ watt.

$\therefore$ Mechanical o/p power for forward field

$P_{mf} = (1 - 5) P_{gf}$

$= (1 - 0.03) * 181.187$

$= 175.751$ watt.

and mechanical o/p poew for backward field.

$P_{mb} = \{1 - (2 - 5)\} P_{gb}$

$= \{1 - (2 - 0.03)\} * 9.23$

$= -8.956$ watt

$\therefore$ Power developed $(P_m) = P_{mf} + P_{mb}$

$= 175.751 - 8.956$

$= 166.795$ watt.

iii) Mechanical shaft power $(P_{mech}) = P_m - P_{losses}$

$= 166.795 - 7$

$= 159.795$ watt.

iv) $\eta = \dfrac{o/p \times_{watt}}{i/p} = \dfrac{159.795}{253.42} \times 100\% = 63.05\%$

v) Torque,

Torque developed due to forward field

$I_f = \dfrac{9.55}{N_s} \cdot P_{gf}$

$= \dfrac{9.55}{1800} \times 181.187$

$= 0.961$ N-m

Here $N_s = \dfrac{120f}{P} = \dfrac{120 \times 60}{4} = 1800$ rpm

Torque developed due to backward field

$T_b = \dfrac{9.55}{N_s} * P_{gb} = \dfrac{9.55}{1800} * 9.233 = 0.049$ N-m

$\therefore$ Gross torque $(\tau) = \tau_f - \tau_b$

$= 0.961 - 0.049$

$= 0.912$ N-m

15. A 220v, single phase induction motor gave the following test results.

Blocked or rotor test : 110v, 10A, 400W

No load lest : 220v, 4A, 100w

Find the parameters of equivalent circuit. Neglect R_0 **[2070]**

a) Find the parameters of equivalent circuit. Neglect R_0

b) Find iron-friction and winding losses

Solution:

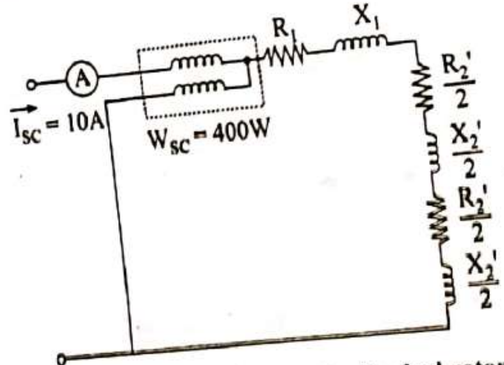


Fig. (i) Equivalent ckt diagram for blocked rotor test

$\therefore \quad R_{sd} = R_1 + R'_2 + R'_2 = \dfrac{W_{sd}}{I_{sd}^2} = \dfrac{400}{(10)^2} = 4\Omega$

Assuming $R_1 = R_2'$

$\therefore \quad R_1 = R_2' = 2\Omega$

$\therefore \quad Z_{sc} = \frac{V_{sc}}{I_{sc}} = \frac{110}{10} = 11\Omega$

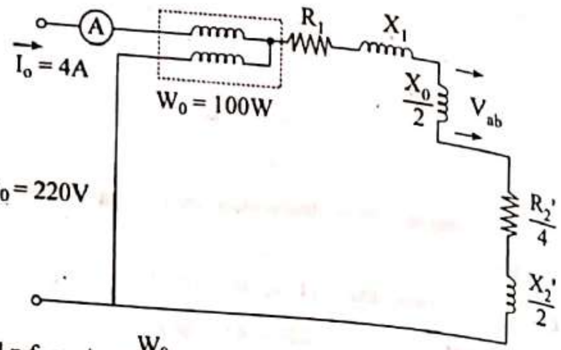
$\therefore \quad X_1 + X_2' = (2_{sc}^2 - R_{sc}^2)^{1/2} = (11^2 - 4^2)^{1/2} = 10.247\Omega$

Assuming $X_1 = X_2'$

$\therefore \quad X_1 = X_2' = \frac{10.247}{2} = 5.1235\Omega$

Again,

For no load test



No load p.f. $\cos\phi_0 = \frac{W_0}{V_0 I_0}$

$\Rightarrow \quad \cos\phi_0 = \frac{100}{220 \times 4} = 0.1136$

$\Rightarrow \quad \phi_0 = 83.47°$

$\therefore \quad V_{ab} = v_0 < 0 - (I_0 < -\phi_0) \left\{\left(R_1 + \frac{R_2'}{4}\right) + j\left(X_1 + \frac{X_2'}{2}\right)\right\}$

$\Rightarrow \quad Vab = 220 < 0 - (4 < 83.47°) \left(\left\{2 + \frac{2}{4} + j\left(5.1235 + \frac{5.1235}{2}\right)\right\}\right)$

$= 188.43 < 1.96°$

$\therefore \quad \frac{X_0}{2} = \frac{V_{ab}}{I_0} = \frac{188.43}{4} = 47.1\Omega$

b) Iron, friction and winding losses $= w_0 - I_0\left(R_1 + \frac{R_2'}{4}\right) = 60w$

□□□

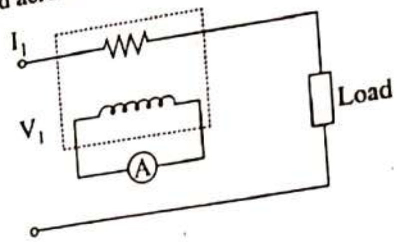
APPENDIX

1. **Describe working principle of current transformer. Why secondary winding of a CT shall not be kept open without ammeter?**

⇒ The current transformer are designed to sense the high current through primary circuit and steps down the current in a known ratio. The primary winding of a CT is supplied by a current source rather than a voltage source. The primary winding of a CT will have few turns of thick wire enough to carry the primary high current and is connected in series with the load. The secondary winding will have many no. of turns made of thin wire connected across a low range ammeter.

Let, I_f = High current through primary circuit to be measured.

I_2 = Secondary current through ammeter.



K = Transformation Ratio $= \frac{I_1}{I_2}$

$\therefore \quad I_1 = KI_2$

If the secondary is kept open, there will be no. current through the secondary and the secondary winding will not produce the opposing flux which is required for cancelling high voltage will induce in the winding due to higher value of flux density in the care and may cause insulating failure. Hysteresis loss and eddy current loss with be high due to high value of flux density in the core. This may lead to overheating of core which will again damage, the insulation of winding. hence, the secondary winding will be short circuited while the ammeter is disconnected.

2. **Derive an emf equation of a DC generator. Explain voltage build up process of a DC shunt generator.**

⇒ Let, ϕ = magnetic flux per pole

Z = total no. of armature conductors.

P = No. of magnetic poles.

N = speed of armature in rpm.

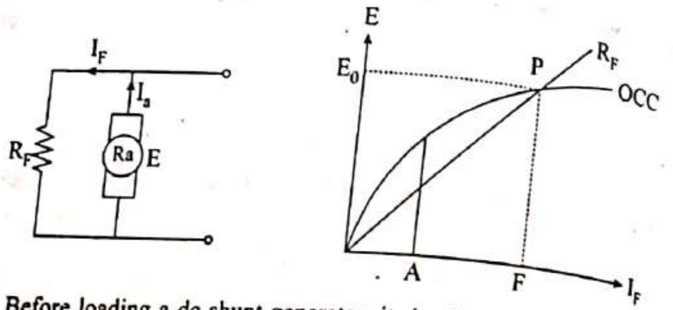
Average emf generated per conductor $= \frac{d\phi}{dt}$ magnetic flux cut by each conductor in one revolution $d\phi = \phi p$.

Time for one revolution, $dt = \frac{60}{N}$ sec.

Average emf generated per conductor $= \frac{d\phi}{dt} = \frac{4PN}{60V}$. Let A = No. of parallel paths in the armature winding. Then, no. of conductors in series $= \frac{Z}{A}$.

$\therefore$ Total emf across the brushes, $E = \frac{\phi PN}{60} \times \frac{Z}{A}$ Volts.

$\therefore \quad E = \frac{Z\phi N}{60} \times \frac{P}{A}$ Volts.



Before loading a dc shunt generator, it should be allowed to build up its voltage. Usually, there is always some residual magnetic flux produced by the field pole even in the absence of field current. Therefore, at initial, when the armature rotates, a small emf is induced across the armature due to this residual flux. the emf circulates a small current in the field current which will increase the flux per pole. When the flux increases, the emf will increase which further increases the flux and so on until the generator generates steady rated voltage. The maximum value up to which the voltage builds up depends on the value of field winding resistance.

Emf generated, E = AC ohmic voltage in R_f = AB

$BC = L\frac{dI_L}{dt}$

3. **Explain torque-slip characteristics of a 3-phase induced motor and explain the effect of rotor resistance on T-S characteristics.**

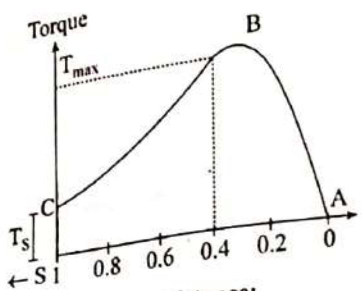
$\Rightarrow$ The generator torque equation is

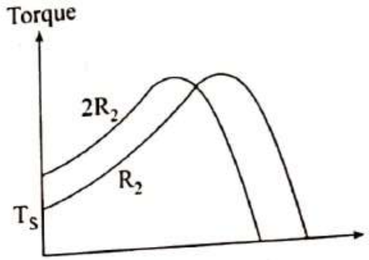
$$T_R = \frac{KS\,E_2^2\,R_2}{R_2^2 + S^2 X_2^2} \quad ...(i)$$

At start, S = 0 and Hence, $T_R = 0$ corresponds to point A. When speed decreases (slip increases), then, $R_2^2 >> S^2 X_2^2$ so, equation (i) for such conditions will be,

$$T_P = \frac{KS\,E_2^2\,R_2}{R_2^2} \Rightarrow T_R \times S$$

Hence, torque will be linearly proportional to slip shown by line AB upto $S = \frac{R_2}{X_2}$. Beyond this value of slip, $R_2^2 << S^2 X_2^2$. So, equation (i) becomes, $T_R \times \frac{1}{S}$. So, torque decreases with increase in slip as shown by curve BC. At, S = 1 i.e. N = 0, torque becomes, $T_S = \frac{K\,E_2^2\,R_2}{R_2^2 + X_2^2}$





Effect of rotor resistance:

At normal working: $T_R \times \frac{S}{R_2}$

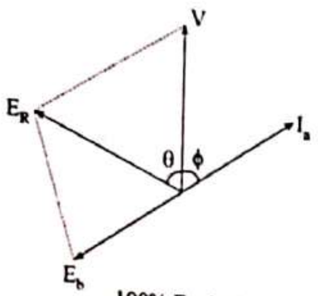
At starting $T_S \times \frac{R_2}{S}$

Hence, external rotor resistance are used when high starting torque is required. Once, the motor has picked up its normal operating speed (N), the external, rotor resistance is removed to improve the running torque.

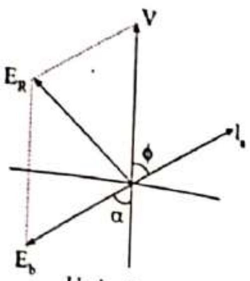
4. With the help of phasor diagrams, explain the effect of excitation in a 3-phase synchronous motor.

⇒ The dc current supply to the rotor field winding is known as excitation in synchronous motor. As the speed of synchronous motor is constant, the magnitude of back emf remains constant provided the flux per pole produced by the rotor does not change. So, the magnitude of back emf can be changed by field excitation. If the excitation is changed at a constant load, the magnitude of armature current and p.f. will change. by changing the excitation, the motor can be operated at both lagging and leading pf. This foot can be analysed by the following way.

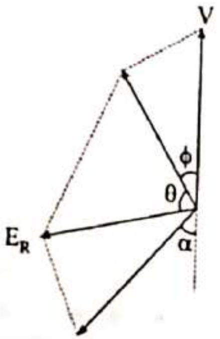
The value of excitation for which magnitude of back emf E_b is equal to applied voltage V is known as 100% excitation. If the excitation is more than if the excitation is less than 100%, then the motor is said to be under excited.



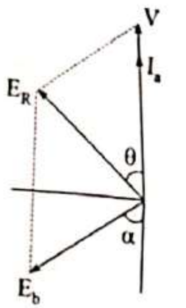
100% Excitation



Under Excitation



Over Excitation



Unity pf

5. A 3000V, 3-ϕ sychronous motor running at 1500 rpm has its excitation kept constant corresponding to no-load terminal voltage of 3000 V. Determine the power input, power factor and torque developed for an armature per phase and armature resistance is neglected.

Solution:

$R_a = 0, X_s = 5\Omega$

$I_a = 250$ A

Supply voltage per phase, $V = \frac{3000}{\sqrt{3}} = 1732$ V

Induced emf per phase, $E = \frac{3000}{\sqrt{3}} = 1732$ V

Synchronous impedance, $Z_s = R_a + {}_jX_s = {}_j5 = 5\angle 90°$ for lagging p.f.

$E^2 = (V\cos\phi - I_a R_a)^2 + (V\sin\phi - I_a X_S)^2$

or, $1732^2 = (1732 \times \cos\phi - 0)^2 + (1732\sin\phi - 250 \times 5)^2$

or, $\sin\phi = 0.3608$

So, $\cos\phi = 0.9326$ (lag)

Input power, $P_1 = \sqrt{3}\, V_L\, I a \cos\phi$

$= \sqrt{3} \times 1732 \times 1250 \times 0.9326$

$= 3.49$ mW

and torque $= \frac{P_1 \times 60}{2 \times N_S}$

$N_s = 1500$ rpm

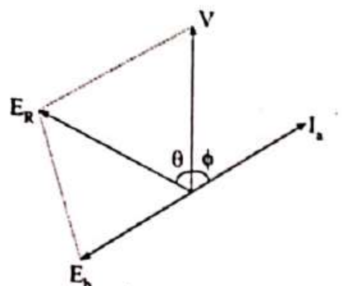
$P_i = 3.49$ MW

So, torque $= \frac{3.49 \times 10^6 \times 60}{2\pi \times 1500} = 22.26$ K-Nm

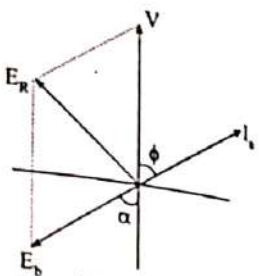
4. With the help of phasor diagrams, explain the effect of excitation in a 3-phase synchronous motor.

⇒ The dc current supply to the rotor field winding is known as excitation in synchronous motor. As the speed of synchronous motor is constant, the magnitude of back emf remains constant provided the flux per pole produced by the rotor does not change. So, the magnitude of back emf can be changed by field excitation. If the excitation is changed at a constant load, the magnitude of armature current and p.f. will change. by changing the excitation, the motor can be operated at both lagging and leading pf. This foot can be analysed by the following way.

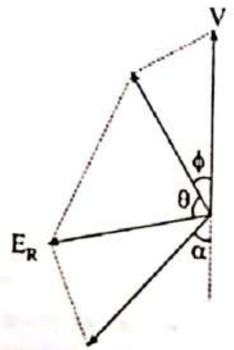
The value of excitation for which magnitude of back emf E_b is equal to applied voltage V is known as 100% excitation. If the excitation is more than if the excitation is less than 100%, then the motor is said to be under excited.



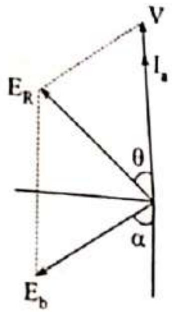
100% Excitation



Under Excitation



Over Excitation



Unity pf

5. A 3000V, 3-ϕ sychronous motor running at 1500 rpm has its excitation kept constant corresponding to no-load terminal voltage of 3000 V. Determine the power input, power factor and torque developed for an armature per phase and armature resistance is neglected.

Solution:

$R_a = 0, X_s = 5\Omega$

$I_a = 250$ A

Supply voltage per phase, $V = \frac{3000}{\sqrt{3}} = 1732$ V

Induced emf per phase, $E = \frac{3000}{\sqrt{3}} = 1732$ V

Synchronous impedance, $Z_s = R_a + {}_jX_s = {}_j5 = 5\angle 90°$ for lagging p.f.

$$E^2 = (V\cos\phi - I_a R_a)^2 + (V\sin\phi - I_a X_s)^2$$

or, $1732^2 = (1732 \times \cos\phi - 0)^2 + (1732\sin\phi - 250 \times 5)^2$

or, $\sin\phi = 0.3608$

So, $\cos\phi = 0.9326$ (lag)

Input power, $P_1 = \sqrt{3}\, V_L\, I\, a\cos\phi$

$= \sqrt{3} \times 1732 \times 1250 \times 0.9326$

$= 3.49$ mW

and torque $= \frac{P_1 \times 60}{2 \times N_s}$

$N_s = 1500$ rpm

$P_1 = 3.49$ MW

So, torque $= \frac{3.49 \times 10^6 \times 60}{2\pi \times 1500} = 22.26$ K-Nm

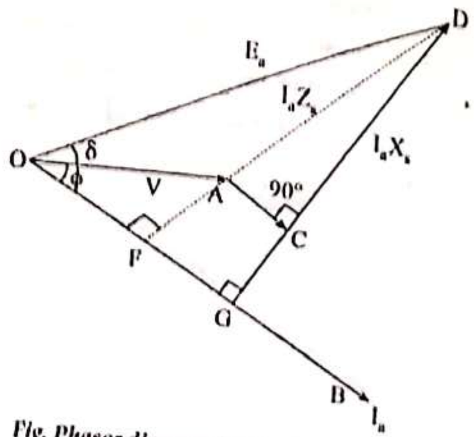


Fig. Phasor diagram for lagging power factor cos ϕ

The magnitude of E_a can be found from the right-angled ΔOGD.

$$OD^2 = OG^2 + GD^2 = (OF + FG)^2 + (GC + CD)^2$$

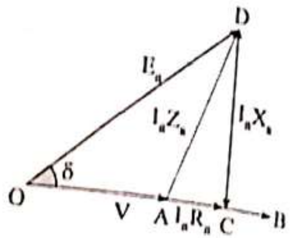
or, $$E_a^2 = (v\cos\phi + +aR_a)^2 + (V\sin\phi + I_aX_s)^2$$

Unity pf

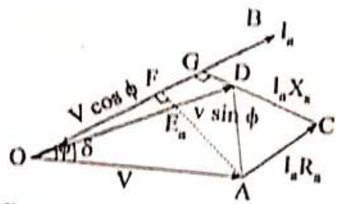
From right-angle ΔOCD

$$OD^2 = (OC)^2 + (CD)^2$$

$$E_a^2 = (V + I_aR_a) + (I_aX_s)^2$$



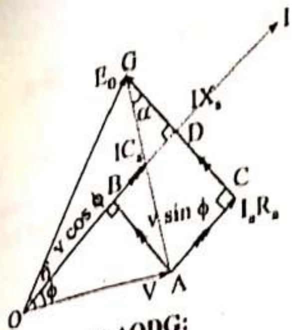
Leading power factor



From right-angled triangle OGC

$$OD^2 = OG^2 + GD^2 = (OF + FG)^2 + (GC - CD)^2$$

or, $$E_a^2 = (V\cos\phi + I_aR_a)^2 + V\sin\phi - I_aX_s)^2$$



Right angle ΔODG:

$$OG^2 = OD^2 + GD^2$$
$$= (OB^2 + BD^2) + (CG - CD)^2$$
$$= (V\cos\phi + I_aR_a)^2 + (IX_s - V\sin\phi)^2$$

$$\boxed{(V\sin\phi - IX_s)^2 = (IX_s - V\sin\phi)^2}$$

$$\boxed{(5-3)^2 = (3-5)^2}$$

Questions

1. Draw the phasor diagram of a loaded alternator for the following conditions:
   (a) lagging power factor
   (b) leading power factor
   (c) Unity power factor.
2. What is armature reaction? Explain the effect of armature recation on the terminal voltage of an alternator at (i) unity power factor load, (ii) zero lagging PF load and (iii) zero leading Pf load. Draw the relevant phasor diagrams.
3. Name and explain the factors responsible for marking terminal voltage of an alternator less than the induced voltage.
4. Define the terms synchronous reactance and voltage regulation of alternator.
5. Wht is the necessity of parallel operator of alternators?
6. State the conditions necessary for paralleling alternators?
7. What is an infinite bus? state the characteristics of an infinite bus. What are the operating characteristics of an alternator connected to an infinite bus?
8. Show that in order to obtain a constant-voltage, constant-frequency of a practical bus bar system, the number of alternators connected in parallel should be as large as possible.

9. What conditions must be fulfilled before and alternator can be connected to an infinite bus?
10. Why is rotating field system used in preference to a stationary field?
11. Derive emf equation for an alternator. Explain clearly the meaning of (a) distribution factor and (b) coil-span factor. Give expressions for them.

Automatic Generation Control

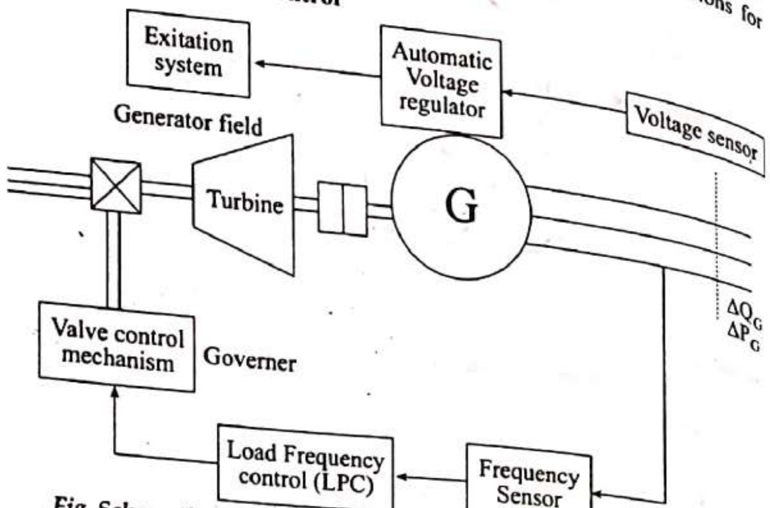
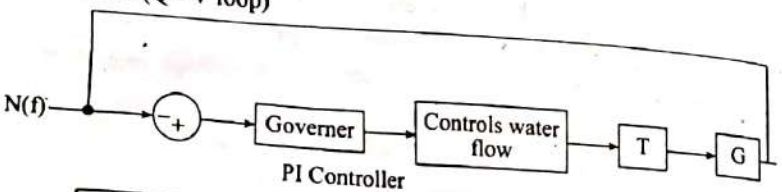


Fig. Schematic diagram of LFC and AUR of a synchronous generator.

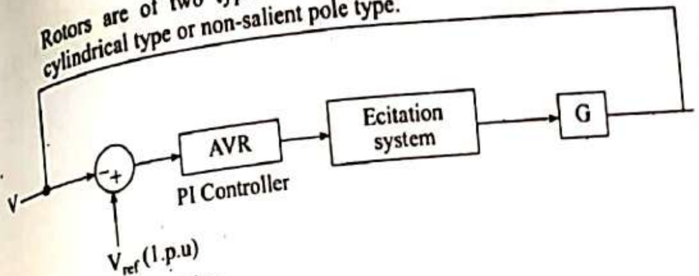
- The generator is supplying power to the load which is the mixture of the active power and reactive power.
- Speed governor (P - f loop).
- AUR (Q - V loop)



P = Qgh

- The exacting current is supplied to the rotor through two slip ring and brushes.
- The power rating of the exciter is ordinarily 0.5 to 1% of power rating of the synchronous generator.

Rotors are of two types namely (i) salient pole type (ii) smooth cylindrical type or non-salient pole type.



Induction machine

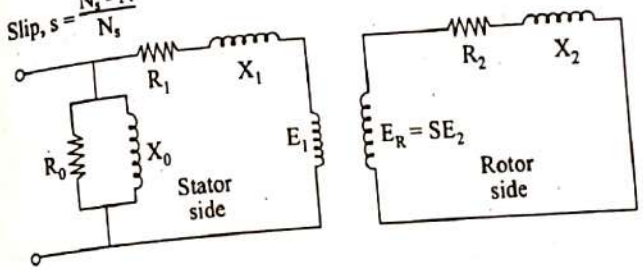
→ 3 main parts: i) stator: ii) Rotor: iii) Yoke

$\Phi_R = \phi_m \sin\omega t$

$\phi_Y = \phi_m \sin(\omega t - 120°)$

$\phi_B = \phi_m \sin(\omega t - 240) = \phi_m \sin(\omega t + 120°)$

Slip, $s = \frac{N_s - N}{N_s}$



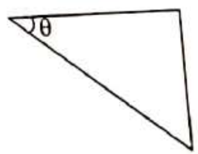
$S = \frac{R_2}{X_L}$ for maximum torque.

\# $T_R = \frac{k_1 SE_2^2 R/z}{R_2^2}$ or, $T_R \propto \frac{SE_2^2}{R_2}$ $\therefore T_R \propto \frac{S}{R_2}$

\# Sped control of Induction Motor:

\# Testing of Induction Motors:

a) $\frac{\text{No - load test}}{\text{iron loss}}$



Concentrated winding

- If are slot per pole or slots equal to number of poles are employed. then concentrated winding is obtained.
- Such windings give maximum induced emfs for a given number of conductors but the view form of induced emf is not exactly of sinusoidal form.

In Skeleton wave winding, the number of conductors in each slot is equal to the number of poles.

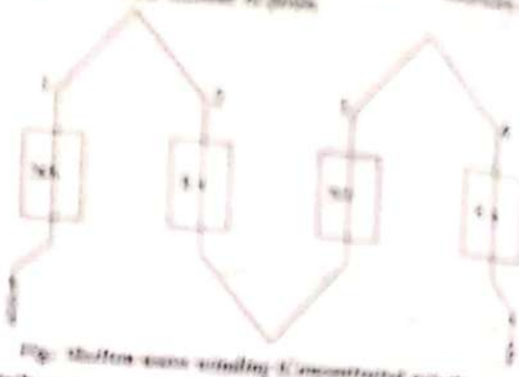


Fig: Skeleton wave winding (Concentrated windings)

Distributed winding

If the conductors are placed in several slots under one pole, the winding is known as distributed winding.

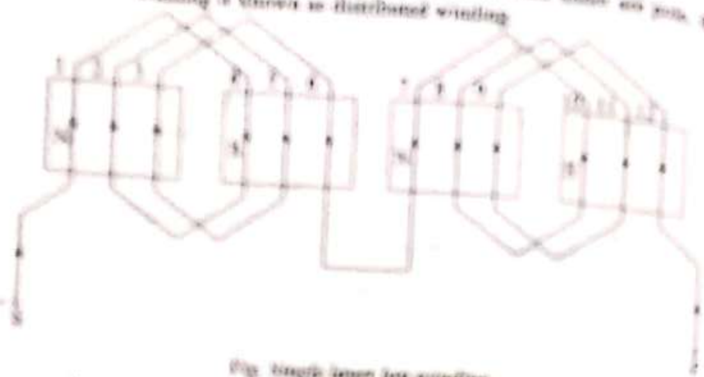
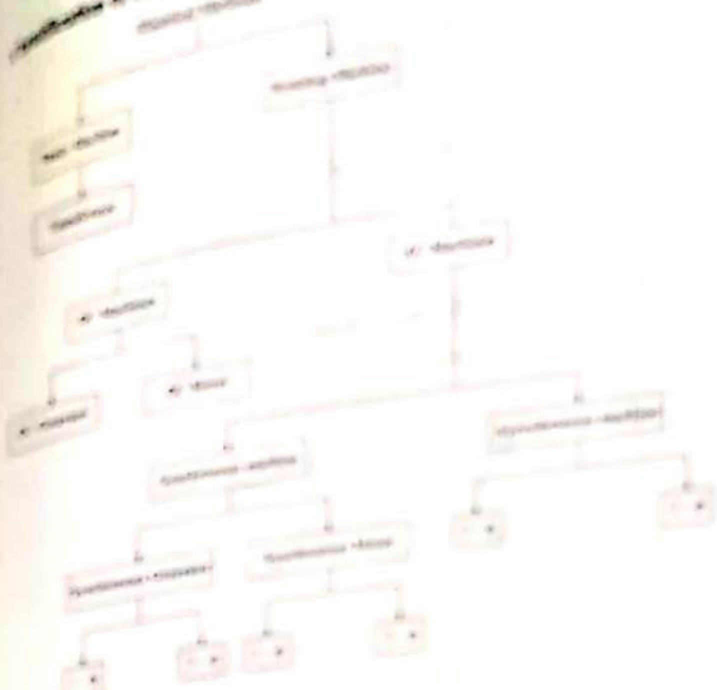


Fig: Single layer lap winding

Assignments

1. Describe a working principle of a current transformer. Why secondary winding of a CT shall not be kept open without ammeter?
2. Derive an emf equation of a DC generator. Explain voltage build up process of a DC generator.
3. Explain torque-slip characteristics of 3-phase induction motor and explain the effect of rotor resistance on T-S characteristics.
4. With the help of phasor diagrams explain the effect of excitation in a 3-phase synchronous motor.
5. Explain the operating and characteristics of capacitor start and run motor with neat sketches.

Classification of electrical machines



DC motor

The magnitude of back emf is given by

$$E_b = \frac{\phi Z N}{60} \times \frac{P}{A} \quad \ldots (1)$$

$$I_a = \frac{V - E_b}{R_a}$$

or, $I_a R_a = V - E_b$, multiplying both side by I_a & rearranging

$$V I_a = E_b I_a + I_a^2 R_a$$

Input power to armature − (copper loss in armature) = Power developed by armature.

$E_b \propto N\phi$

$E_b \propto N$

$N \propto 1/\phi$

- In Skelton wave winding, the number of conductors or coil sides is equal to the number of poles.

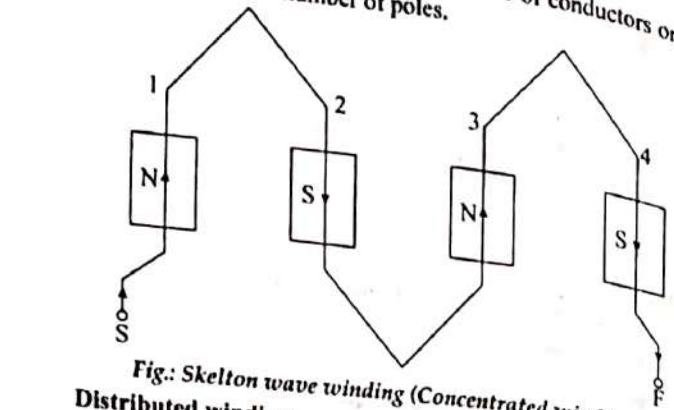


Fig.: Skelton wave winding (Concentrated windings)

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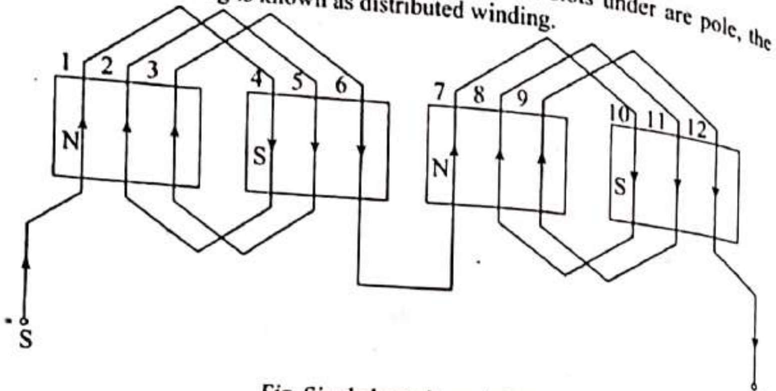

Fig. Single layer lap winding.

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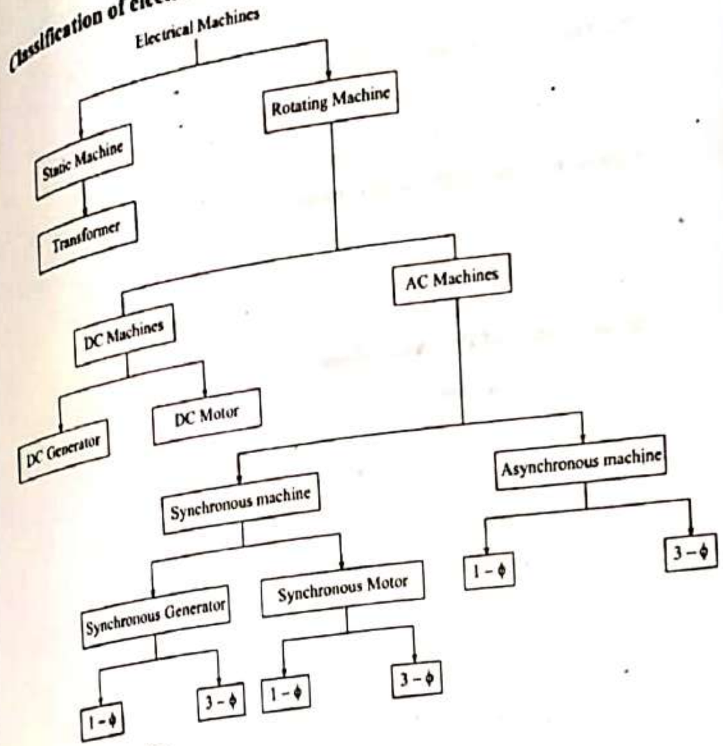


DC motor

The magnitude of back emf is given by

$$E_b = \frac{z\phi N}{60} * \frac{P}{A} \quad ...(i)$$

$$I_a = \frac{V - E_b}{R_a}$$

or, $I_aR_a = V - E_b$, multiplying both side by I_a & rearranging.

$$VI_a = I_a^2R_a = E_bI_a$$

Input power to armature - (copper loss in armature) = Power developed by armature.

$E_b \propto N$;

$E_b \propto \phi$;

$N \propto 1/\phi$;

Characteristics of DC shunt motor:

$T_a \propto \phi I_a$: & $\phi \propto I_f$.

We know that, the sped of DC shunt motor

$$N \propto \frac{E_b}{\phi} ; N \propto \frac{1}{\phi} ;$$

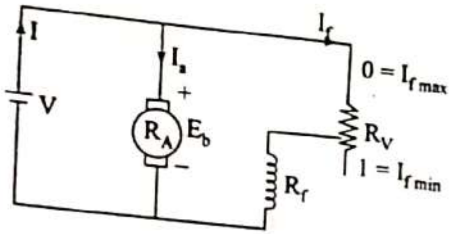
Characteristics of DC series motor:

$T_a \propto \phi I_a$ but, $\phi \propto I_a$

$\therefore T_a \propto I_a^2$

Speed control of DC shunt Motor;

i) Flux control method:

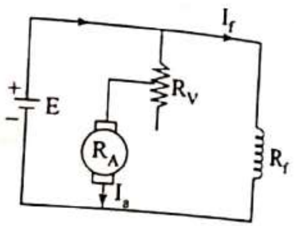


$I_f = \frac{V}{R_f}$ if R_v is not connected.

$I_f = \frac{V}{R_f + R_v\uparrow}$ if R_v is connected.

$\phi \propto I_f$

Armature control method



$I_{a1} = I_{a2}$ ($\because T_a \propto \phi I_a$)

$E_{b1} = V - I_{a1} R_a$ ...(i)

$E_{b2} = V - I_{a1} (R_a + R_v)$ ...(ii)

& $Eb \propto N\downarrow$ & vice versa.

(1) Power electronics/Electric drives.

(2) Power system - Renewable energy/smart grid.

(3) Control system

(4) HVDC - FACTS.

$(E + E\cos\alpha)^2 + (E\sin\alpha)^2$

$= E^2 + 2E^2\cos\alpha + E^2\cos\alpha^2 + E^2\cos^2\alpha$

$= 2E^2 + 2E\cos\alpha$

$= \sqrt{2}\,E\sqrt{1 + \cos\alpha}$

$= \sqrt{2}\,E\sqrt{\cos^2\alpha/2 + \sin^2\alpha/2 + \cos^2\alpha/2 + \sin\alpha/2}$

$= \sqrt{2}\,E\sqrt{2\cos^2\alpha/2}$

$= 2E\cos\alpha/2$

$$r_B = \sqrt{\left(\frac{\phi}{2}\right)^2 + \left(\frac{\phi}{2}\right)^2 + 2\frac{\phi}{2}\cdot\frac{\phi}{2}.\cos 60^\circ}$$

$= \phi\sqrt{1/4 + 1/4 + 2/4 \cos.60^\circ}$

$= \phi\sqrt{2/4 + 2/4.1/2} = \phi\sqrt{\frac{3}{4}} = \phi\frac{\sqrt{3}}{2}$

$$\phi_T = \sqrt{\left(\frac{\sqrt{2}}{2}\right)^2 + (\phi m)^2}$$

$= \sqrt{\left(\frac{3}{4} + 1\right)}\,\phi_m$

□□□