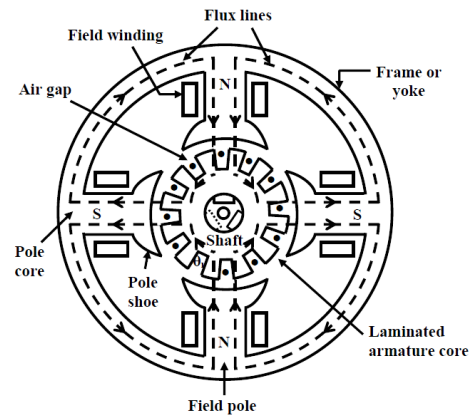


DC Generator

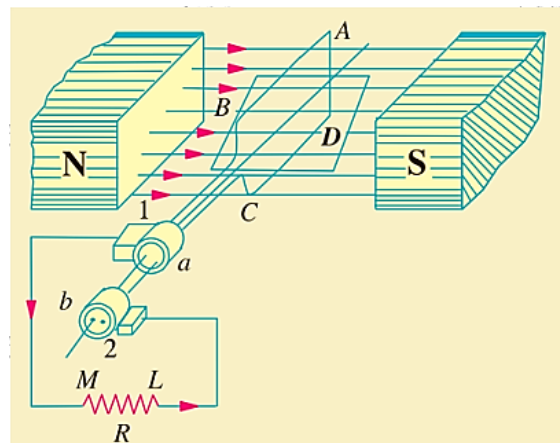
A DC generator is a machine which converts mechanical energy (or power) into electrical energy.



Cross-sectional view of a 4-pole DC machine

Construction Generator:

➤ A single turn rectangular copper ABCD rotating about its own axis in a magnetic field provided by either permanent magnet or electromagnet. The two ends of the coil are joined to slip ring 'a' and 'b' which are insulated from each other and from the central shaft. Two collecting brushes press against the slip rings; their function is to collect the current induced in the coil and to convey it to external load resistance. The rotating coil is called the 'armature'.



Types of DC Generators

1. Stator:

The stator of a DC machine provides the mechanical support for the machine and consists of the yoke and the poles (or field poles).

1. Yoke: Is the outer part of the DC generator, it serves double purpose:

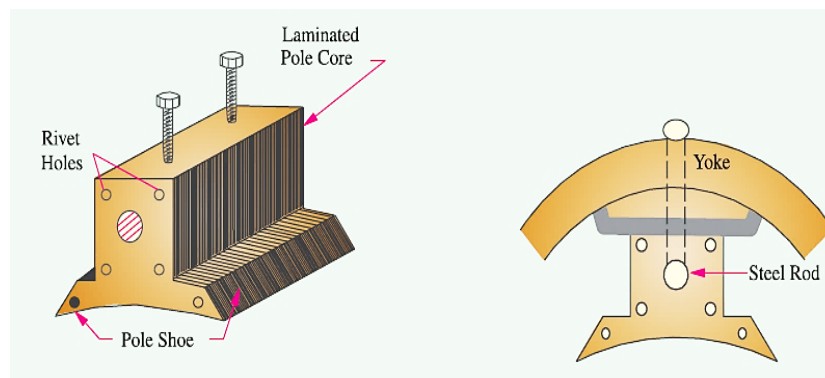
- It provides mechanical support for the poles and acts as a protecting cover for the whole machine.
- It carries the magnetic flux produced by the poles.

2. Field Poles

The field poles are mounted inside the yoke and it consists of the **pole core** and the **pole shoes**.

Pole Core:

The pole core is made of thin laminations stacked together. Note that the cross-sectional area of the pole core is smaller than that of the pole shoe.



The **pole shoes** serve two purposes:

- They spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path.
- They support the field coils as shown in the following figure.

3. Field Coils:

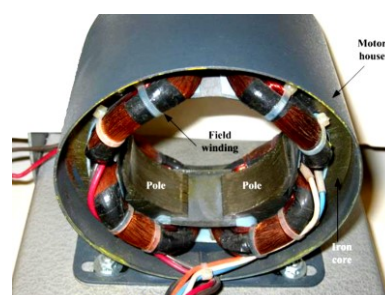
The field coils are wound on the field poles; the function of the field pole is to produce a uniform magnetic flux. There are two types of field windings: a shunt field winding and a series field winding.

1- Shunt Field Winding

The shunt field winding has large number of turns of small section copper conductor (many turns of fine wire).

2- Series Field Winding

In the case of series field winding a few turns of heavy cross section conductor is used.

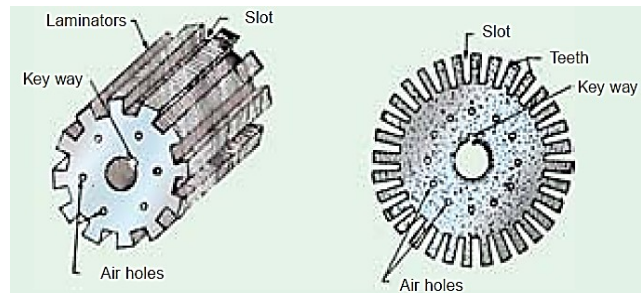
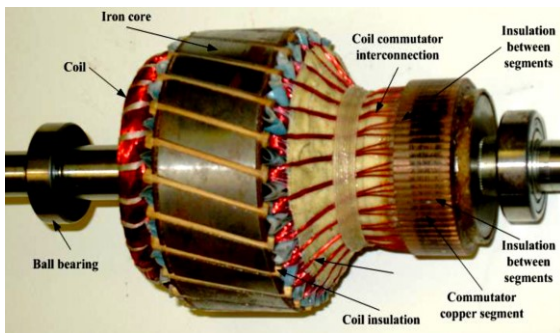


4. Armature:

The rotating part of a dc machine is called the armature. The length of the armature is usually the same as that of the pole.

a. Armature Core:

It is cylindrical or drum-shaped and is built up of usually circular sheet steel discs or laminations approximately 0.5 mm thick. It is keyed to the shaft. The laminations have axial slots on their periphery to house the armature windings.

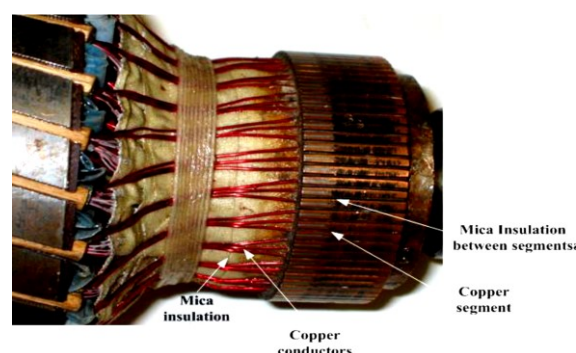


b. Armature Winding:

Is the heart of a DC machine; in which the e.m.f. (electro motive force) is induced (in generator action) and the torque is developed (in motor action).

5. Commutator:

- It is a cylindrical structure and it is made of copper segments insulated from each other by mica and mounted on the shaft of the machine.
- The armature windings are connected to the commutator segments.
- ***The function of the commutator*** is to convert the alternating e.m.f. induced in the armature windings in to a unidirectional voltage. (*is used to converting the AC from the generator's windings to DC in the external load circuit*)



Brushes:

- The material for the brush is normally carbon or carbon-graphite.
- Brushes are held in a fixed position by means of brush holders and remain in sliding contact with the commutator segments.
- An adjustable spring inside the brush holder exerts a constant pressure on the brush in order to maintain a proper contact between the brush and the commutator.

- The purpose of the brush is to ensure electrical connections between the rotating commutator and stationary external load circuit and collecting of current without any sparking.

☒ Advantages Carbon:

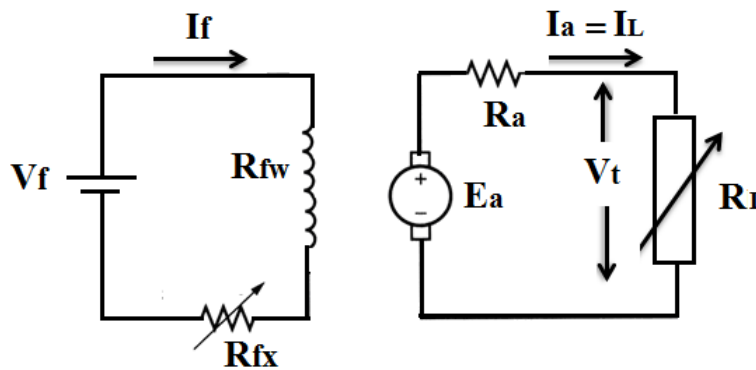
1. It is very soft.
2. It is a conductor.
3. It self-lubricates

Types of Direct Current (DC) Generator

DC generators are classified according to field excitation **into two types:**

1- Separately-Excited DC Generator

- The external source can be:
 1. Another DC generator.
 2. Rectifier (AC to DC converter).
 3. Simply a battery.



Equivalent circuit of a separately excited generator

E_a is the induced e.m.f. in the armature winding

R_a is the armature winding resistance. I_a is the armature current.

V_t is the terminal output voltage. I_L is the load current.

I_f is the field winding current.

R_{fw} is the field winding resistance

R_{fx} is the external resistance added in series with the

R_{fw} to control I_f

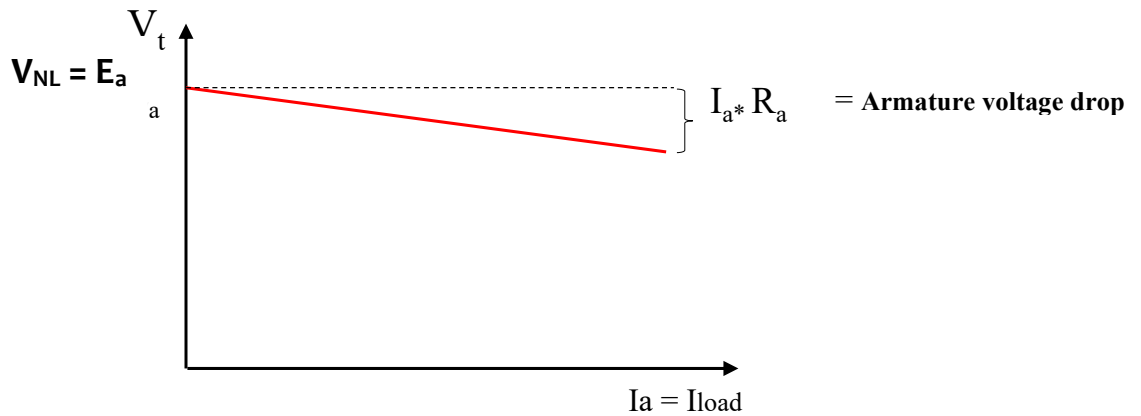
$R_f = R_{fw} + R_{fx} = \text{total field resistance}$

$$V_f = I_f * (R_{fw} + R_{fx}) = I_f * R_f \quad \dots\dots (1)$$

$$V_t = E_a - I_a * R_a \quad \dots\dots (2)$$

$$I_L = I_a \quad \dots\dots (3)$$

When the I_f is held **constant** and the armature is rotating at a **constant speed**, the E_a will be **constant**. As the I_L **increases**, the V_t **decreases** due to the increases in the armature **voltage drop** ($I_a * R_a$). A plot of the V_t versus I_L is called the external characteristic of a generator.



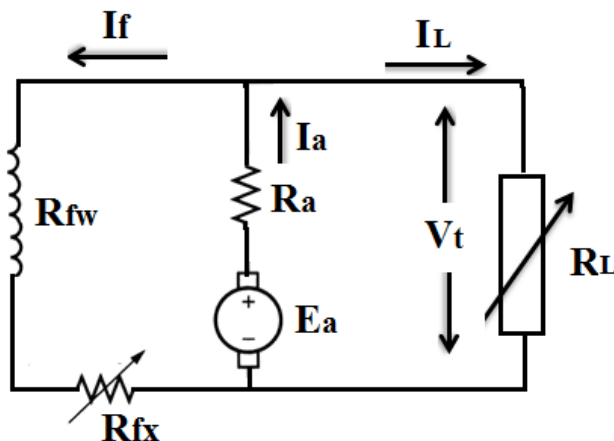
The external characteristic of a separately excited DC generator

2- Self-Excited DC Generator

The field windings are supplied by a current produced by the generator itself. According to the method of connection of the field windings, a self-excited DC generator can be sub-divided into three types:

A. Shunt Generator

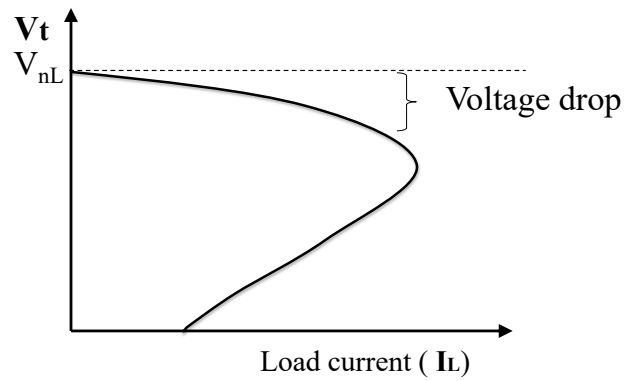
The shunt field winding connected across (in parallel with) the armature terminals.



$$I_a = I_L + I_f \quad \dots\dots 1$$

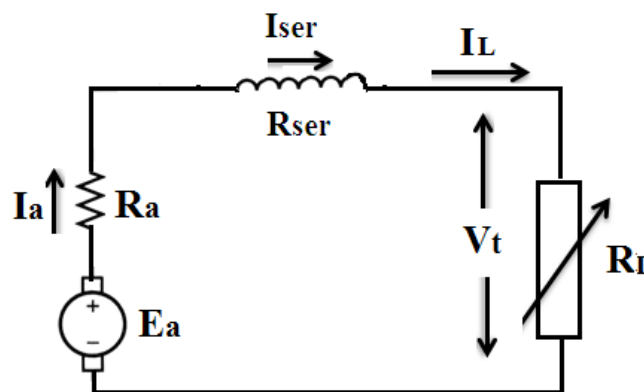
$$V_t = I_f * (R_{fw} + R_{fx}) = I_f * R_f \quad \dots\dots 2$$

$$V_t = I_L * R_L = E_a - I_a * R_a \quad \dots\dots 3$$



B. Series Generator

- The series field winding (R_s) connected in series with the armature winding (R_a).
- Series generator cannot operate at no-load because the flux produced by the series field winding is zero. Since, the flux in series field winding increases as I_L increases as shown in the external characteristic.



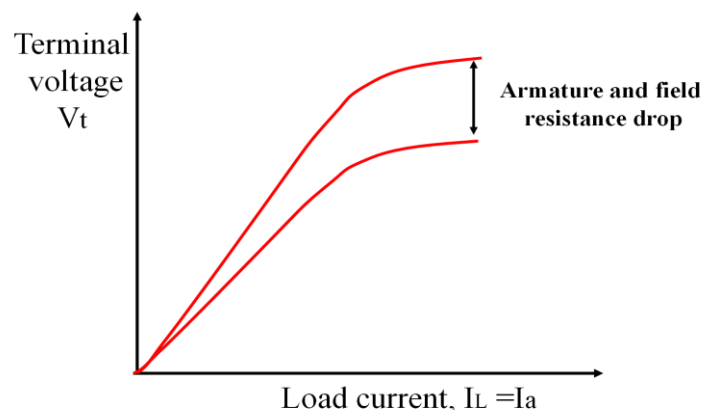
$$V_t = E_a - (I_a * R_a + I_{ser} * R_{ser})$$

$$I_a * R_a + I_{ser} * R_{ser} = \text{Voltage Drop}$$

$$I_a = I_L = I_{ser}$$

The external characteristic of a series generator

C. Compound Generator: Both shunt and series field windings are connected with the armature windings in short-shunt or long-shunt.



- **short-shunt compound generator.** When the shunt field winding is connected directly across the armature terminals, it is called a

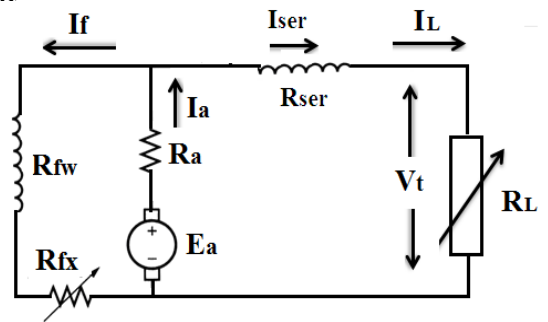
$I_f = \text{Voltage across shunt windings} / R_f$

$$I_f = \frac{V_t + (I_{ser} * R_{ser})}{R_f}$$

$$I_a = I_L + I_f$$

$$I_L = I_{ser}$$

$$E_a = V_t + (I_a * R_a) + (I_{ser} * R_{ser})$$



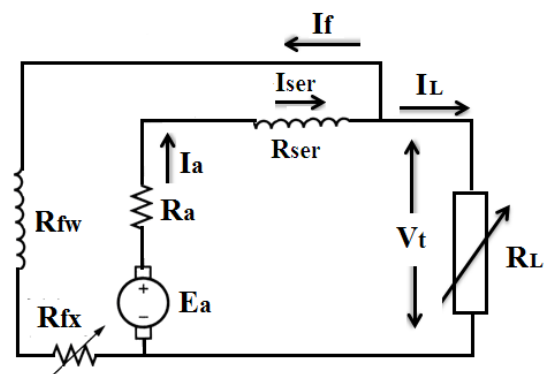
Short-Shunt Compound Generator

- **long-shunt compound generator.** When the shunt field winding is connected across the load, it is called a

$$I_f = \frac{V_t}{R_f}$$

$$I_a = I_{ser} = I_L + I_f$$

$$E_a = V_t + (I_a * R_a) + (I_{ser} * R_{ser})$$



Long-Shunt Compound Generator

Losses in DC Machines

1- Copper losses.

Whenever current flows in a wire, a copper loss associated with it, it consists of:

- Armature copper loss = $I_a^2 * R_a$. This loss is about 30 to 40% of full-load losses.
- Field copper loss. This loss is about 20 to 30% of full-load losses.
 - 1- Shunt copper loss = $I_f^2 * R_f$.
 - 2- Series copper loss = $I_{ser}^2 * R_{ser}$.
 - 3- The loss due to brush contact resistance.

2- Magnetic losses (iron or core losses):

This loss is about 20 to 30% of full-load losses. It consists of:

- Hysteresis loss.
- Eddy current loss.

3- Mechanical losses:

This loss is about 10 to 20% of full-load losses. It consists of:

These consist of:

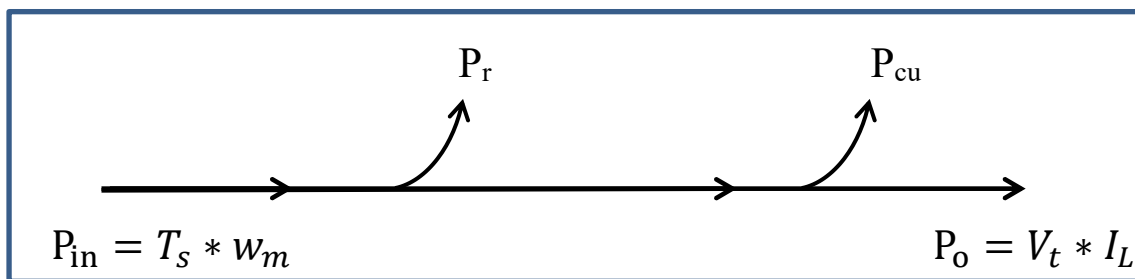
- Friction between the bearings and the shaft.
- Friction between the brushes and the commutator.
- Air-friction or winding loss of rotating armature.

Usually, **magnetic** and **mechanical losses** are collectively known as **Rotational Losses**. **Rotational Losses = magnetic losses + mechanical losses**

4- Stray losses: These losses cannot be easily accounted.

Power-Flow Diagram

A DC generator is a machine which converts mechanical energy (or power) into electrical energy (or power).



Power-Flow Diagram of a DC Generator

P_{in} = Mechanical input power = $T_s * w_m$.

T_s = Applied shaft torque.

w_m = Angular velocity P_{cu} = Copper losses

P_o = Electrical output power = $P_{in} - (P_r + P_{cu})$

P_r = **Rotational Losses = mechanical losses + magnetic losses.**

Efficiency(η)

The efficiency of a machine is simply the ratio of its output power to input power.

$$\begin{aligned} \text{Efficiency}(\eta) &= \frac{\text{Output Power } (P_o)}{\text{Input Power } (P_i)} * 100 \\ &= \frac{P_o}{P_o + \text{Total Losses}} * 100 \end{aligned}$$

\therefore Input Power (P_i) = $P_o + \text{Total Losses}$

Voltage Regulation (V.R.)

The voltage regulation (VR) is defined as the difference between the no-load terminal voltage (V_{NL}) to full load terminal voltage (V_{FL}) and is expressed as a percentage of full load terminal voltage. It is therefore can be expressed as.

The voltage regulation of a DC generator is the change in its terminal voltage with the change in load current when it is running at a constant speed.

$$V.R. \% = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100$$

$V_{NL} = E_a$ is the terminal voltage at no-load current

V_{FL} the terminal voltage at full-load current.

If $V_{FL} > V_{NL}$ the voltage regulation is negative

If $V_{NL} > V_{FL}$ the voltage regulation is positive

For ideal generator the voltage regulation should be zero. $V_{NL} = V_{fL}$

Examples of DC Generator

Ex: A 4-pole shunt DC generator is delivering 20A to a load of 10Ω. If the armature resistance is 0.5 Ω and the shunt field resistance is 50 Ω, calculate the induced emf and the efficiency of the machine. Allow a drop of 1V per brush.

$$\text{Terminal Voltage} = I_L R = 20 \times 10 = 200V$$

$$I_f = 200 \div 50 = 4A$$

$$I_A = I_L + I_f = 20 + 4 = 24A$$

$$I_A R_A = 24 \times 0.5 = 12V$$

$$E_A = I_A R_A + V + \text{brush drop} = 12 + 200 + 2 = 214V$$

$$\eta_e = \frac{V I_L}{E_A I_A} \times 100\% = \frac{200 \times 20}{214 \times 24} \times 100\% = 77.9\%$$

$$VR = \frac{E_A - V_{FL}}{V_{FL}} \times 100\% = \frac{214 - 200}{200} \times 100\% = 7\%$$

Q1/ A shunt generator delivers a load current of 450A at 230V, and have armature resistance (0.03Ω), and shunt field resistance (50Ω). Calculate the generated e.m.f.

Ans. /

$$E_a = V_t + I_a * R_a .$$

$$I_a = I_L + I_f.$$

$$I_f = V_t / R_f = 230 / 50 = 4.6A$$

$$\therefore I_a = 450 + 4.6 = 454.6\text{A.}$$

$$E_a = 230 + (454.6 * 0.03) = 243.6\text{V}$$

Q2/ An 8-pole DC shunt generator with 778 wave-connected armature conductors and running at 500 r.p.m. Supplies a load of 12.5Ω resistance at $V_t = 250\text{V}$, and have armature resistance (0.24Ω), and shunt field resistance (250Ω). Calculate:

- 1- Armature current.
- 2- Generated e.m.f. (E_a).
- 3- The flux per pole (ϕ_p)

Answer/

$$1- I_L = V_t / R_L = 250 / 12.5 = 20\text{A}$$

$$I_f = V_t / R_f = 250 / 250 = 1\text{A}$$

$$I_a = I_L + I_f = 20 + 1 = 21\text{A}$$

$$2- E_a = V_t + I_a * R_a \\ = 250 + (21 * 0.24) = 255.04\text{V}$$

$$3- E_a = \frac{NPZ\phi_p}{60 A}$$

$$N = 500\text{r.p.m.}$$

$$P = 8, \quad Z = 778, \quad A = 2 \text{ Wave}$$

$$255.04 = \frac{500 * 8 * 778 * \phi_p}{60 * 2} \quad \therefore \phi_p = 9.83\text{mWb}$$

Q3/ A 25KW, 250V DC shunt generator has an armature resistance of 0.11Ω , shunt field resistance of 185Ω , and rotational loss is 1500W . Calculate:

- 1) Load current (I_L).
- 2) Shunt field current (I_f) and armature current (I_a).
- 3) Armature voltage drop ($I_a * R_a$).
- 4) Generated e.m.f. (E_a).
- 5) Voltage regulation (V.R.).

Ans.

- 1) Load current (I_L).

$$P_{\text{out}} = V_t * I_L$$

$$I_L = P_{\text{out}} / V_t = 25000 / 250 = 100\text{A}$$

- 2) Shunt field current, armature current.

$$I_f = V_t / R_f = 250 / 185 = 1.35\text{A}$$

$$I_a = I_L + I_f = 101.35\text{A}$$

- 3) Armature voltage drop = $I_a * R_a = 101.35 * 0.11 = 11.149\text{V}$

- 4) Generated e.m.f. (E_a) = $V_t + I_a * R_a = 250 + 11.149 = 261.149V$
 5) Voltage regulation (V.R.) = $((E_a - V_t) / V_t) * 100 = 4.46\%$



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Q5/ A long-shunt compound generator running at 1000rpm supplies 22KW at terminal voltage of 220V. The resistances of armature, shunt field, and the series field are 0.05, 110 and 0.06 Ω respectively. The overall efficiency at the above load is 88%. Find: (a) Cu losses, (b) Iron and friction losses, and (c) The torque exerted by the prime-mover (T_s).

Ans. /

(a) Total Cu losses = Armature copper loss + Shunt copper loss + Series copper loss

$$I_f = V_t / R_f = 220/110 = 2 \text{ A}$$

$$I_L = P_o / V_t = 22,000/220 = 100 \text{ A,}$$

$$I_a = I_L + I_f = 100 + 2 = 102 \text{ A}$$

$$\text{Armature copper loss} = I_a^2 * R_a = 102^2 * 0.05 = 520.2 \text{ W}$$

$$\text{Shunt copper loss} = I_f^2 * R_f = 4 * 110 = 440 \text{ W}$$

$$\text{Series copper loss} = I_{ser}^2 * R_{ser} = 102^2 * 0.06 = 624.3 \text{ W}$$

$$\text{Total Cu losses} = 520.2 + 624.3 + 440 = 1584.5 \text{ W}$$

$$\text{(b) Output Power } (P_o) = 22000 \text{ W ;}$$

$$\text{Input Power } (P_{in}) = 22000/0.88 = 25000 \text{ W}$$

$$\therefore \text{Total losses} = 25000 - 22000 = 3000 \text{ W}$$

$$\therefore \text{Iron and friction losses} = 3000 - 1584.5 = 1415.5 \text{ W}$$

$$\text{(c) } P_{in} = T_s * W_m$$

$$W_m = \frac{2 \pi N}{60} = \frac{2 \pi * 1000}{60} = 104.7$$

$$T_s = \frac{P_{in}}{W_m} = \frac{25000}{104.7} = 238.74 \text{ N. m}$$

Q6/ In a 120V compound generator, the resistances of the armature, shunt and series windings are 0.06Ω , 25Ω and 0.04Ω respectively. The load current is 100A at 120V. Find the induced e.m.f. and the armature current when the machine is connected as (a) long-shunt and as (b) short-shunt.

Ans. /

1- (Long Shunt)

$$I_f = V_t / R_f = 120/25 = 4.8 \text{ A}$$

$$I_L = 100 \text{ A}$$

$$I_a = I_f + I_L = 104.8 \text{ A}$$

$$E_a = V_t + I_a * R_a + I_{ser} * R_{ser}$$

$$I_a = I_{ser}$$

$$E_a = V_t + I_a * R_a + I_a * R_{ser}$$

$$= 120 + (104.8 * 0.06) + (104.8 * 0.04) = 130.48 \text{ V}$$

2- (Short Shunt)

$$\text{Voltage drop in series winding} = 100 * 0.04 = 4 \text{ V}$$

$$\text{Voltage across shunt winding} = 120 + 4 = 124 \text{ V}$$

$$\therefore I_f = 124/25 = 4.96 \text{ A}$$

$$\therefore I_a = I_f + I_L = 100 + 4.96 = 104.96 \text{ A}$$

$$\therefore E_a = V_t + I_a * R_a + I_L * R_{ser}$$

$$= 120 + (104.96 * 0.06) + (100 * 0.04) = 130.3 \text{ V}$$

Q7/ A long-shunt compound generator delivers a load current (I_L) 50A at 500V, and has ($R_a = 0.05 \Omega$), ($R_{ser} = 0.03 \Omega$), and ($R_f = 250 \Omega$). Calculate the armature current and induced e.m.f.

Ans. /

$$I_f = V_t / R_f = 500 / 250 = 2 \text{ A}$$

$$I_a = I_L + I_f = 50 + 2 = 52 \text{ A}$$

$$E_a = V_t + (I_a * R_a) + (I_a * R_{ser})$$

$$= 500 + (52 \times 0.05) + (52 \times 0.03) = 504.16\text{V}$$

Q8/ A short-shunt compound generator delivers a load current of 30A at 220V, and has armature, series field, shunt field resistance of 0.05Ω , 0.30Ω , and 200Ω respectively. Calculate induced e.m.f. and the armature current.

Ans. /

$$I_a = I_L + I_f$$

$$I_f = \text{Voltage across shunt windings} / R_f$$

$$I_f = (V_t + (I_L \times R_{ser})) / R_f$$

$$= (220 + (30 \times 0.3)) / 200 = 1.145\text{A}$$

$$\therefore I_a = 30 + 1.145 = 31.145\text{A}$$

$$E_a = V_t + (I_a \times R_a) + (I_L \times R_{ser})$$

$$= 220 + (31.145 \times 0.05) + (30 \times 0.3) = 230.56\text{V}$$

Q9/ A shunt generator delivers 195A at terminal voltage 250V, and has ($R_a = 0.02 \Omega$), ($R_f = 50 \Omega$). The iron and friction losses are 950W. Find

- 1- The induced e.m.f.
- 2- Copper (Cu) losses.
- 3- Efficiency of the generator

Ans. /

$$1- I_f = V_t / R_f = 250 / 50 = 5\text{A}$$

$$I_a = I_L + I_f = 195 + 5 = 200\text{A}$$

$$E_a = V_t + (I_a \times R_a)$$

$$= 250 + (200 \times 0.02) = 254\text{V}$$

2- Cu losses = Armature copper loss + Shunt copper loss

$$\text{Armature copper loss} = I_a^2 \times R_a = 200^2 \times 0.02 = 800\text{W}$$

$$\text{Shunt copper loss} = I_f^2 \times R_f = 5^2 \times 50 = 1250\text{W}$$

$$\text{Cu losses} = 800 + 1250 = 2050\text{W}$$

$$3- \text{Efficiency}(\eta) = \frac{\text{Output Power (Po)}}{\text{Input Power (Pi)}} \times 100$$

$$= \frac{P_o}{P_o + \text{Total losses}} \times 100$$

$$\text{Output Power (P}_o) = V_t \times I_L = 250 \times 195 = 48750\text{W}$$

$$\text{Input Power (P}_i) = P_o + \text{Total losses}$$

$$\text{Total losses} = \text{Cu losses} + \text{iron and friction losses} = 2050 + 950 = 3000\text{W}$$

$$\eta = \frac{48750}{48750 + 3000} \times 100 = 94.2\%$$

Q10/ A 4-pole, long-shunt lap-wound generator supplies 25 kW at a terminal voltage of 500 V. The armature resistance is 0.03 Ω, series field resistance is 0.04 Ω and shunt field resistance is 200 Ω.

- 1- Determine the e.m.f. generated.
- 2- Calculate also the No. of conductors if the speed is 1200r.p.m. and flux per pole is 0.02 weber.

Ans. /

$$1- I_L = \frac{P_o}{V_t} = \frac{25000}{500} = 50A$$

$$I_f = V_t / R_f = 500 / 200 = 2.5A$$

$$I_a = I_L + I_f = 50 + 2.5 = 52.5A$$

$$E_a = V_t + (I_a * R_a) + (I_a * R_{ser})$$

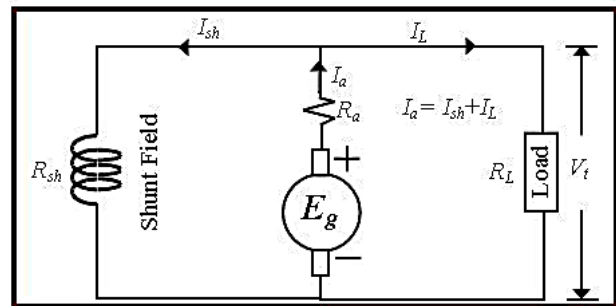
$$= 500 + (52.5 * 0.03) + (52.5 * 0.04) = 503.68V$$

$$2- E_a = \frac{NPZ\phi p}{60 A}$$

$$503.68 = \frac{1200 * 4 * Z * 0.02}{60 * 4}$$

$$Z = 1260$$

Example 26.11 An 8 pole DC shunt generator with 778 armature conductors and running at 500 rpm. Supplies a load 12.5 ohm resistance at terminal of 250 V. The armature resistance is 0.24Ω and the field resistance is 250Ω. Find the armature current, the induced e.m.f. and the flux per pole for (a) wave-connected winding and (b) Triplex lap-connected winding.



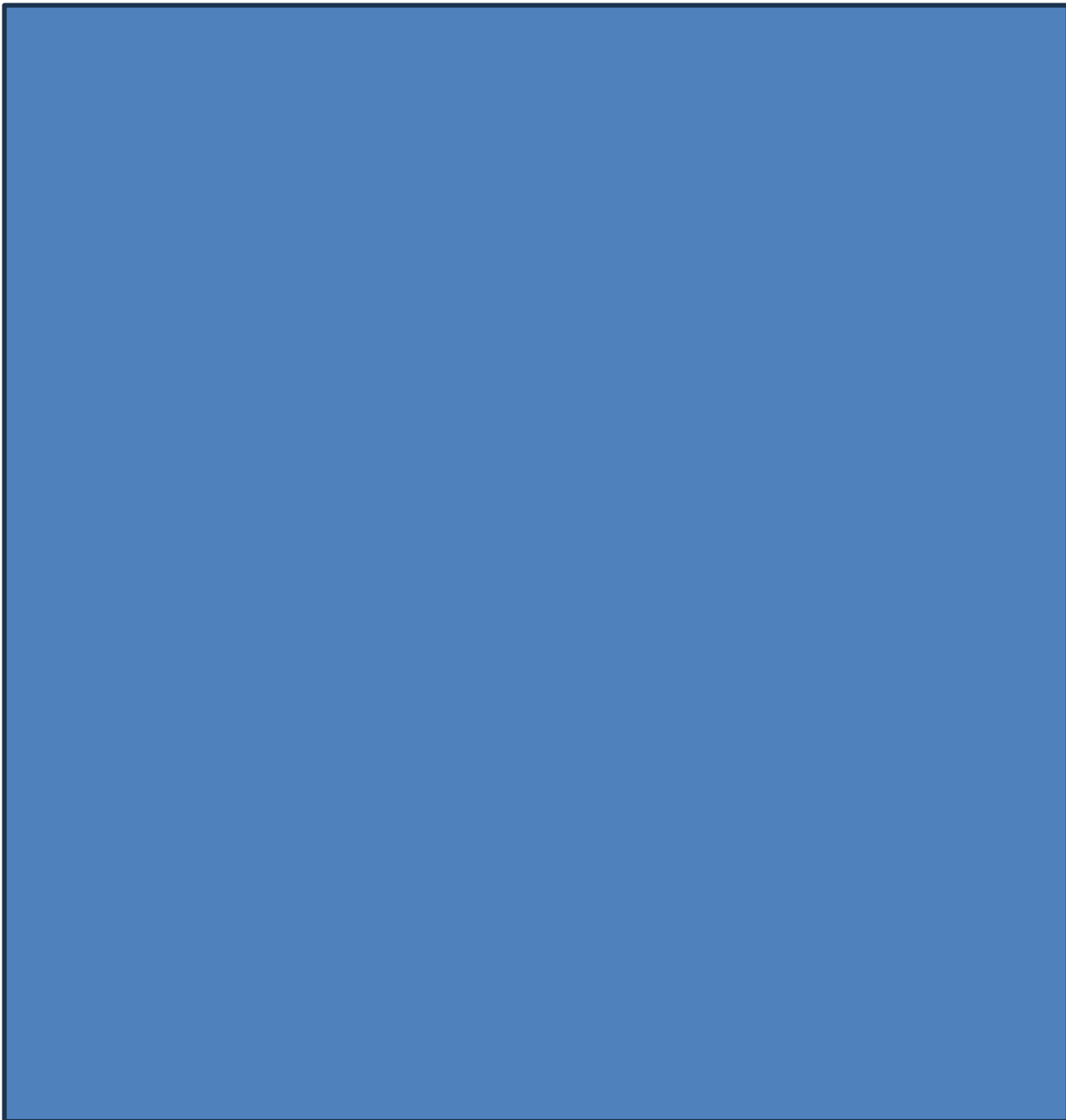
Solution: Generator circuit is shown in Fig. 26.53.

Given, $P=8$, $Z=778$, $N= 500$ rpm, $V_t=250V$, $R_a=0.24$ ohm, $R_{sh}=250\Omega$, $I_a=?$, $E_g=?$ $\Phi=?$
 Load current, $I_L = V_t/R_a = 250/12.5=20A$; Shunt current, $I_{sh} = V_t/R_{sh} = 250/250= 1 A$.
 Armature current, $I_a = I_L + I_{sh} = 20+1=21 A$; Induced e.m.f. = $250+(21 \times 0.24)=255.04 V$

We know that $E_g = \frac{\Phi Z N P}{60 A}$ volt (V) thus $\Phi = \frac{60 E_g A}{Z N P}$

(a) For wave-connected winding, $A=2m=2$ ($m=1$), Thus $\Phi = \frac{60 E_g A}{Z N P} = \frac{60 \times 255.04 \times 2}{778 \times 500 \times 8} = 9.83 \text{ mWb}$

(b) For triplex lap-connected winding, $A=mP=3 \times 8=24$, Thus $\Phi = \frac{60 E_g A}{Z N P} = \frac{60 \times 255.04 \times 24}{778 \times 500 \times 8} = 118.01 \text{ mWb}$



Q12/ A 15 kW shunt generator having an armature circuit resistance of 0.4Ω and a field resistance of 100Ω , generates a terminal voltage of 240V at full load. Determine the efficiency of the generator at full load, assuming the iron, friction and windage losses amount to 1 kW.

$$\text{Output power} = 15000 \text{ W} = V I$$

$$\text{from which, current, } I = \frac{15000}{V} = \frac{15000}{240} = 62.5 \text{ A}$$

$$\text{Field current, } I_f = \frac{V}{R_f} = \frac{240}{100} = 2.4 \text{ A}$$

$$\text{Armature current, } I_a = I_f + I = 2.4 + 62.5 = 64.9 \text{ A}$$

$$\therefore \eta = 82.14\%$$

Q13/ The shaft torque required to drive a d.c. generator is 18.7 Nm when it is running at 1250 rev/min. If its efficiency is 87% under these conditions and the armature current is 17.3 A, determine the voltage at the terminals of the generator

$$\text{Efficiency, } \eta = \frac{\text{output power}}{\text{input power}} = \frac{VI}{T(2\pi n)} \times 100\%$$

$$\text{i.e. } 87 = \frac{(V)(17.3)}{(18.7)\left(2\pi \times \frac{1250}{60}\right)} \times 100\%$$

$$\text{from which, terminal voltage, } V = \frac{(87)(18.7)\left(2\pi \times \frac{125}{60}\right)}{17.3 \times 100} = 123.1 \text{ V}$$

Q14/ Calculate the torque developed by a 240 V d.c. motor whose armature current is 50 A, armature resistance is 0.6 Ω and is running at 10 rev/s.

$$V = 240 \text{ V, } I_a = 50 \text{ A, } R_a = 0.6 \Omega \text{ and } n = 10 \text{ rev/s.}$$

$$\text{Back e.m.f., } E = V - I_a R_a = 240 - (50)(0.6) = 210 \text{ V}$$

$$\text{Torque, } T = \frac{E I_a}{2\pi n} = \frac{(240)(50)}{2\pi \times 10} = 167.1 \text{ N m}$$

Q// What is difference between ac and dc generator

AC Generators	DC Generators
1. AC generator is a mechanical device which converts mechanical energy into AC electrical power.	DC generator is a mechanical device which converts mechanical energy into DC electrical power.
2. In an AC generator, the electrical current reverses direction periodically.	In a DC generator, the electrical current flows only in one direction.
3. AC generator does not have commutators.	DC generators have commutators to make the current flow in one direction only.
4. AC generators have slip-rings.	DC generators have split-ring commutators.

Single-Phase Induction Motors

Introduction:

A single-phase induction motor is a small-size motor with a fractional-kilowatt rating. They work on the principle of electromagnetic induction to create a rotating magnetic field. It's also widely used in various applications due to their simplicity, cost-effectiveness, and ease of operation. Here are some common applications of single-phase induction motors:

- Household Appliances.
- Pumps.
- Compressors.
- Blowers.
- Food Processors.
- Refrigerators, washing machines, clocks, drills, fans.

Advantages:

- single phase motors are reliable, cheap in cost, simple in construction and easy to repair.

Disadvantages:

- Lower power-factor
- Lower efficiency
- Low starting torque
- Small torque.
- Large rotor losses.
- Poor overload capacity.

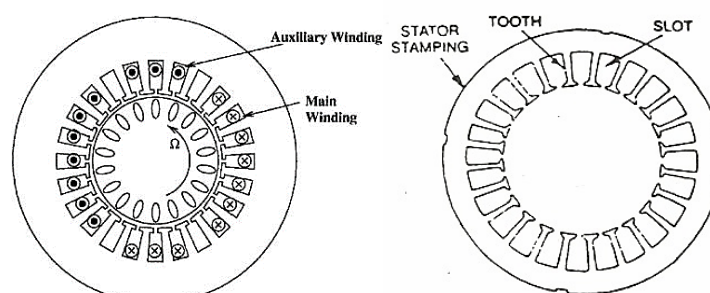
Construction:

It consists of main two parts: *Stationary stator* and *revolving rotor*. The stator separates from rotor by small air gap have ranges from 0.4mm to 4mm depends to size of motor.



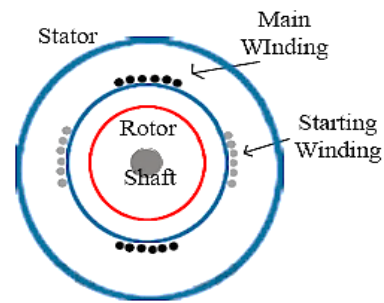
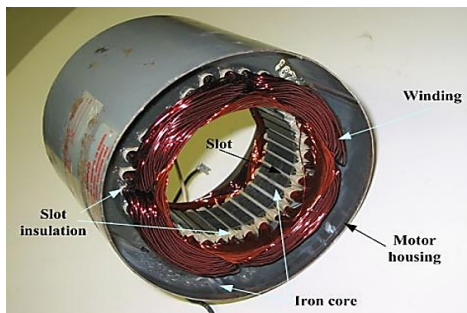
• Stator:

The single-phase motor stator has a **laminated iron core** with slots



Two windings arranged vertically inside the slots of stator:

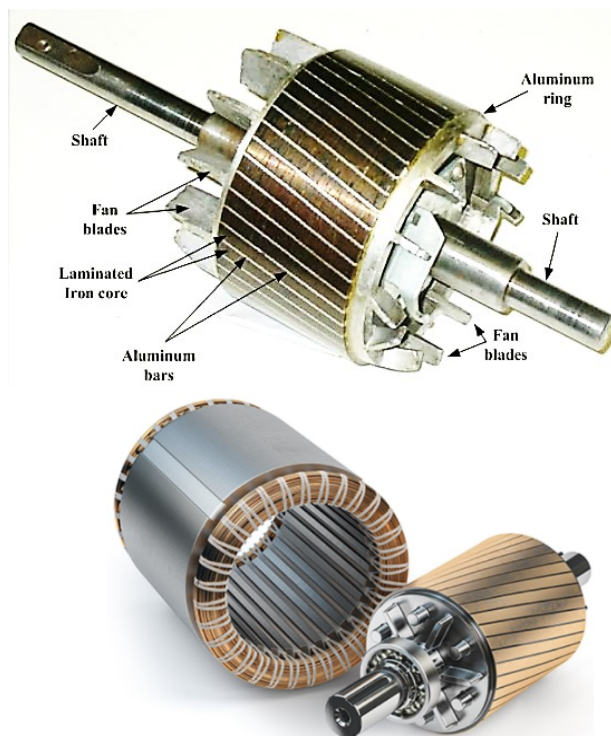
- 1- Main winding (or running winding).
2. Auxiliary winding (or starting winding).



- **Rotor:**

The rotor, mounted on a shaft, it consists of a laminated cylindrical core with slots; aluminum bars are molded on the slots and short-circuited at both ends with a ring. that it is slightly skewed.

The rotor bars are skewed to reduce the noise and vibrations. The rotor lies in the core of the stator, and the stator is laminated to reduce the eddy current loss. This type of rotor is called **Squirrel cage rotor**.



Squirrel cage rotor

- **Bearings:**

used to support and allow the rotor to rotate within the stator. It reduces friction.

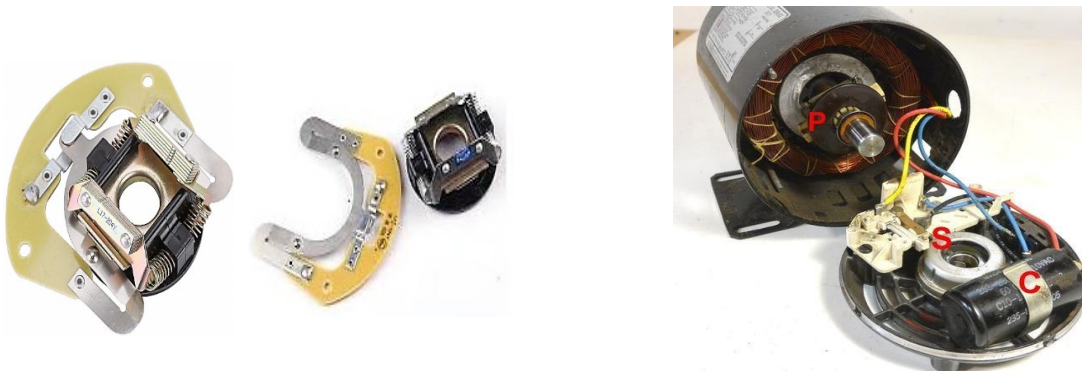
➤ **Characteristic Single phase induction motors use squirrel cage rotor:**

- It has a remarkably simple and robust construction.
- low starting torque. It is because the rotor bars are permanently short-circuited.

- type of rotor, the bars conductor is skew to reduce the noise.
- it is not possible to add any external resistance to the rotor circuit to have a large starting torque.

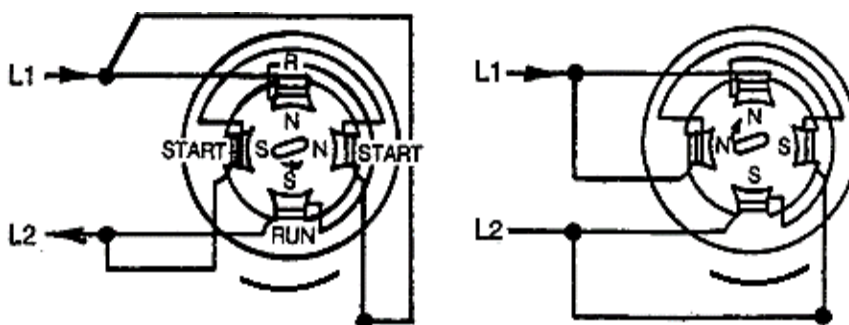
Centrifugal Switch:

1. Many single-phase motors are not designed to operate continuously on both windings (main & auxiliary).
2. At **75 percent of the rated rotor speed**, the centrifugal switch opens its contacts.
3. It only takes a few moments for the motor to obtain this speed, an audible click can be heard when the centrifugal switch opens or closes.
4. Once the start winding is disconnected from the circuit, the momentum of the rotor and the oscillating stator field will continue rotor rotation.



Reversal of Direction of Rotation:

1. To reverse rotation on a single-phase motor, we need to reverse the polarity of the starter winding. This will cause the magnetic field to change directions.
2. The polarity of only one of the fields must be reversed. In this manner, only one field polarity will change, and the rotor will still move toward the run winding of the same polarity as the start winding.



Reversal of Direction of Rotation

Synchronous speed (N_s):

When the stator winding is given a 1-phase AC supply, the magnetic field is produced and the motor rotates at a speed (rotor speed (N_r)) slightly less than the synchronous speed (N_s) which is given by

$$N_s = \frac{120 f}{p}$$

N_s : Synchronous speed (Is the speed of magnetic field) in rpm

f : Supply voltage frequency. p : No. of pole

Ex: Calculate the synchronous speed of 4 poles single phase induction motor. The line frequency is 60Hz. **Sol:** $N_s = \frac{120 f}{p} = (120 \times 60) / 4 = 1800 \text{ rpm}$

Slip (S):

Is the difference between synchronous speed (N_s) and rotor speed (N_r). Expressed as % or per-unit of Synchronous speed. The slip is a ratio and doesn't have units.

عندما يدور العضو الدائر (rotor) بسرعة N لفة في الدقيقة , فان السرعة النسبية بين المجال المغناطيسي الدائر بسرعة التزامن N_s وملفات العضو الدائر هي ($N_s - N$) تسمى سرعة الانزلاق (Slip Speed) ويرمز له بالرمز (S) وتتراوح قيمته في المحركات الصغيرة ما بين ١٪ او ٢٪ و في المحركات الكبيرة تصل الى ٥,٥ ٪ في حالة عدم التحميل وفي حالة التحميل يتراوح الانزلاق من ٣٪ الى ٥٪ ويحسب من :

$$S = \frac{N_s - N_r}{N_s} . \quad N_r = (1-S)N_s$$

- **Slip speed** = sync. speed – rotor speed = $N_s - N_r$
- If the rotor runs at synchronous speed (**No load**), then $S = 0$
 - ان قيمة الانزلاق يساوى **صفر** عندما يدور سرعة العضو الدائر بنفس السرعة التزامنية
- If the rotor is stationary (**locked**), then $S = 1$
 - الانزلاق يساوى **واحد** عندما يكون العضو الدائر في حالة السكون. ($N=0$)

Q// What happens when rotor runs at synchronous speed?

- Slip is Zero: Induction motors operate on the principle of slip, at synchronous speed, the slip is zero, meaning there is no relative motion between the rotating magnetic field and the rotor.
- No Torque Production: Since torque in an induction motor is generated due to the relative motion between the magnetic field and the rotor (which induces current in the rotor), operating at synchronous speed means there is no induced current

Q// Why Single-Phase Induction Motor is not Self Starting?

- motor lacks a naturally rotating magnetic field, which makes it non-self-starting.
- rely on a single alternating current that produces a pulsating magnetic field, this field is unable to provide sufficient starting torque. Unlike three-phase motors that generate a rotating magnetic field.

Ex: 6-pole induction motor is excited by a 1-phase. If the full-load speed is 1140 rpm frequency is 60HZ, calculate: The Synchronous speed, slip speed, and the Slip.

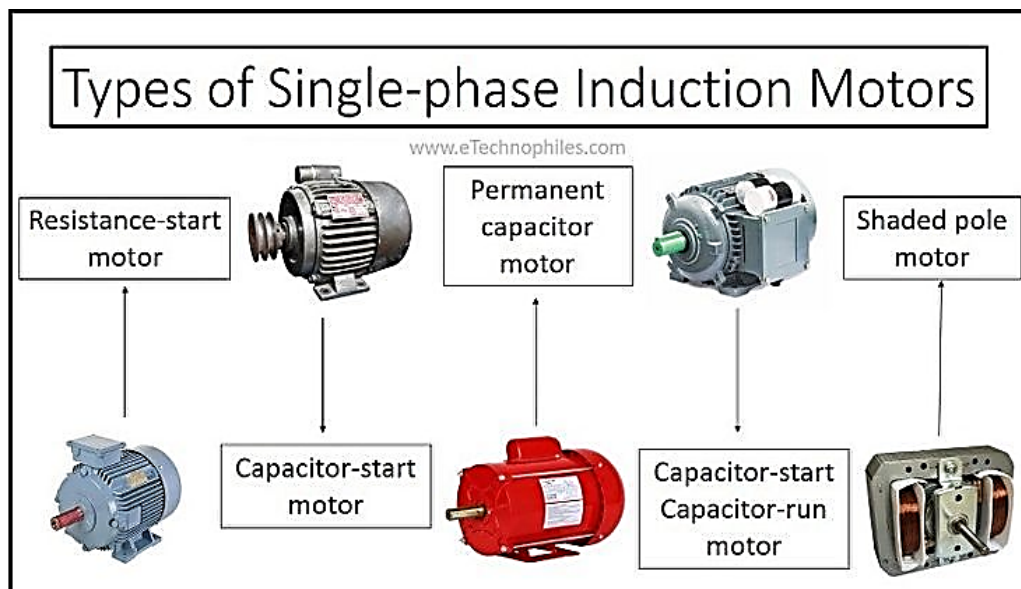
Sol:

1. Synchronous speed (N_s) = $120f/p = 120 * 60/6 = 1200$ rpm
2. Slip speed = $N_s - N_r = 1200 - 1140 = 60$ rpm
3. Slip = $(N_s - N_r)/N_s = (60 / 1200) = 0.05$

Types of Single-Phase Induction Motor:

A single-phase induction motor is not self-starting (as 3-phase squirrel cage induction motor) but requires some starting means, the starting and running or main winding are **spaced 90 electrically**.

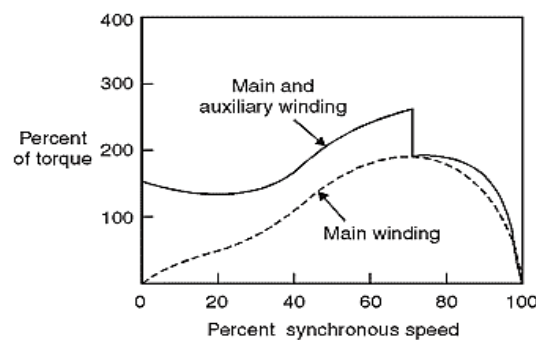
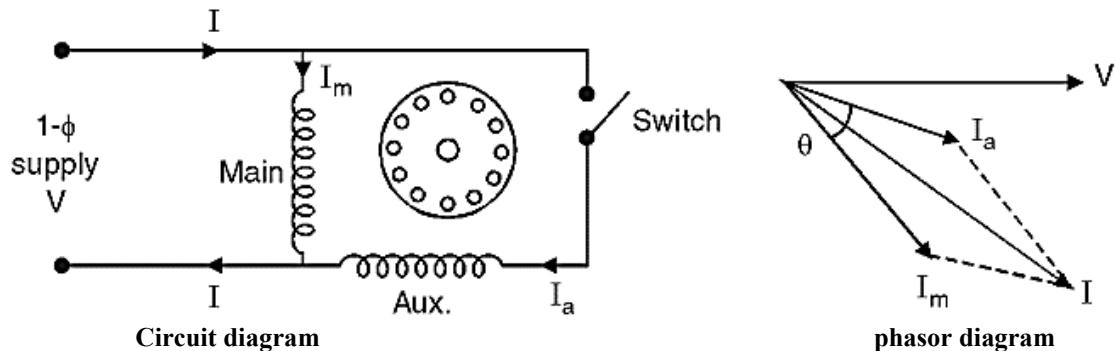
1. Split-phase motor
2. Capacitor-start motor
3. Capacitor-start capacitor-run motor (or two-value capacitor motor)
4. Permanent-split capacitor (PSC) motor (or single-value capacitor motor)
5. Shaded-pole motor



1. Split Phase Induction Motor:

- It consists of two parts **main winding (running winding)**, and **auxiliary winding (starting winding)**.
- The two winding (**main & auxiliary**) are connected in parallel to the source.
- A **centrifugal switch** is connected in series with auxiliary winding. The purpose of this switch is to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to **75 to 80%** of the synchronous speed.
- The auxiliary windings are displaced in **space by 90 electric degrees**.
- When the two stator windings are energized from a single-phase supply, the current (I_a) in the auxiliary winding lags the voltage (V) by an angle, ϕ_a , which is small, whereas the current (I_m) in the main winding lags the voltage (V) by an angle, ϕ_m , which is **nearly 90°**.

- **Because the starting winding** has a high resistance and relatively small reactance while the main winding has relatively low resistance and large reactance.
- Consequently, the currents flowing in the two windings have reasonable phase difference (25° to 30°) as shown in the phasor diagram this shifting in current it's necessary for starting torque.



Torque-speed characteristic of a split-phase motor

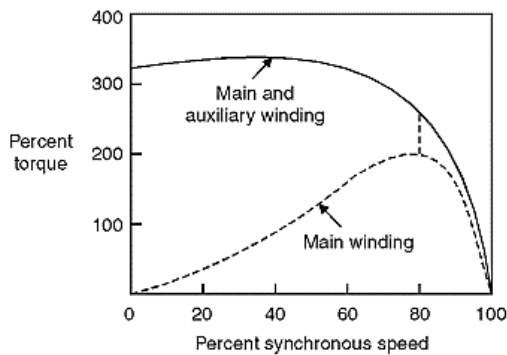
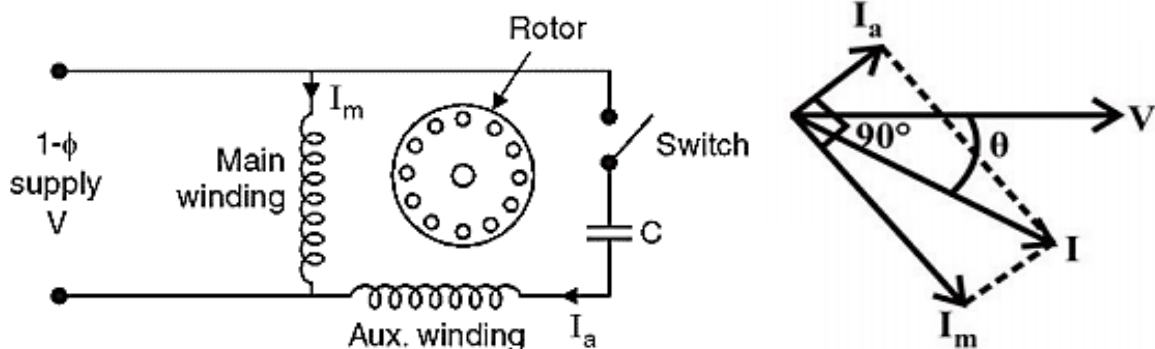
Applications:

- a. Fans. b. washing machines. c. oil burners d. power rating between 60W & 250W.

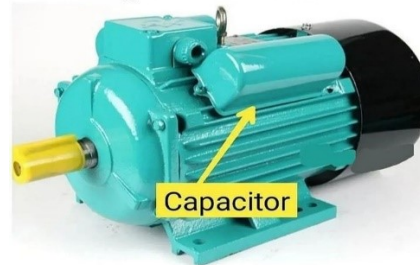
2. Capacitor Start Induction Motor:

- The capacitor-start motor is identical to a split-phase motor except that a capacitor C (3-20 μF) is connected in series with the starting winding.
- The auxiliary winding and the capacitor are disconnected at about 75% of the synchronous speed. Therefore, at the rated speed the capacitor start motor operates only on the main winding like a split-phase motor.
- The main problem in split-phase induction motor is **low starting torque**, as this torque is a function of, or related to the phase difference (angle) between the currents in the two windings.
- To get high starting torque, the phase difference required 90° . when the starting torque will be proportional to the product of the magnitudes of two currents ($T_s = k * I_m * I_a * \sin\phi$). As the current in the main winding is lagging by ϕ_m , the current in the auxiliary winding has to lead the input voltage by ϕ_a , with ($\phi_a + \phi_m = 90^\circ$).
- (where k is a constant whose magnitude depends upon the design of the motor)

- This can be achieved by having a capacitor in series with the auxiliary winding, which results in additional cost, with the increase in starting torque
- However, a capacitor start motor is used when the starting torque requirements are 4 to 5 times the rated torque. (not as in split phase motor).



Why Capacitor is Required for Single Phase Motor



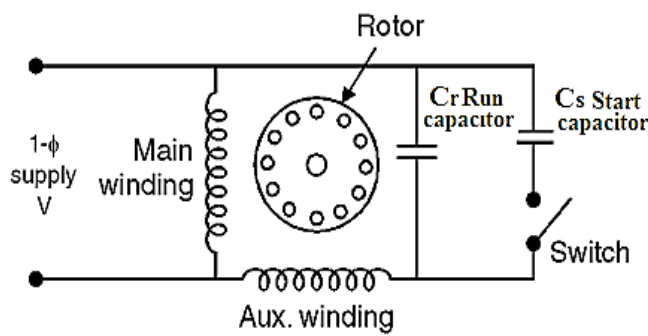
Torque-speed characteristic of a capacitor start motor

Applications:

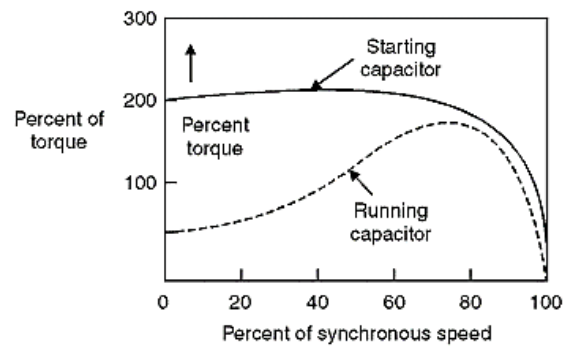
1. Refrigerators.
2. Air-conditioners.
3. Compressors
4. Reciprocating pumps.
5. The power rating between 120W & 750W.

3. Capacitor Start Capacitor-Run Induction Motor:

- This motor is identical to a capacitor-start motor except that starting winding is **not opened after starting so that both the windings remain connected to the supply when running as well as at starting.**
- Two capacitors C_r and C_s are used in the starting winding.
- The smaller capacitor C_r required for optimum running conditions is permanently **connected in series with the starting winding.**
- The much larger capacitor C_s is connected in parallel with C_r for optimum starting and remains in the circuit during starting.
- The starting capacitor C_s is disconnected when the motor approaches about 80% of synchronous speed. The motor then runs as a single-phase induction motor.



Capacitor-start capacitor-run motor



Torque-speed characteristic of a capacitor-start capacitor-run motor

Applications:

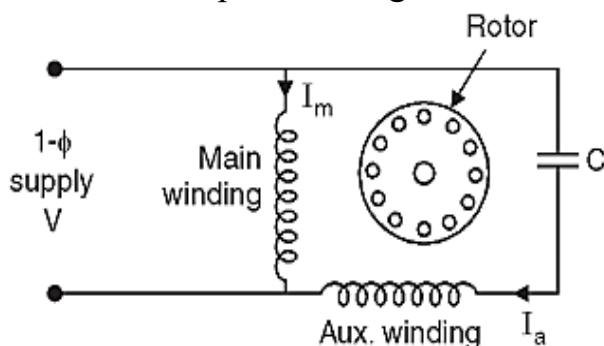
- a. Hospitals. Pumps. Medical equipment like X-Ray machines,

Advantages:

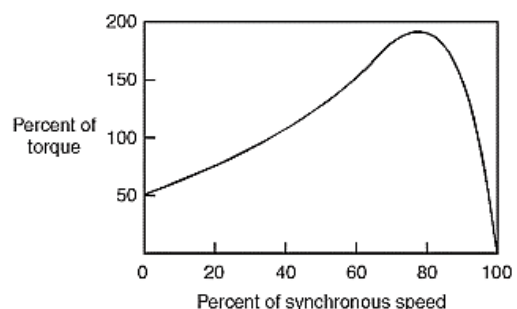
1. Improvement of overload capacity of the motor.
2. Higher power factor.
3. Higher efficiency.
4. Quieter running of the motor which is very much.

4. permanent split capacitor motor:

- This type of motor does not have a centrifugal switch, thus reducing maintenance problems.
- This type of motor is essentially the same as a two-value capacitor motor operating on the running connection and will have approximately the same torque characteristics. Since only the running capacitor (which is of relative low value) is **connected in series with the auxiliary winding on starting (during starting and running)**, the starting torque is greatly reduced.
- The power factor of this motor, when it is operating (running), is high. The operation is also quiet and smooth.
- The application of this type of single-phase motor is normally limited to the direct drive of such loads as those of ceiling fans and blowers in heaters and air conditioners, which do not require normal or high starting torques.
- These motors are not suitable for belt-driven applications and are generally limited to the lower horsepower ratings.



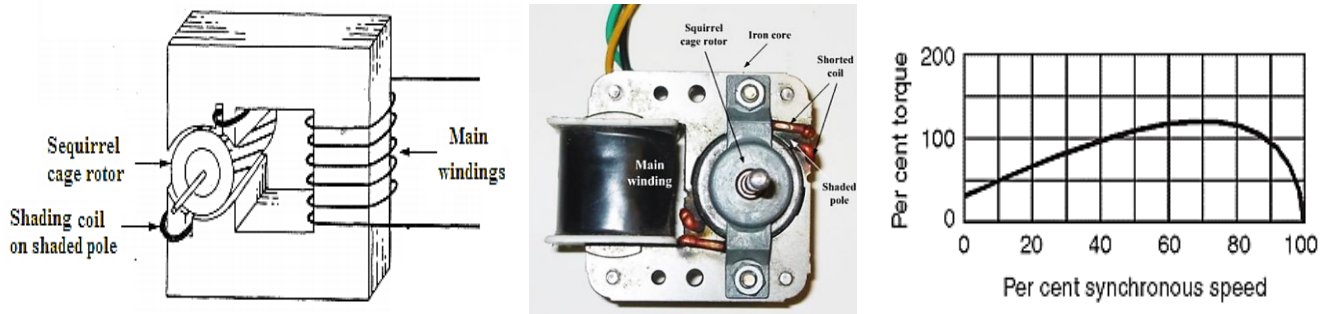
Permanent split capacitor motor



Torque-speed characteristic of a permanent split capacitor motor

5. Shaded-Pole Induction Motor:

- does not use two windings to develop the torque necessary to turn the rotor.
- It has salient poles on the stator excited by single-phase supply.
- Each pole is surrounded by a short-circuited turn of copper strip called shading coil called the shaded pole.



Torque-speed characteristic of a shaded-pole motor

The operation:

- The main winding produces a pulsating flux that links with the squirrel cage rotor. This flux induces a voltage in the shorted winding.
- The induced voltage produces a current, this current generates a flux that opposes the main flux in the shaded pole.
- The result is that the flux in the unshaded and shaded parts of the pole can unequal.
- These two fluxes generate an unbalanced rotating field. The field amplitude changes as it rotates. This rotating field produces a torque, which starts the motor in the direction of the shaded pole.

Advantages

1. Very economical and reliable.
2. Construction is simple and robust because there is no centrifugal switch.

Disadvantages:

1. Low power factor.
2. starting torque is very poor.
3. The efficiency very low.
4. copper losses are high due to presence of copper band.
5. The speed reversal is also difficult and expensive as it requires another set of copper rings.

Applications:

- a. low starting torques
- b. reasonable cost these motors are mostly.
- c. hair dryers, toys, record players,

d. small fans, electric clocks and ventilation fans.

Ex: Single phase 50Hz, 6-pole induction motor is running at a slip of 3.5 percent. Find: (a) The speed of the magnetic fields in revolutions per minute (b) The speed of the rotor in revolutions per minute (c) The slip speed of the rotor (d) The rotor frequency.

(a) The speed of the magnetic fields is

$$n_{\text{sync}} = \frac{120 f_e}{P} = \frac{120(50 \text{ Hz})}{6} = 1000 \text{ r/min}$$

(b) The speed of the rotor is

$$n_m = (1 - s) n_{\text{sync}} = (1 - 0.035)(1000 \text{ r/min}) = 965 \text{ r/min}$$

(c) The slip speed of the rotor is

$$n_{\text{slip}} = s n_{\text{sync}} = (0.035)(1000 \text{ r/min}) = 35 \text{ r/min}$$

(d) The rotor frequency is

$$f_r = \frac{n_{\text{slip}} P}{120} = \frac{(35 \text{ r/min})(6)}{120} = 1.75 \text{ Hz}$$

Ex: 4-pole, 50Hz single-phase Induction motor, the power absorbed by the forward and backward field rotor equivalent resistances are 200W & 21W respectively at a motor speed of 1440rpm. The mechanical losses total 20W. find the shaft torque at the above speed.

$$N_s = \frac{120 f_s}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$$S = \frac{N_s - N_r}{N_s} = 0.04$$

$$T_d = T_{df} - T_{db} = 200 - 21 = 179 \text{ W}$$

$$P_d = T_d (1 - S) = 179(1 - 0.04) = 171.84 \text{ W}$$

$$P_0 = P_d - W_m = 171.84 - 20 = 151.84 \text{ W}$$

$$P_0 = \frac{2\pi N_r T}{60}$$

$$T = \frac{60 \times 151.84}{2\pi \times 1440} = 1.007 \text{ Nm}$$

H.W: A 50-kW, 440-V, 50-Hz, two-pole induction motor has a slip of 6 percent when operating at full-load conditions. At full-load conditions, the friction and windage losses are 520W, and the core losses are 500W. Find the following values for full load conditions:

- (a) The shaft speed n_m
- (b) The output power in watts
- (c) The load torque τ_{load} in newton-meters
- (d) The induced torque τ_{ind} in newton-meters
- (e) The rotor frequency in hertz

SOLUTION

- (a) The synchronous speed of this machine is

$$n_{sync} = \frac{120 f_e}{P} = \frac{120(50 \text{ Hz})}{2} = 3000 \text{ r/min}$$

Therefore, the shaft speed is

$$n_m = (1 - s)n_{sync} = (1 - 0.06)(3000 \text{ r/min}) = 2820 \text{ r/min}$$

- (b) The output power in watts is 50 kW (stated in the problem).

- (c) The load torque is

$$\tau_{load} = \frac{P_{OUT}}{\omega_m} = \frac{50 \text{ kW}}{(2820 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)} = 169.3 \text{ N} \cdot \text{m}$$

- (d) The induced torque can be found as follows:

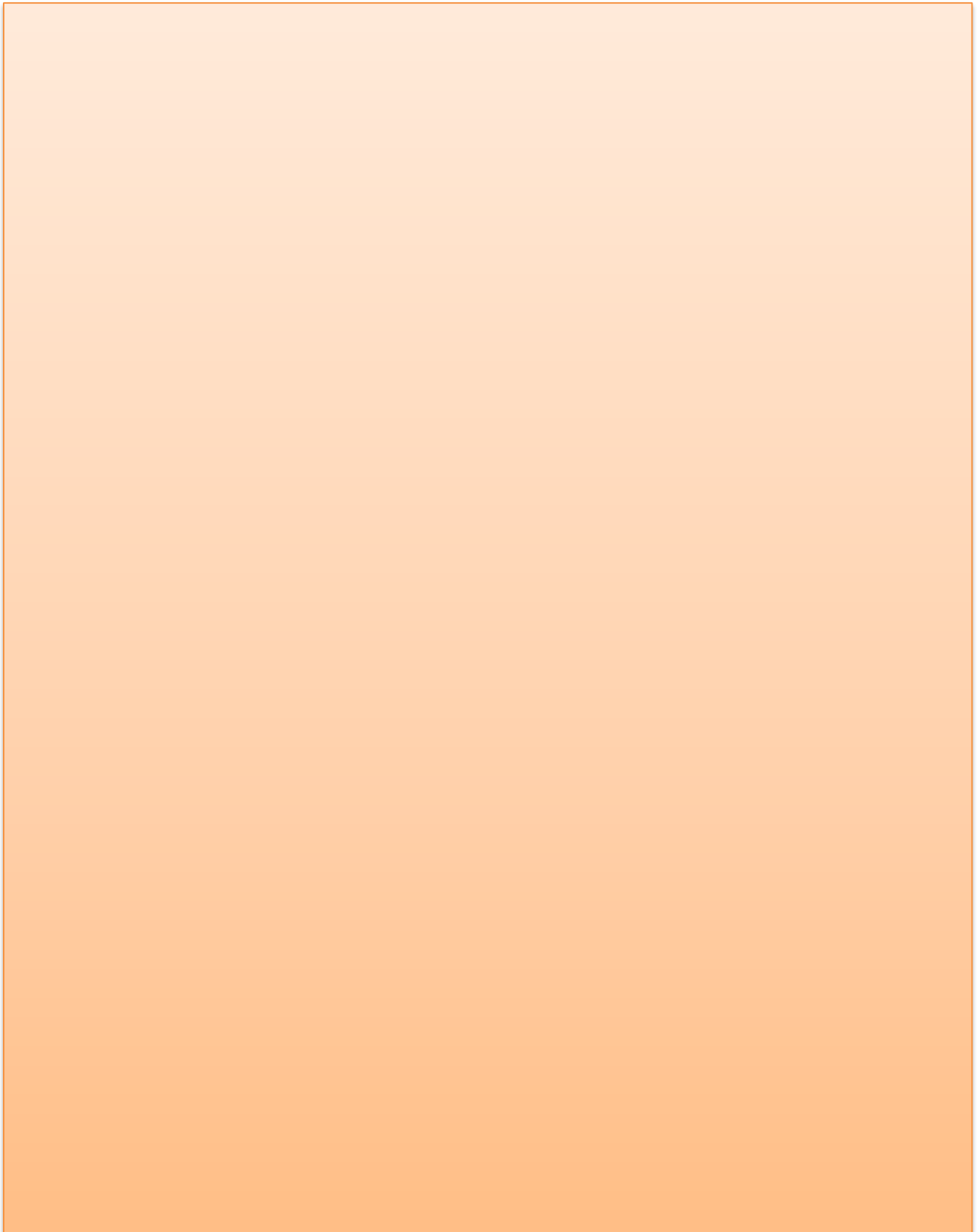
$$P_{conv} = P_{OUT} + P_{F\&W} + P_{core} + P_{misc} = 50 \text{ kW} + 520 \text{ W} + 500 \text{ W} = 51.2 \text{ kW}$$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{51.2 \text{ kW}}{(2820 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)} = 173.4 \text{ N} \cdot \text{m}$$

- (e) The rotor frequency is

$$f_r = s f_e = (0.06)(50 \text{ Hz}) = 3.00 \text{ Hz}$$

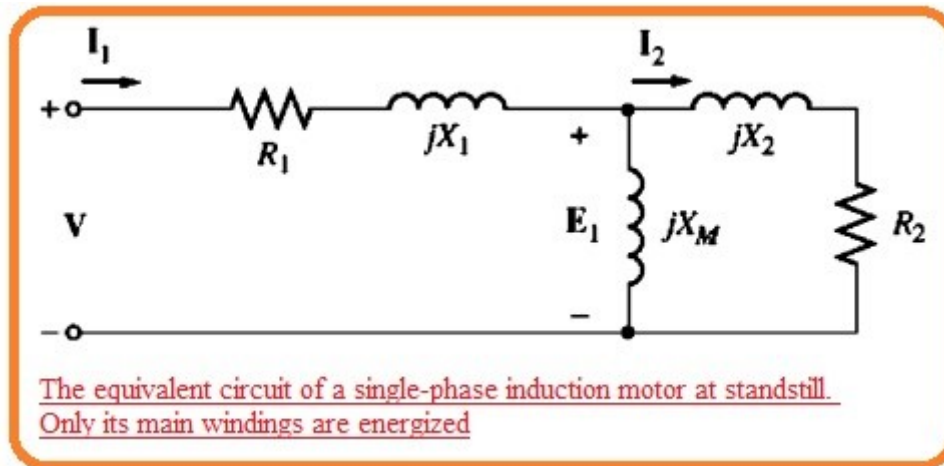
Example 7–4. A two-pole, 50-Hz induction motor supplies 15 kW to a load at a speed of 2950 r/min.



Equivalent Circuit of Single-Phase Induction Motor:

Equivalent circuit of a single-phase induction motor based on two revolving field theories. Most single-phase induction motors are two-phase motors in which auxiliary winding is disconnected from the supply when the machine reaches a certain value. Consider a case when the rotor is stationary and only the main winding is excited with its secondary short-circuited.

- A single-phase induction motor behaves as a single-phase transformer when the secondary is short-circuited.
- The core loss of the branch is not considered, only the mechanical and stray losses are considered as the rotational losses of the motor.



Where;

- R_1 = resistance of the main stator winding.
- jX_1 = leakage reactance of the main stator winding.
- jX_m = magnetizing reactance.
- jX_2 = standstill rotor leakage reactance referred to the main stator winding.
- R_2 = standstill rotor resistance referred to the main stator winding.
- V = applied voltage
- I = main winding current.

Ex: A 208-V, two-pole, 60-Hz, Y-connected wound-rotor induction motor is rated at 15-hp. Its equivalent circuit components are:

$$R_1 = 0.200\Omega \quad R_2 = 0.120\Omega \quad X_M = 15.0\Omega$$

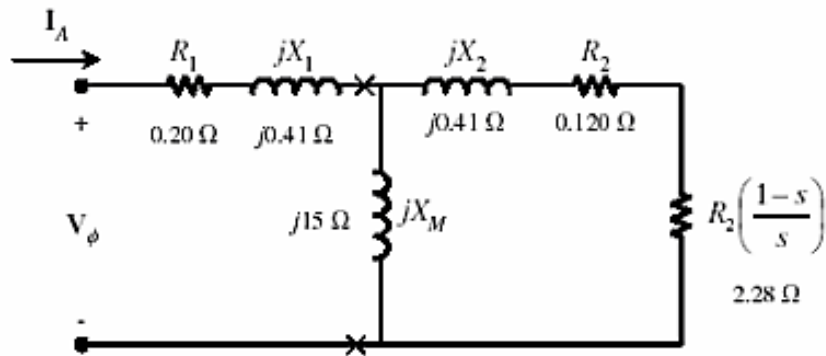
$$X_1 = 0.410\Omega \quad X_2 = 0.410\Omega$$

$$P_{mech} = 250W \quad P_{misc} \approx 0 \quad P_{core} = 180W$$

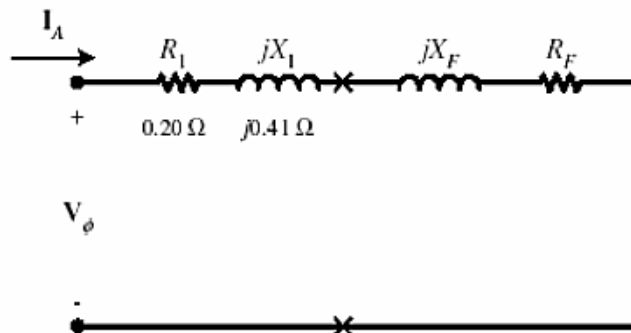
For a slip of 0.05, find

- (a) The line current I_L . (b) The stator copper losses P_{SCL} .
 (c) The air-gap power P_{AG} . (d) The power converted from electrical to mechanical form P_{conv} .
 (e) The induced torque τ_{ind} . (f) The load torque τ_{load} . (g) The overall machine efficiency.
 (h) The motor speed in revolutions per minute and radians per second

Sol: The equivalent circuit of this induction motor is shown below:



(a) The easiest way to find the line current (or armature current) is to get the equivalent impedance Z_F of the rotor circuit in parallel with jX_M , and then calculate the current as the phase voltage divided by the sum of the series impedances, as shown below:



The equivalent impedance of the rotor circuit in parallel with jX_M is

$$Z_F = \frac{1}{\frac{1}{jX_M} + \frac{1}{Z_2}} = \frac{1}{\frac{1}{j15} + \frac{1}{2.40 + j0.41}} = 2.220 + j0.745 = 2.34 \angle 18.5^\circ \Omega$$

The phase voltage is

$$V_\phi = V_T / \sqrt{3} = 208 / \sqrt{3} = 120V$$

So the line current I_L is

$$I_L = I_A = \frac{V_\phi}{R_1 + jX_1 + R_F + jX_F} = \frac{120 \angle 0^\circ}{0.20 + j0.41 + 2.22 + j0.745} = 44.8 \angle -25.5^\circ A$$

(b) The stator copper losses are

$$P_{SCL} = 3I_A^2 R_1 = 3(44.8)^2(0.20) = 1205W$$

(c) The air gap power is $P_{AG} = 3I_2^2 \frac{R_2}{s} = 3I_A^2 R_F$

(Note that $3I_A^2 R_F$ is equal to $3I_2^2 \frac{R_2}{s}$, since the only resistance in the original rotor circuit was R_2/s , and the resistance in the Thevenin equivalent circuit is R_F . The power consumed by the Thevenin equivalent circuit must be the same as the power consumed by the original circuit.)

$$P_{AG} = 3I_2^2 \frac{R_2}{s} = 3I_A^2 R_F = 3(44.8)^2(2.220) = 13.4kW$$

(d) The power converted from electrical to mechanical form is

$$P_{conv} = (1-s)P_{AG} = (1-0.05)(13.4k) = 12.73kW$$

(e) The induced torque in the motor is

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{13.4k}{\left(\frac{120(60)}{2}\right)(1\text{min}/60s)(2\pi\text{rad}/1r)} = 35.5N \cdot m$$

(f) The output power of this motor is

$$P_{out} = P_{conv} - P_{mech} - P_{core} - P_{misc} = 12.73k - 250 - 180 - 0 = 12.3kW$$

The output speed is

$$n_m = (1-s)n_{sync} = (1-0.05)\left(\frac{120(60)}{2}\right) = 3420r/\text{min}$$

Therefore the load torque is

$$\tau_{load} = \frac{P_{out}}{\omega_m} = \frac{12.3k}{(3420r/min)(1min/60s)(2\pi rad/1r)} = 34.3N \cdot m$$

(g) The overall efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{P_{out}}{3V_{\phi}I_A \cos \theta} \times 100\% = \frac{12.3k}{3(120)(44.8)(\cos 25.5^{\circ})} \times 100\% = 84.5\%$$

(h) The motor speed in revolutions per minute is 3420 r/min. The rotor speed in radians per second is

$$\omega_m = (3420r/min)(2\pi rad/1r)(1min/60s) = 358rad/s$$

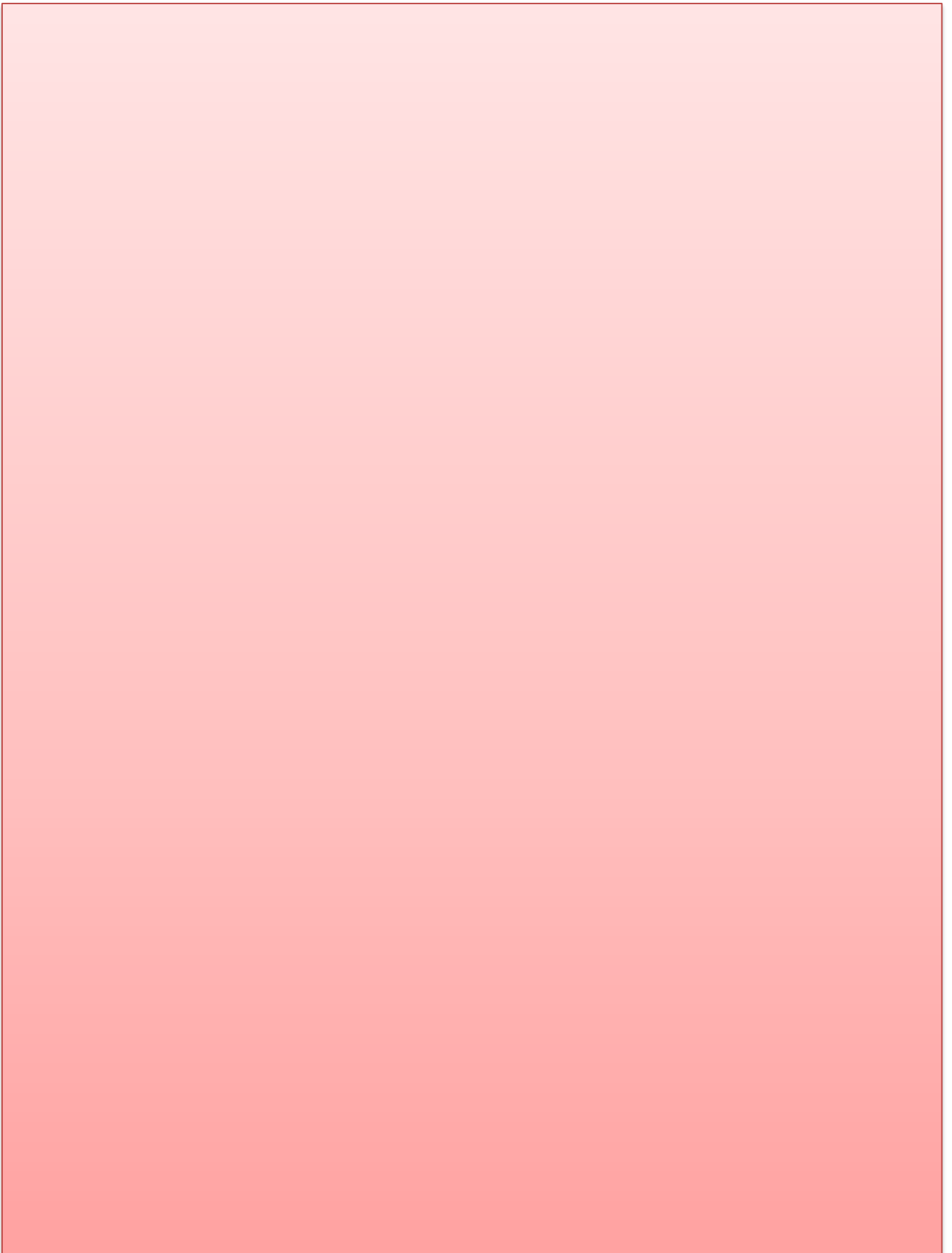
H.W: A 440-V, 50-Hz, six-pole, Y-connected induction motor is rated at 75 kW. The equivalent circuit parameters are

$$\begin{array}{lll} R_1 = 0.082\Omega & R_2 = 0.070\Omega & X_M = 7.2\Omega \\ X_1 = 0.19\Omega & X_2 = 0.18\Omega & \\ P_{F\&W} = 1.3kW & P_{misc} = 150W & P_{core} = 1.4kW \end{array}$$

For a slip of 0.04, find

- (a) The line current IL . (b) The stator power factor. (c) The rotor power factor
 (d) The stator copper losses $PSCL$. (e) The air-gap power PAG
 (f) The power converted from electrical to mechanical form $Pconv$
 (g) The induced torque τ_{ind} . (h) The load torque τ_{load}
 (i) The overall machine efficiency η . (j) The motor speed in revolutions per minute and radians per second





The output speed is

$$n_m = (1 - s)n_{\text{sync}} = (1 - 0.04)(1000 \text{ r/min}) = 960 \text{ r/min}$$

Therefore the load torque is

$$\tau_{\text{load}} = \frac{P_{\text{OUT}}}{\omega_m} = \frac{85.9 \text{ kW}}{(960 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)} = 854 \text{ N} \cdot \text{m}$$

(i) The overall efficiency is

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{P_{\text{OUT}}}{3V_{\phi} I_A \cos \theta} \times 100\%$$

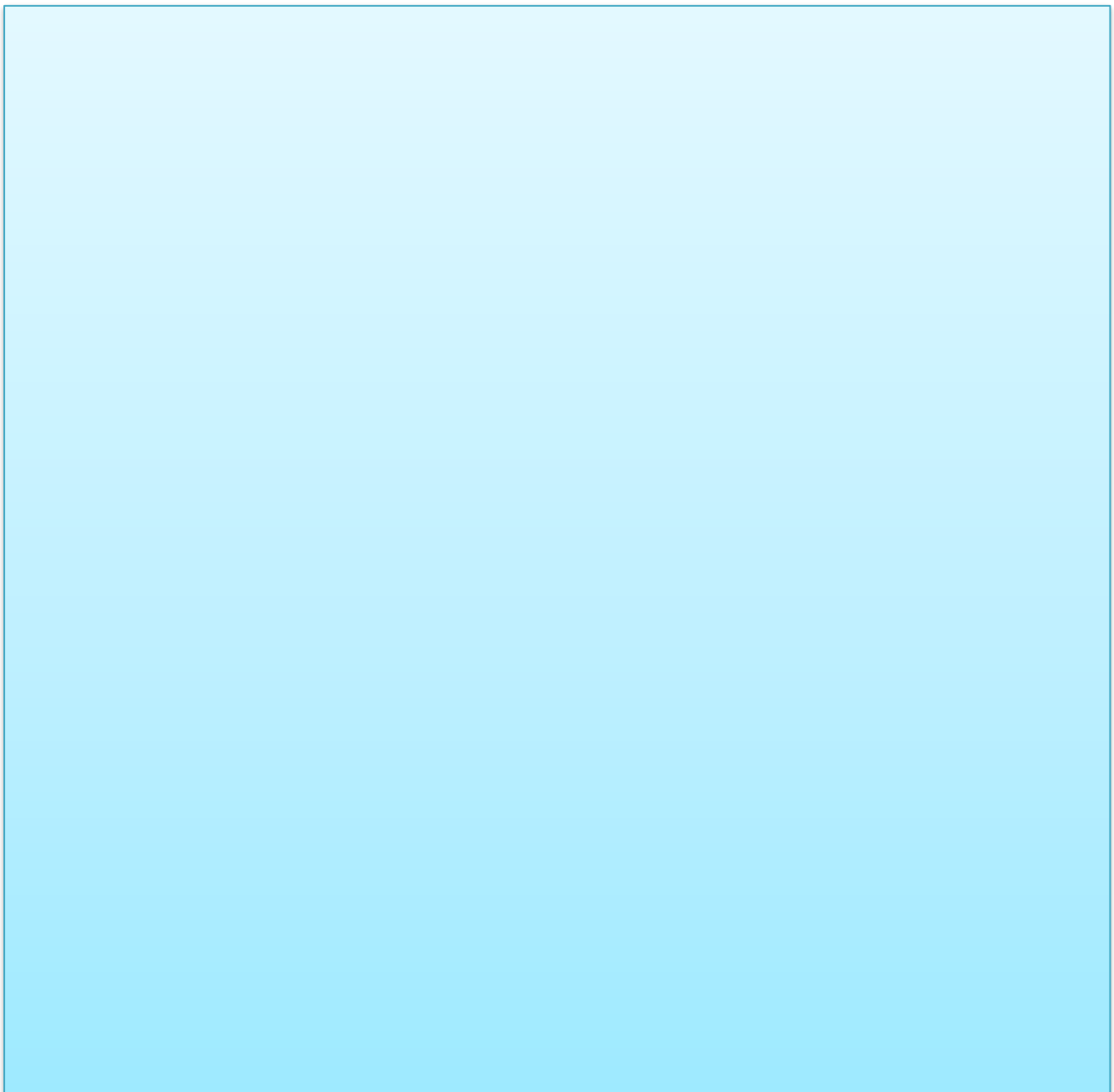
$$\eta = \frac{85.9 \text{ kW}}{3(254 \text{ V})(141 \text{ A}) \cos 24.3^\circ} \times 100\% = 87.7\%$$

(j) The motor speed in revolutions per minute is 960 r/min. The motor speed in radians per second is

$$\omega_m = (960 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) = 100.5 \text{ rad/s}$$

H.W: A would-rotor induction motor is operating at rated voltage and frequency with its slip rings shorted and with a load of about 25 percent of the rated value for the machine. If the rotor resistance of this machine is doubled by inserting external resistors into the rotor circuit, explain what happens to the following:

- Slip s
- Motor speed n_m
- The induced voltage in the rotor
- The rotor current
- τ_{ind}
- P_{out}
- PRCL
- Overall efficiency η



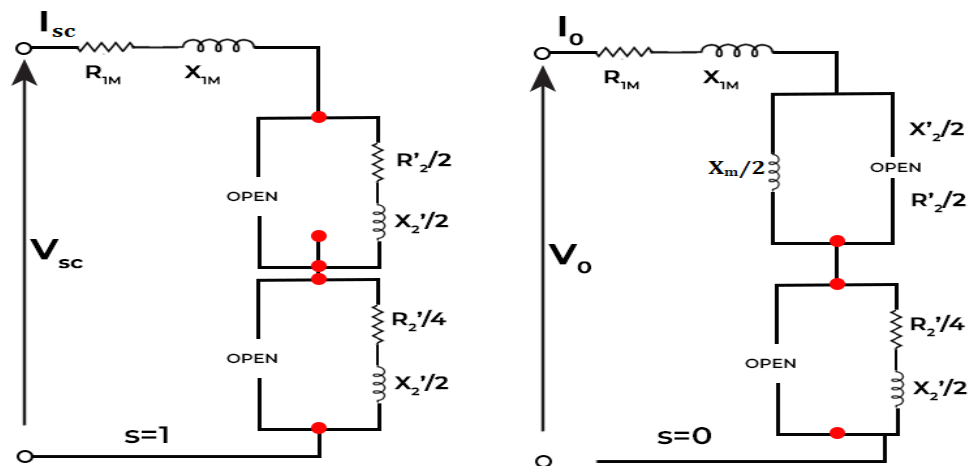
Determination of Equivalent Circuit Parameters

The parameters of the equivalent circuit of a single-phase induction can be determined from: -

- *Blocked-rotor test.* *No-load test*

- **Blocked-rotor test**

In this, the rotor is at rest. A low voltage is applied to the stator so that rated current flows in the main winding. The voltage, current, and power input are measured.



Simplified equivalent circuit of single induction motor with locked rotor and at no load

- $Z_e = \frac{V_{sc}}{I_{sc}}$

Equivalent series resistance R_e of the motor, $R_e = \frac{P_{sc}}{I_{sc}^2}$

Equivalent reactance, $X_e = X_{1m} + X_2'$

Since leakage reactances X_{1m} and X_2' cannot be separated therefore, $X_{1m} = X_2'$

- $X_{1m} = 0.5 * (Z_e^2 - R_e^2)^{1/2}$

NO Load Test:

The motor is run without load at rated voltage and rated frequency.

At no load, the slip 's' is very close to zero and $\frac{R_2'}{2s}$ is very large as compared to $\frac{X_M}{2}$.

The resistance $\frac{R_2'}{2(2-s)}$ associated with the backward field is so small as compared to $\frac{X_M}{2}$.

- $X_0 = X_{1m} + \frac{X_M}{2} + X_2'$

Since X_{1m} and X_2' are already known from the blocked rotor test.

Let V_0 , I_0 denote and P_0 denote the voltage, current, and power at the no-load test. Then no-load power factor is

- $\cos\Phi_0 = \frac{P_0}{V_0 I_0}$

The no-load impedance is, $Z_0 = V_0/I_0$

The no-load equivalent reactance is,

$$X_0 = Z_0 \sin\Phi_0 = Z_0 \times (1 - \cos^2 \Phi_0)$$

Ex: A 230V, 50Hz, 4-pole single phase induction motor has the following equivalent circuit impedances: $R_{1m} = 2.2\Omega$, $R_2 = 4.5\Omega$, $X_{1m} = 3.1\Omega$, $X_2' = 2.6\Omega$, $X_M = 80\Omega$. Friction, windage and core loss = 40W for a slip of 0.03 pu. calculate:

1. input current
2. power factor
3. developed power
4. output power
5. efficiency

Sol:

$$\frac{R_2'}{2s} = \frac{4.5}{2 \times 0.03} = 75 \Omega .$$

$$\frac{R_2'}{2(2-s)} = \frac{4.5}{2 \times (2-0.03)} = 1.142 \Omega$$

$$\frac{1}{2X_2'} = \frac{1}{2 \times 2.6} = 1.3 \Omega$$

$$\frac{1}{2X_M} = 1/2 * 80 = 40 \Omega$$

For the forward field circuit,

$$\begin{aligned} Z_f &= R_f + jX_f = \left(\frac{R_2'}{2s} + \frac{jX_2'}{2} \right) \left(\frac{jX_M}{2} \right) / \left(\frac{R_2'}{2s} + \frac{jX_2'}{2} + \frac{jX_M}{2} \right) \\ &= ((75+j1.3)(j40)) / (75+j1.3+j40) = 16.37 + j 30.98 \Omega \end{aligned}$$

For the backward field,

$$\begin{aligned} Z_b &= R_b + jX_b = \left(\frac{R_2'}{2(2-s)} + \frac{jX_2'}{2} \right) \left(\frac{jX_M}{2} \right) / \left(\frac{R_2'}{2s} + \frac{jX_2'}{2} + \frac{jX_M}{2} \right) \\ &= (1.142 + j 1.3)(j 40) / (1.142 + j 1.3 + j 40) \\ &= 2.2 + j 3.1 \Omega \end{aligned}$$

The total series impedance

$$\begin{aligned} Z_c &= Z_{1m} + Z_f + Z_b \\ &= 2.2 + j 3.1 + j 16.37 + j 30.98 + 1.07 + j 1.29 \\ &= 19.64 + j 35.37 \end{aligned}$$

(a) Input Current

$$I_m = V_m / Z_c = -1.68 + j 5.42 A$$

(b) Power factor (P.f) = $\cos (-60.95) = 0.4856$ lagging

(c) Developed power

$$P_{conv} = Pd = I_m^2 (R_f - R_b) (1-s)$$

$$= (5.685)^2 (16.37 - 1.07) (1 - 0.03) = 479.65 \text{ W}$$

$$\text{(d) Output power} = Pd - P_{rvt} = 479.65 - 40 = 439.65 \text{ W}$$

$$\text{Input power} = VI_m \cos\Phi = 230 * 5.685 * 0.4856 = 634.9 \text{ W}$$

$$\text{(e) Efficiency} = \text{output/input} = 439.65 / 634.9 = 0.692 \text{ pu.}$$

Ex: A 220V, single-phase induction motor gave the following results:

Blocked-rotor test: 120V, 9.6A, 460W

No-load test: 220V, 4.6A, 125W

The stator winding resistance is 15Ω , and during the blocked-rotor test, the starting winding is open. Determine the equivalent circuit parameters. Also, find the core friction and windage losses.

Solution:

Blocked-rotor test,

$$V_{sc} = 120V, I_{sc} = 9.6A, P_{sc} = 460W$$

$$Z_e = V_{sc}/I_{sc} = 120/9.6 = 12.5 \Omega$$

$$R_e = P_{sc}/I_{sc}^2 = 460/(9.6)^2 = 4.99 \Omega$$

$$X_e = (Z_e^2 - R_e^2)^{1/2} = ((12.5)^2 - (4.99)^2)^{1/2} = 11.46 \Omega$$

$$X_{1m} = X_2' = 1/2 X_e = 1/2 * 11.46 = 5.73 \Omega$$

$$R_{1m} = 1.5 \Omega$$

$$R_e = R_{1m} + R_2'$$

$$R_2' = R_e - R_{1m} = 4.99 - 1.5 = 3.49 \Omega$$

No-load power factor,

$$\cos\Phi = P_o/V_o I_o = 125/220 * 4.6 = 0.1235$$

$$\sin\Phi = 0.9923$$

$$Z_o = V_o/I_o = 220/4.6 = 47.83 \Omega$$

$$X_o = Z_o \sin\Phi = 47.83 * 0.9923 = 47.46 \Omega$$

Core, friction and windage losses

= power input to the motor at no load – no load copper loss

$$= P_o - I_o^2 (R_{1m} + R_2'/4)$$

$$= 125 - (4.6)^2 (1.5 + 3.49/4) = 74.8 \text{ W}$$

Q1: Why do some single-phase motors require capacitors, and role of capacitor in motor operation?

Capacitors are used to create a phase shift in the windings, which helps start and run the motor. Start capacitors are used primarily for starting, while run capacitors assist in maintaining a constant speed and power factor during operation.

Q2// What happens when motor rotates in reverse direction?

Reversing the direction of your motor will cause the carbon brushes to be pushed over the commutator, facing more friction than the other direction. This can cause the carbon brushes to wear faster and, if not maintained properly, could cause damage to the critical commutator segments, which are not interchangeable

Q3// Can a single-phase induction motor be used for to produce high-torque?

Single-phase induction motors are not able to produce high-torque because of their limited starting torque.

Q4//What are the challenges faced while in reversing the direction of rotation of a single-phase motor with a capacitor?

ما هي المشاكل التي تواجه عكس اتجاه دوران محرك أحادي الطور باستخدام مكثف

- It requires reconfiguration of capacitor connections.
- It may also require changes to the rotor or the capacitor value, depending on the motor design.

Three-Phase Induction Motors

Introduction:

A three-phase induction motor is theoretically self-starting. The stator of an induction motor consists of 3-phase windings, which when connected to a 3-phase supply creates a rotating magnetic field. This will link and cut the rotor conductors which in turn will induce a current in the rotor conductors and create a rotor magnetic field. The magnetic field created by the rotor will interact with the rotating magnetic field in the stator and produce rotation. Therefore, 3-phase induction motors employ a starting method not to provide a starting torque at the rotor.

Advantages

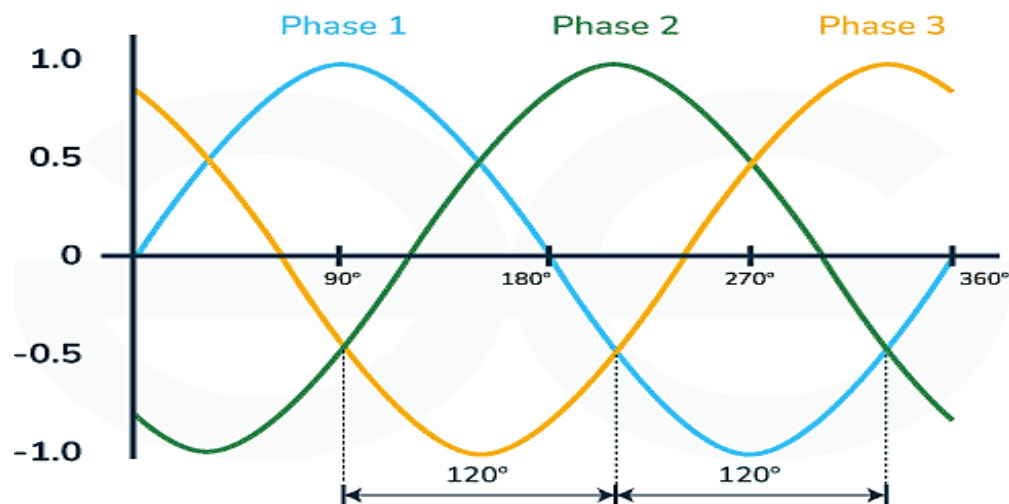
- It has simple and rugged construction.
- It is relatively cheap.
- It requires little maintenance.
- It has high efficiency and reasonably good power factor.
- It has self-starting torque.

Disadvantages of 3 Phase Induction Motor

- **Starting Torque:** The starting torque induction motor is lower contrasted with a few other motor types.
- **Complex Control:** Accomplishing exact speed control can be more intricate with 3-phase induction motor contrasted with a few other engine types.
- **Power Factor:** The power component of 3-phase induction motor may not be ideal under all working circumstances.
- **Harmonics Generation:** 3-phase enlistment engines can bring sounds into the electrical framework, which might require extra separating or rectification devices.
- **Speed Control:** wide speed reach can be more difficult contrasted with a few other motor types.
- **Size and Weight:** 3-phase induction motors can be bigger and heavier than identical DC motors.

What is 3-Phase Power?

Three-phase power is a type of electrical power transmission or distribution wherein three sinusoidal voltages of a similar recurrence are produced or utilized. It is a typical strategy utilized in electrical systems, industrial systems, and huge electrical motor.



Here are the key components and attributes of three-phase power:

- **Phases:** In a three-phase system, there are three separate electrical waveforms, frequently alluded to as phases. These phases are assigned as Phase 1, Phase 2, Phase 3. The voltage waveforms for these three phases are counterbalanced by 120 degrees from one another, making a balanced system.
- **Voltage:** The voltage in a three-phases system is estimated between any two phases. This voltage is known as the line voltage or phases to-phases voltage. There is likewise the stage voltage, which is the voltage estimated between a phase and the neutral point in systems where a neutral is available.
- **Balanced System:** Basically, in a decent three-phase system, the load and impedance across the three phases are equivalent. This equilibrium assists in keeping a smooth and consistent power with streaming.

Construction of 3-phase Induction Motor:

It consists of two parts called as the **Stator** and the **Rotor**. The stator is the stationary part of the induction motor, and the rotor is the rotating part.

Stator:

The stator is built up of high-grade alloy steel laminations to reduce eddy current losses. It has three main parts, namely outer frame, the stator core and a stator winding.

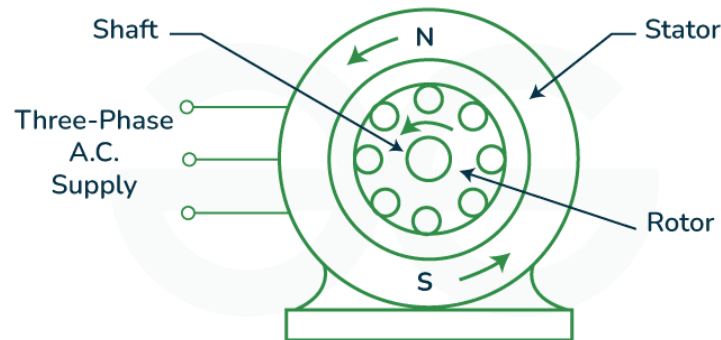
- **Outer frame**

It is the outer body of the motor. Its main function is to support the stator core and to protect the inner parts of the machine. For small machines, the outer frame is casted, but for the large machine, it is fabricated.

- **Stator Core**

The stator core is built of high-grade silicon steel stampings. Its main function is to carry the alternating magnetic field which produces hysteresis and eddy current losses. The stampings are fixed to the stator frame. Each stamping is insulated from

the other with a thin varnish layer. The thickness of the stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner side of the stampings.



- Stator windings:

The core of the stator carries three phase windings which are usually supplied from a three-phase supply system. The six terminals of the windings (two of each phase) are connected in the terminal box of the machine. **The stator of the motor is wound for a definite number of poles**, depending upon the speed requirement, as speed is inversely proportional to the number of poles, given by the formula:

$$N_s = \frac{120 f}{p}$$

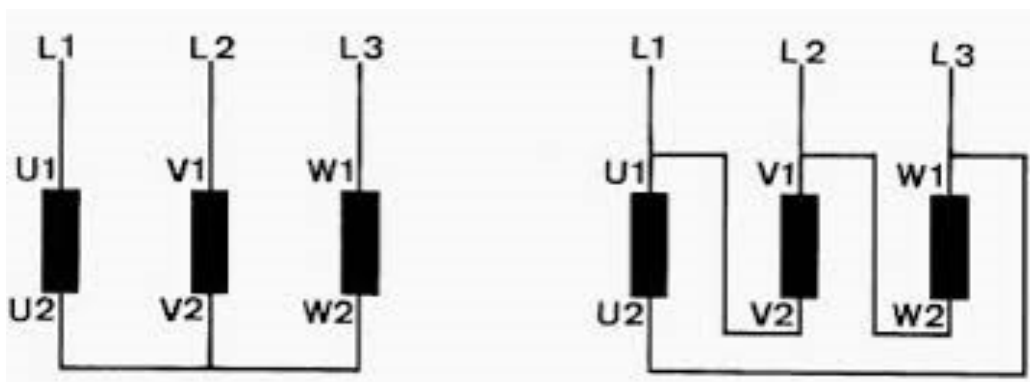
Where:

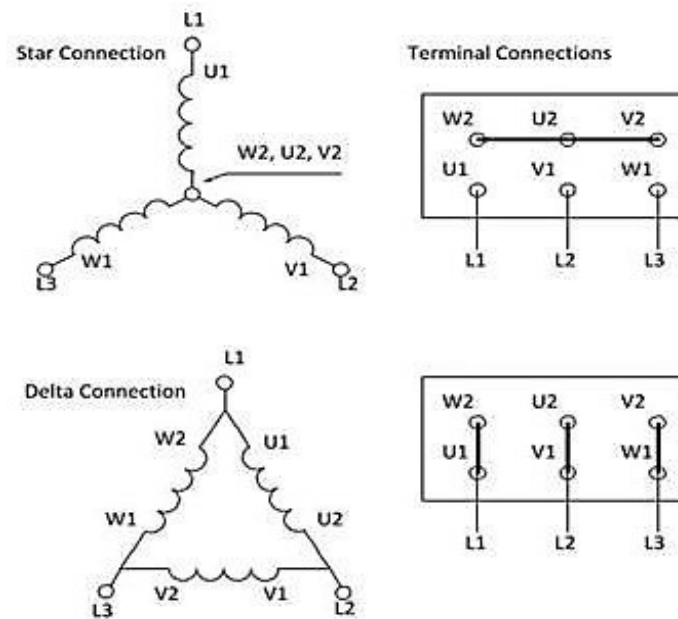
N_s = synchronous speed

f = Frequency

p = no. of poles

The windings may be connected in star and delta.





• Rotor

The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding). Three phase motors are arranged mainly in two classes in light of the rotor winding (Armature coil winding) for example squirrel cage and slip ring (wound rotor motor).

- Squirrel Cage Induction Motor
- Slip-ring or Wound Rotor Induction Motor

(i) Squirrel cage rotor:

The rotor slots are usually not parallel to the shaft but are skewed. The skewing of the rotor conductors has the following advantages given below.

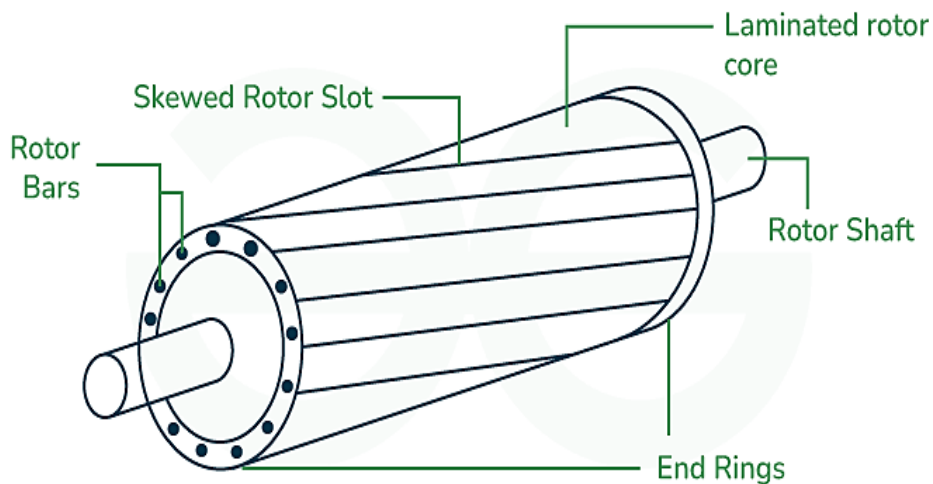
- It reduces humming and provides smooth and noise free operation.
- It results in a uniform torque curve for different positions of the rotor.
- The locking tendency of the rotor is reduced. As the teeth of the rotor and the stator attract each other and lock.
- It increases the rotor resistance due to the increased length of the rotor bar conductors.

Advantages of Squirrel Cage Induction Motor

- The cage rotor is cheaper, and the construction is robust.
- The absence of the brushes reduces the risk of sparking.
- Its Maintenance is less.
- The power factor is higher
- The efficiency of the cage rotor is higher

Disadvantages of Squirrel Cage Induction Motor

- **Limited Speed Control:** Speed control options for squirrel cage motors are limited, and their speed is largely determined by the voltage and frequency applied.
- **Limited Starting Control:** While slip-ring motors have greater command over starting force, squirrel cage motors typically have greater starting torque.



Squirrel cage rotor

(ii) Slip-Ring Induction Motor:

The Slip Ring Rotor is also called as **Phase wound rotor**. It consists of a cylindrical core which is laminated. The outer periphery of the rotor has a semi-closed slot which carries a 3 phase insulated windings. The rotor windings are connected in star.

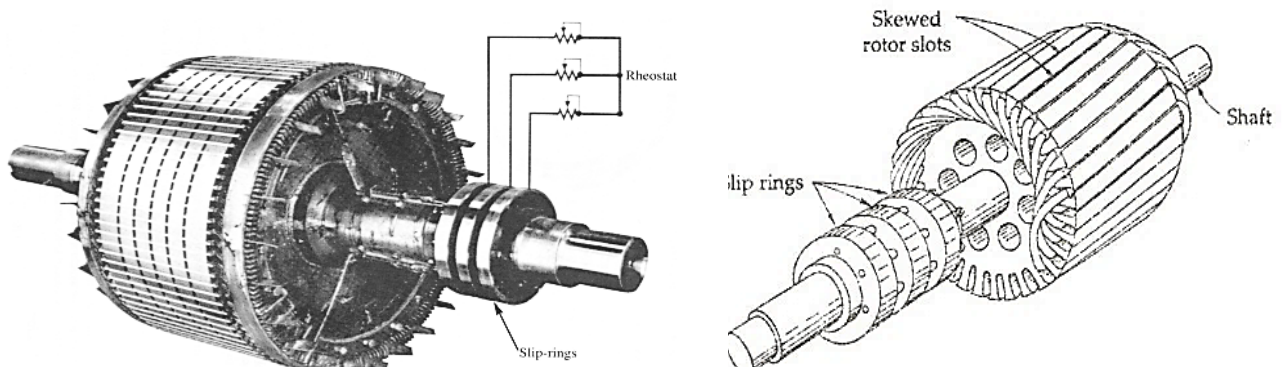
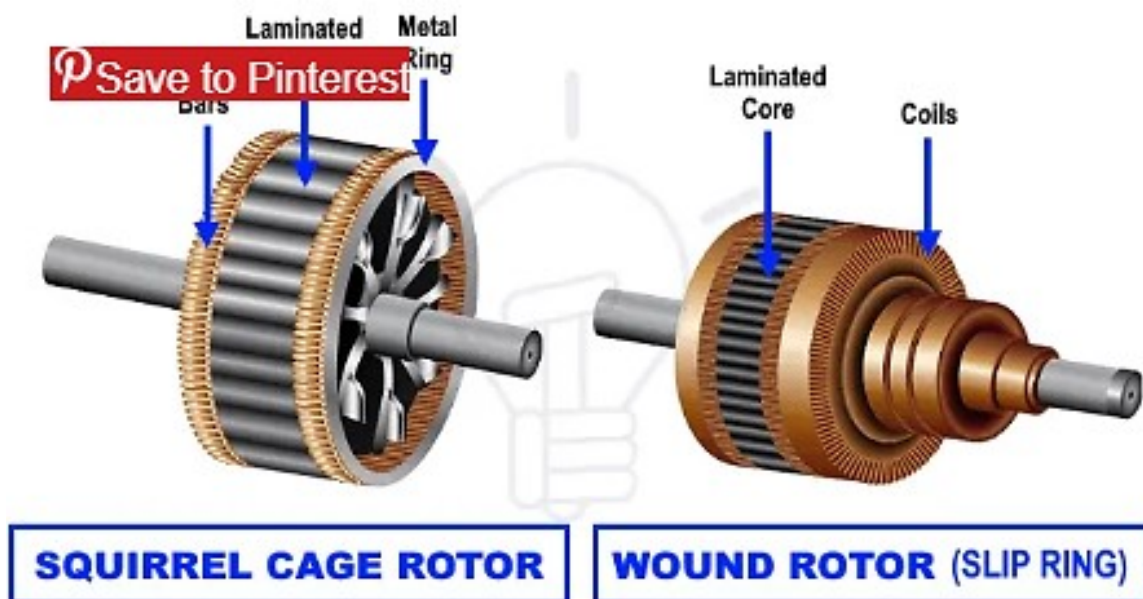
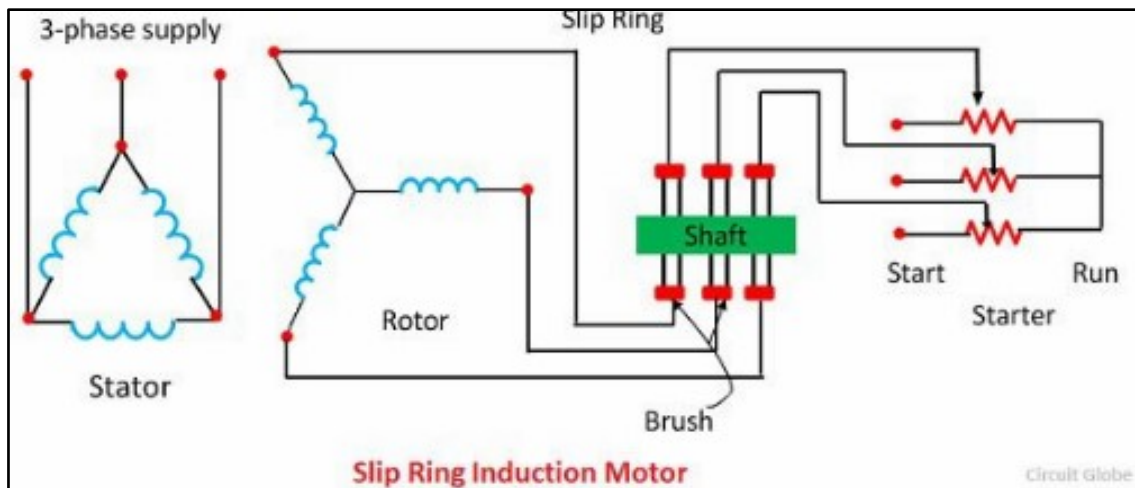


Figure 3.8 Wound rotor induction motor showing rheostat connections

The slip rings are mounted on the shaft with brushes resting on them. The brushes are connected to the variable resistor. The function of the slip rings and the brushes is to provide a means of connecting external resistors in the rotor circuit. The resistor enables the variation of each rotor phase resistance to serve the following purposes given below.

- It increases the starting torque and decreases the starting current.
- It is used to control the speed of the motor.

In this type also, the rotor is skewed. A mild steel shaft is passed through the center of the rotor and is fixed to it. The purpose of the shaft is to transfer mechanical power.



Advantages of slip ring induction motors

- The main advantage of a slip ring induction motor is that its speed can be controlled easily.
- "Pull-out torque" can be achieved even from zero RPM.
- It has a high starting torque when compared to squirrel cage induction motor. Approximately 200 - 250% of its full-load torque.

- A squirrel cage induction motor takes 600% to 700% of the full load current, but a slip ring induction motor takes a very low starting current approximately 250% to 350% of the full load current.

Disadvantages of slip ring induction motors

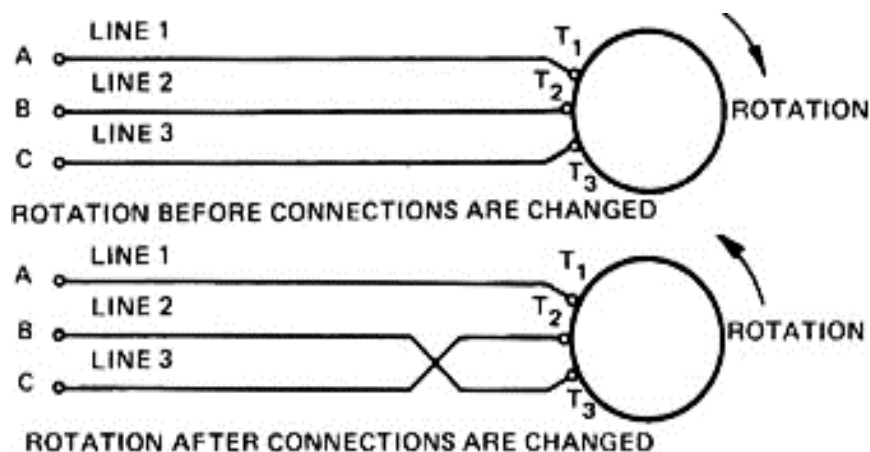
- **Complex Construction:** Slip-ring motors have a more marvelous improvement as a result of the external securities and slip rings, inciting higher gathering and backing costs.
- **Higher Maintenance:** The slip rings and brushes in the rotor require high maintenance, and the external devices are requiring.
- **Lower Efficiency:** Due to the complexity of the rotor development and the additional losses in the external protections, slip-ring motors typically have lower performance than squirrel confine motors.

Differences between three phase induction machine and synchronous machine

<i>Three phase induction machine</i>	<i>Synchronous machine</i>
Stator phases either star or delta connected	Stator phase are star connected only
Rotor windings are not fed by electricity, currents flow through rotor due to induction process.	Rotor windings are fed by dc source.
Run below synchronous speed, as a motor Run above synchronous speed, as a generator	Run at synchronous speed for both motor and generator
Self starting , as a motor	Need damper bars to start , as a motor
Operate with lagging power factor only	Operate with lagging, leading, and unity power factor

Reversing Rotation:

The direction of rotation of a three-phase induction motor can be reversed readily. The motor will rotate in the opposite direction if any two of the three-line leads are reversed. The leads are reversed at the motor.



Comparison between Single Phase and Three Phase Induction Motors

1. Single phase induction motors are simple in construction, reliable and economical for small power rating as compared to three phase induction motors.
2. The electrical power factor of single-phase induction motors is low as compared to three phase induction motors.
3. For same size, the single-phase induction motors develop about 50% of the output as that of three phase induction motors.
4. The starting torque is also low for asynchronous motors / single phase induction motor.
5. The efficiency of single-phase induction motors is less as compare it to the three phase induction motors.

Single phase induction motors are simple, robust, reliable and cheaper for small ratings. They are generally available up to 1 KW rating.

OPERATION

When a balanced 3-phase voltage is supplied to the armature, a rotating magnetic field is produced (just as in a synchronous machine). The speed of rotation is the synchronous speed given by

$$\omega_s = \frac{4\pi f_1}{p} \text{ rad / s} \quad \text{or} \quad n_s = \frac{120 f_1}{p} \text{ rpm,}$$

where p is the number of poles of the armature winding and f_1 is the line frequency.

However, the rotor rotates at a speed less than the synchronous speed. We will designate the angular speed of the rotor in rad/s by ω and the speed in rev/min (rpm) by n . The slip speed is speed of the rotor relative to the field, i.e.,

$$\text{Slip speed} = \omega_s - \omega \text{ (rad/s)}$$

$$= n_s - n \text{ rpm}$$

The per-unit slip, or, simply slip, is defined as

$$s = \frac{\omega_s - \omega}{\omega_s} = \frac{n_s - n}{n_s}$$

The magnitude and frequency of the rotor induced voltage depends on the speed of the relative motion (between rotor and field), which is

$$\text{slip speed} = \omega_s - \omega = s \omega_s.$$

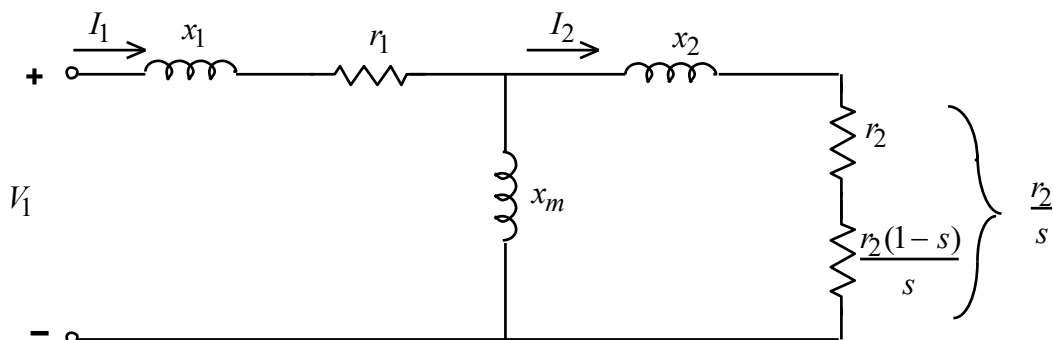
The rotor frequency is, thus,

$$f_2 = sf_1$$

The voltage induced (and thereby the current) in the squirrel cage rotor is balanced three-phase with the same number of poles as in the armature. The balanced 3-phase current at the frequency of f_2 causes a rotating magnetic field that rotates at the slip speed $(\omega_s - \omega)$ with respect to the rotor, which means at synchronous speed with respect to the stator. The two rotating fields (stator field and rotor field) rotate at the same (synchronous) speed and maintain a certain angular relationship with each other in steady state.

Equivalent Circuit:

The equivalent circuit given in Figure 1 serves as an approximate circuit model for one phase of the induction motor.



The symbols used in Figure 1 are defined below:

V_1 = line-to-neutral terminal voltage. The phase windings are considered to be in a Y configuration.

r_1 = stator resistance per phase

x_1 = stator leakage reactance per phase

r_2 = rotor resistance referred to the stator, per phase

x_2 = rotor leakage reactance referred to the stator, per phase

x_m = shunt reactance supplied to provide a path for the magnetizing component of the current flowing in the stator. It is this current which produces the revolving field in the motor.

Note that core losses and rotational losses are not accounted for in the equivalent circuit. Omitting core losses causes small but negligible errors. The mechanical power and torque calculated using the equivalent circuit are the generated values. Rotational losses may be subtracted to obtain actual output values. Another approximation is that r_2 is constant. In most general-purpose motors, r_2 varies with the frequency of the rotor currents (and also temperature). It is necessary to use the correct value of r_2 .

The subscript '1' is referring to the stator side while '2' is referring to the rotor side

R_1, X_1, R_2, R_m, X_m are value perphase

Input Power, $P_{in} = 3V_1I_1\cos\theta$

Stator copper loss, $P_{scl} = 3I_1^2R_1$

Core Loss, $P_{cl} = 3V_1^2/R_m$ (always neglected because too small)

Power across the air-gap, $P_{ag} = 3I_2^2R_2/s$
 $= P_{in} - P_{scl} - P_{cl}$

Rotor copper loss, $P_{rc1} = 3I_2^2R_2$

Mechanical power/gross output power/converted power,

$$\begin{aligned} P_{mech} &= P_{ag} - P_{rc1} \\ &= 3I_2^2R_2/s - 3I_2^2R_2 \\ &= P_{ag}(1-s) \end{aligned}$$

Net power output, $P_{output} = P_{mech} - P_{friction \& \ windage \ loss}$

For Torque:

$$T_{mechanical / induced} = T_m = \frac{60P_m}{2\pi n} = \frac{P_m}{\omega_r} = \frac{P_{ag}}{\omega_s}$$

$$T_{output / load} = T_o = \frac{60P_o}{2\pi n} = \frac{P_{out}}{\omega_r}$$

Ex: A Three-phase induction motor with a synchronous speed of 1500 revolutions per minute (RPM) and a slip of 5%. The motor is connected to a 50Hz three-phase supply. Find the synchronous speed, actual rotational speed and Frequency of the Induced EMF.

Sol:

Synchronous Speed

The synchronous speed (N_s) can be calculated using the formula

$N_s = 120 \times \text{frequency} / \text{Number of Poles}$, For a 50 Hz supply and a motor with 4 poles:

$$N_s = 120 \times 50 / 4 = 1500 \text{ RPM}$$

Actual Rotational Speed

$N = N_s \times (1 - \text{slip})$, Given slip is 5% (0.05):

$$N = 1500 \times (1 - 0.05) = 1425 \text{ RPM}$$

Frequency of the Induced EMF

The slip frequency (f -slip) is given by: f -slip = Frequency x Slip for a 50 Hz supply and a slip of 5%:

$$f\text{-slip} = 50 \times 0.05 = 2.5 \text{ Hz}$$

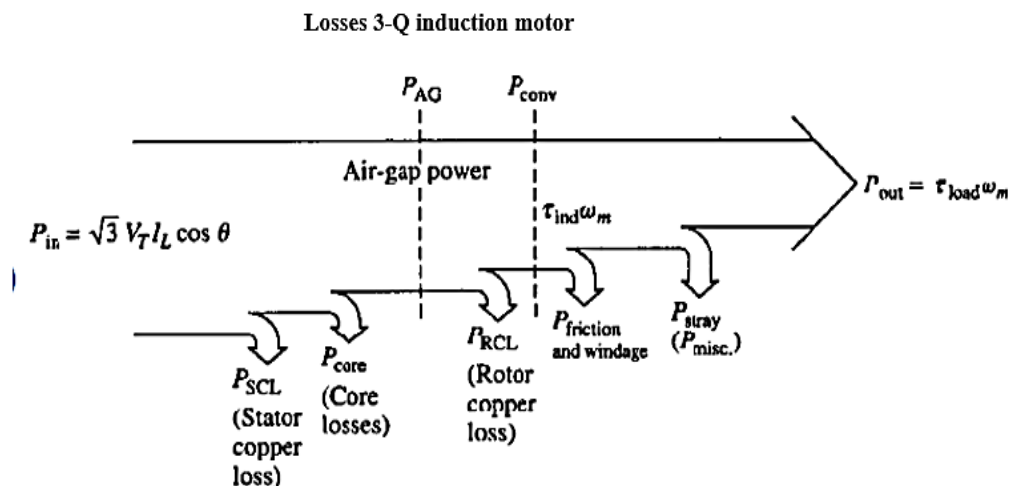
Hence, the induced EMF frequency in the rotor is 2.5 Hz.

Per-phase equivalent circuit of three-phase induction motor

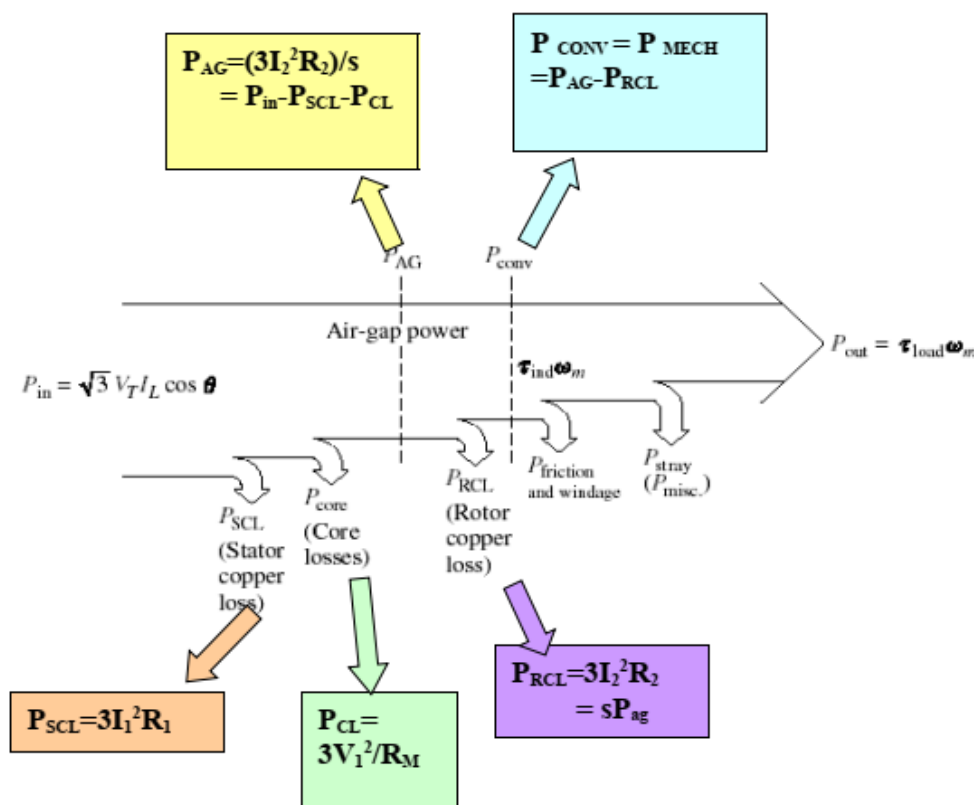
The per-phase equivalent circuit of a three-phase induction motor is just like a single – phase transformer equivalent circuit. The difference is only that the secondary winding is short-circuited unlike in the transformer it is open-circuited as a load is to be connected later. Complete Equivalent Circuit for Induction Machine Referred to the Stator Circuit

POWER FLOW OF AN INDUCTION MOTOR

Motor nameplates provide information vital to the proper selection and installation of the motor. Most useful data given on the nameplate refers to the electrical characteristics of the motor. Given this information and using the National Electrical Code, the electrician can determine the conduit, wire, and starting and running protection sizes. (The NEC gives minimum requirements).



Power flow diagram of the induction motor



Power Flow Diagram

- Induction motor converts electrical power into mechanical power.
- 3ph supply is fed to stator, **input power** P_{in} is

$$P_{in} = \sqrt{3} V_L I_L \cos \varphi$$
- Losses occur in stator called **stator losses** (P_{SL})
- Remaining power is transferred to rotor magnetically,
- It is called output of the stator or **input to the rotor** (P_2)

$$P_2 = P_{in} - P_{SL}$$
- In rotor side, **rotor copper losses** occur (P_{cu}).
- Normally rotor iron losses are very small therefore it should be neglected.
- Remaining part is called **mechanical power developed** (P_m)
- Remaining part is called **mechanical power developed** (P_m)

$$P_{cu} = 3I_2^2 R_2$$

$$P_m = P_2 - P_{cu}$$

•Due to rotating part in motor **mechanical losses (P_{mL})** occur.

$$P_{out} = P_m - P_{mL}$$

$$\text{Rotor Efficiency} = \frac{\text{Rotor Output}}{\text{Rotor Input}} = \frac{P_m}{P_2}$$

$$\text{Motor Efficiency} = \frac{\text{Mechanical power Output at shaft}}{\text{Electrical power Input to the stator}} = \frac{P_{out}}{P_{in}}$$

Ex: A 220-V, three-phase, two-pole, 50-Hz induction motor is running at a slip of 5 percent. Find:

- The speed of the magnetic fields in revolutions per minute
- The speed of the rotor in revolutions per minute
- The slip speed of the rotor
- The rotor frequency in hertz

SOLUTION

- (a) The speed of the magnetic fields is

$$n_{sync} = \frac{120f_e}{P} = \frac{120(50 \text{ Hz})}{2} = 3000 \text{ r/min}$$

- (b) The speed of the rotor is

$$n_m = (1 - s) n_{sync} = (1 - 0.05)(3000 \text{ r/min}) = 2850 \text{ r/min}$$

- (c) The slip speed of the rotor is

$$n_{slip} = sn_{sync} = (0.05)(3000 \text{ r/min}) = 150 \text{ r/min}$$

- (d) The rotor frequency is

$$f_r = \frac{n_{slip}P}{120} = \frac{(150 \text{ r/min})(2)}{120} = 2.5 \text{ Hz}$$

Ex: A three-phase, 60-Hz induction motor runs at 890 r/min at no load and at 840 r/min at full load.

- How many poles does this motor have?
- What is the slip at rated load?
- What is the speed at one-quarter of the rated load?

(d) What is the rotor's electrical frequency at one-quarter of the rated load?

SOLUTION

(a) This machine has 8 poles, which produces a synchronous speed of

$$n_{\text{sync}} = \frac{120f_e}{P} = \frac{120(60 \text{ Hz})}{8} = 900 \text{ r/min}$$

(b) The slip at rated load is

$$s = \frac{n_{\text{sync}} - n_m}{n_{\text{sync}}} \times 100\% = \frac{900 - 840}{900} \times 100\% = 6.67\%$$

(c) The motor is operating in the linear region of its torque-speed curve, so the slip at $\frac{1}{4}$ load will be

$$s = 0.25(0.0667) = 0.0167$$

The resulting speed is

$$n_m = (1 - s) n_{\text{sync}} = (1 - 0.0167)(900 \text{ r/min}) = 885 \text{ r/min}$$

(d) The electrical frequency at $\frac{1}{4}$ load is

$$f_r = sf_e = (0.0167)(60 \text{ Hz}) = 1.00 \text{ Hz}$$

Ex: 10 poles, 50 Hz, Y connection 3-phase induction motor having a rating of 60kW and 415V. The slip of the motor is 5% at 0.6 power factor lagging. If the full load efficiency is 90%, calculate:

- (i) **Input power**
- (ii) **Line current and phase current**
- (iii) **Speed of the rotor (rpm)**
- (iv) **Frequency of the rotor**
- (v) **Torque developed by the motor (if friction and windage losses is 0)**

Solution

$$(i) \eta = \frac{P_{out}}{P_{in}}$$

$$P_{in} = \frac{P_{out}}{\eta} = \frac{60kW}{0.9} = 66666.7W$$

$$(ii) \text{ Y connection, } I_{\phi} = I_L, V_{\phi} = \frac{V_L}{\sqrt{3}}$$

$$P_{in} = 3V_{\phi}I_{\phi}\cos\theta = \sqrt{3}V_L I_L \cos\theta$$

$$I_L = \frac{P_{in}}{\sqrt{3}V_L \cos\theta} = \frac{66.67kW}{\sqrt{3}(415)(0.6)} = 154.59A$$

$$I_{\phi} = I_L = 154.59 \angle \cos^{-1} 0.6 = 154.59 \angle -53.13^{\circ} A$$

Ex: A 3-phase induction motor, delta connection, 5 pair of poles, 60 Hz is connected to a 440V source. The slip is 3% and the windage and friction losses are 3kW. The equivalent circuit per phase referred to the stator circuit is:

R1 = Stator resistance = 0.4Ω.

X1 = Stator leakage inductance = 1.4Ω

R2' = Rotor resistance = 0.6Ω.

X2 = Rotor leakage inductance = 2Ω

Rm = no-load losses resistance = 150Ω.

Xm = magnetizing reactance = 20Ω

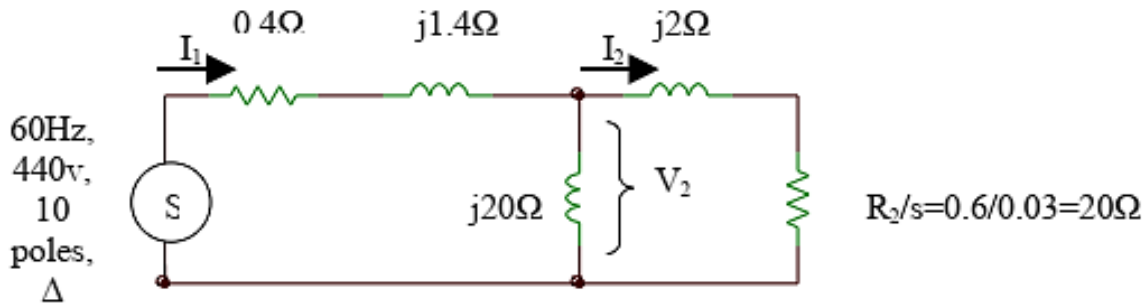
Calculate: (i) Input power.

(ii) Speed of the rotor.

(iii) Mechanical power

(iv) Developed torque.

(v) Efficiency

Solution

$$(i) \quad P_{in} = 3VI\cos\theta$$

$$V = 440V$$

$$Z_{total} = 0.4 + 1.4j + \frac{20j(20 + 2j)}{20j + 20 + 2j} = 9.45 + 11.45j\Omega$$

$$I_1 = \frac{V}{Z_{total}} = \frac{440}{9.45 + 11.45j} = 18.87 - 22.86j = 29.64\angle -50.46^\circ A$$

$$P_{in} = 3(440)(29.64)\cos(-50.46^\circ) = \underline{24907.5W}$$

$$(ii) \quad n_s = \frac{120f}{p} = \frac{120(60)}{10} = 720rpm$$

$$s = \frac{n_s - n}{n_s}$$

$$n = n_s(1-s) \quad , \quad n = 720(1-0.03) = \underline{698.4rpm}$$

$$(iii) \quad P_m = 3(I_2^2 R_2/s - I_2^2 R_2)$$

$$V_2 = 440 - I_1 Z_1$$

$$= 440 - (18.87 - 22.86j)(0.4 + j1.4)$$

$$= 400.45 - 17.27j V$$

$$I_2 = \frac{V_2}{Z_2} = \frac{400.45 - j17.27}{20 + j2} = 19.74 - j2.84 = 19.94\angle -8.19^\circ A$$

$$P_m = 3 \left[19.94^2 \left(\frac{0.6}{0.03} \right) - 19.94^2 (0.6) \right] = \underline{23140.5W}$$

$$(iv) \quad T_{dev} = \frac{P_{ag}}{\omega_s} = \frac{P_m}{\omega_m}$$

$$P_{ag} = 3I_2^2 R_2/s = 3(19.94)^2 (0.6)/(0.03) = 23856.2W$$

$$\omega_s = \frac{2\pi f}{p/2} = \frac{2\pi(60)}{5} = 75.4 rad/s$$

$$T = \frac{23856.2}{75.4} = 316.4 Nm$$

$$(v) \quad \eta = \frac{P_{output}}{P_{in}} = \frac{23140.5W - 3kW}{24901.5W} = 81\%$$

Ex: A 50-kW, 440V, 50Hz, six-pole three phase induction motor has a slip of 6 percent when operating at full-load conditions. At full-load conditions, the friction and windage losses is 300W and the core losses is 600W. Find the following values for full-load conditions:

- (a) The shaft speed n_m
- (b) The output power in watts
- (c) The load torque (τ_{load}) in newton-meters
- (d) The induced torque (τ_{ind}) in newton-meters
- (e) The rotor frequency in hertz

SOLUTION

- (a) The synchronous speed of this machine is

$$n_{\text{sync}} = \frac{120f_e}{P} = \frac{120(50 \text{ Hz})}{6} = 1000 \text{ r/min}$$

Therefore, the shaft speed is

$$n_m = (1 - s) n_{\text{sync}} = (1 - 0.06)(1000 \text{ r/min}) = 940 \text{ r/min}$$

- (b) The output power in watts is 50 kW (stated in the problem).
 (c) The load torque is

$$\tau_{\text{load}} = \frac{P_{\text{OUT}}}{\omega_m} = \frac{50 \text{ kW}}{(940 \text{ r/min}) \frac{2\pi \text{ rad}}{1 \text{ r}} \frac{1 \text{ min}}{60 \text{ s}}} = 508 \text{ N} \cdot \text{m}$$

- (d) The induced torque can be found as follows:

$$P_{\text{conv}} = P_{\text{OUT}} + P_{\text{F\&W}} + P_{\text{core}} + P_{\text{misc}} = 50 \text{ kW} + 300 \text{ W} + 600 \text{ W} + 0 \text{ W} = 50.9 \text{ kW}$$

$$\tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{50.9 \text{ kW}}{(940 \text{ r/min}) \frac{2\pi \text{ rad}}{1 \text{ r}} \frac{1 \text{ min}}{60 \text{ s}}} = 517 \text{ N} \cdot \text{m}$$

- (e) The rotor frequency is

$$f_r = sf_e = (0.06)(50 \text{ Hz}) = 3.00 \text{ Hz}$$

H.W: A three-phase, 60-Hz, four-pole induction motor runs at a no-load speed of 1790 r/min and a full-load speed of 1720 r/min. Calculate the slip and the electrical frequency of the rotor at no-load and full-load conditions. What is the speed regulation of this motor?

Sol:





Ex: a 500V, 6-pole, 50Hz, 3-phase induction motor develops 20kw inclusive of mechanical losses when running at 995 r.p.m., the p.f. being 0.87. Calculate (a) the slip, (b) the rotor I^2R loss, (c) the total input if the stator loss is 1500w, (d) line current, (e) the rotor current frequency.

Solution:

$$N_s = \frac{120f_s}{P} = \frac{120 * 50}{60} = 1000 \text{ r. p. m.}$$

$$s = \frac{N_s - N_r}{N_s} = \frac{1000 - 995}{1000} = 0.005 \text{ pu}$$

Rotor on loss = slip * rotor power input

=s (mech. power developed + rotor Cu loss)

$$P_{rc} = s(P_m + P_{rc})$$

$$P_{rc}(1 - s) = sP_m$$

$$P_{rc} = \frac{sP_m}{(1 - s)} = \frac{0.005}{1 - 0.005} * 20 * 1000 = 100.5 \text{ W}$$

Total input to stator = rotor power input + stator loss

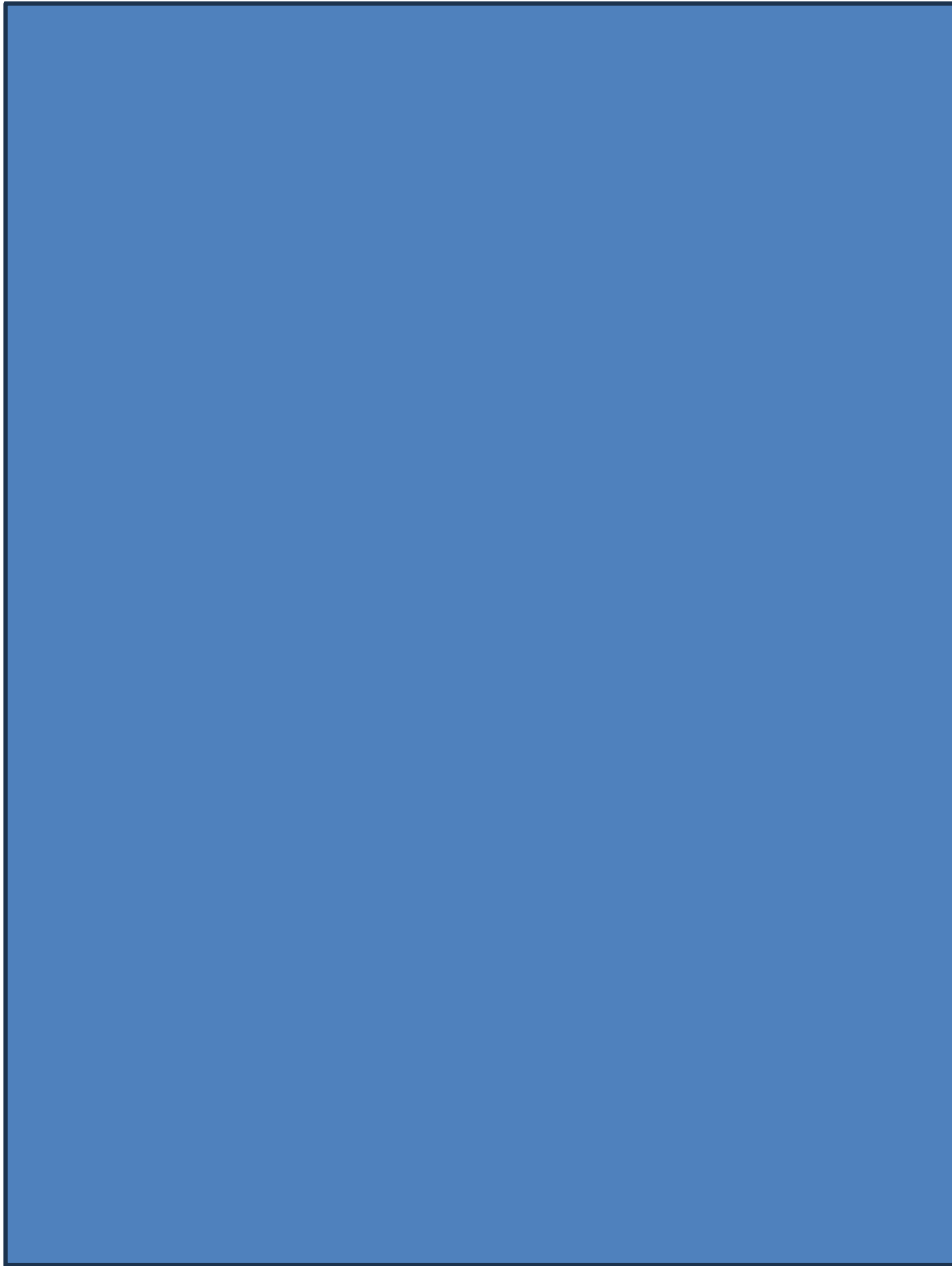
$$\text{Rotor input} = \frac{1}{s} * \text{rotor Cu loss}$$

$$= \frac{1}{0.005} * 100.5 = 20100 \text{ W} = 20.1 \text{ KW}$$

Hence total input = 20.1 + 1.5 = 21.6KW

$$\text{Line current} = \frac{21600}{\sqrt{3} * 500 * 0.87} = 28.7 \text{ A}$$

$$f_r = sf_s = 0.005 * 50 = 0.25 \text{ Hz}$$



How does a 3-phase Induction Motor work?

These motors work on the rule of electromagnetic induction. The turning attractive field created by the three-stage flows associates with the rotor, actuating flows and making it rotate.

What is a 3-phase Induction Motor?

A 3-phase Induction Motor is a kind of AC electric motor that works on a three-phase power supply. It is broadly used for different modern and business applications to change over electrical energy into mechanical energy.

Where are 3-phase Induction Motor usually utilized?

They are used in modern apparatus (fans, blowers), cooling systems, electric traction (trains, electric vehicles), water siphoning stations, producing plants, and different applications.

What are the advantages of 3-Phase Induction Motor?

Benefits incorporate high productivity, unwavering quality, low upkeep, and reasonableness for many modern applications because of their hearty plan and capacity *to convey high power output*.

How is the speed of a 3-Phase Induction Motor controlled?

Speed control can be accomplished using variable frequency drives (VFDs), which change the frequency of the input power. This takes into consideration exact command over the motor speed.

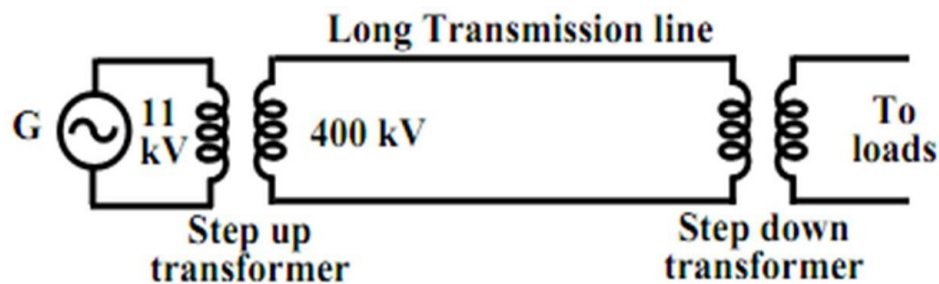
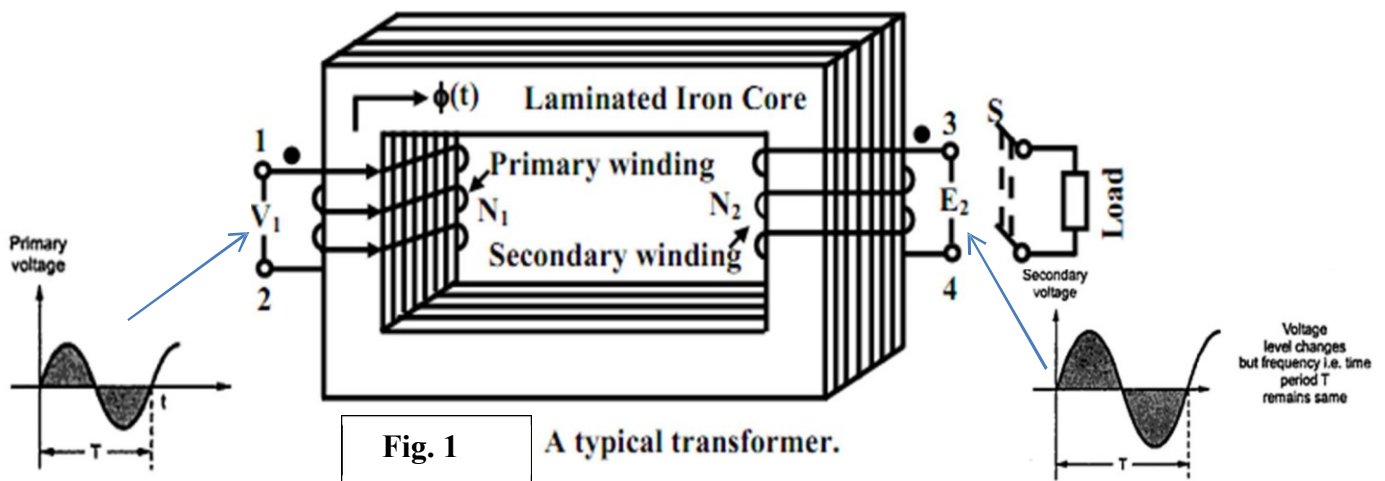
What is the contrast between Single-Phase and 3-Phase Motors?

Single-phase motors work on a single-phase AC voltage, while 3-phase motors use three phase voltage. 3-phase motors by and large give higher efficiency and power yield contrasted with single-phase motors.

Transformer

A **transformer** is a static piece of equipment used either for raising or lowering the voltage of an AC supply with a corresponding decrease or increase in current. The use of transformers in transmission system is shown in the Figure below.

The iron core is made of thin silicon steel laminations. Eddy current losses are reduced by making the laminations very thin. The laminations are electrically insulated from each other by a very thin coating of insulating varnish or by the use of an oxide layer on the surface.



Principle of Operation

A transformer in its simplest form will consist of a rectangular laminated magnetic structure on which two coils of different number of turns are wound as shown in Fig.3 The winding to which AC voltage is impressed is called *the primary* of the transformer and the winding across which the load is connected is called *the secondary* of the transformer.

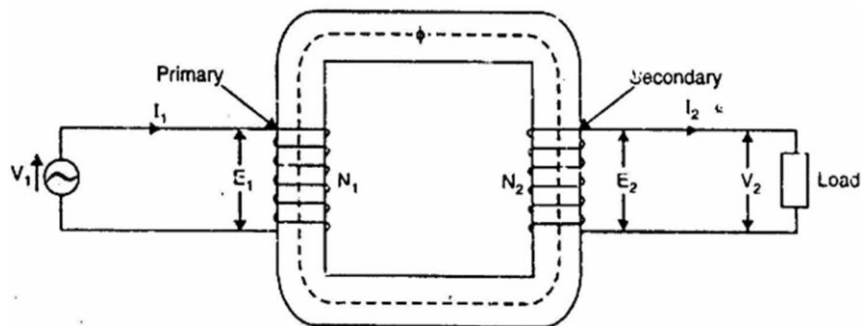


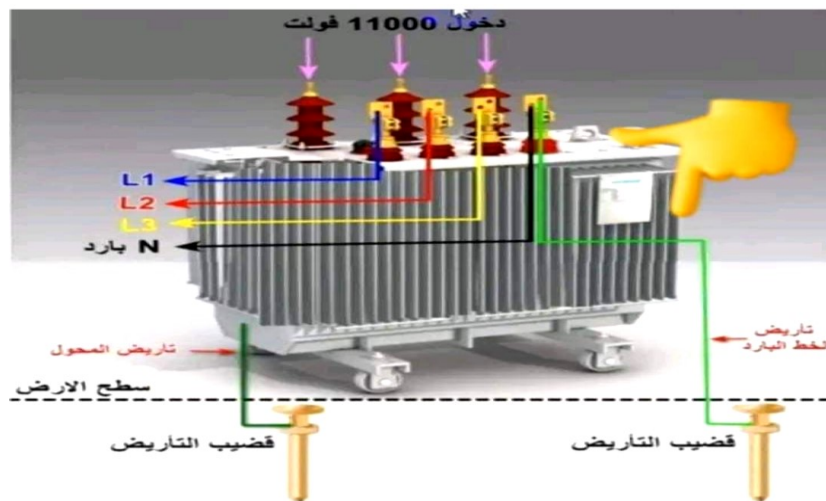
Fig.3

- *Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating emf (E_2) is induced in the secondary. This induced emf (E_2) in the secondary causes a secondary current I_2 . Consequently, terminal voltage V_2 will appear across the load. If $V_2 > V_1$, it is called a *step up-transformer*. On the other hand, if $V_2 < V_1$, it is called a *step-down transformer*.*
- When an alternating voltage V_1 is applied to the primary, an alternating flux Φ is set up in the core. This alternating flux links both the windings and induces emfs E_1 and E_2 in them according to Faraday's laws of electromagnetic induction. The emf E_1 is termed as primary emf and emf E_2 is termed as Secondary emf.

Clearly,
$$E_1 = -N_1 \frac{d\phi}{dt}$$

and
$$E_2 = -N_2 \frac{d\phi}{dt}$$

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

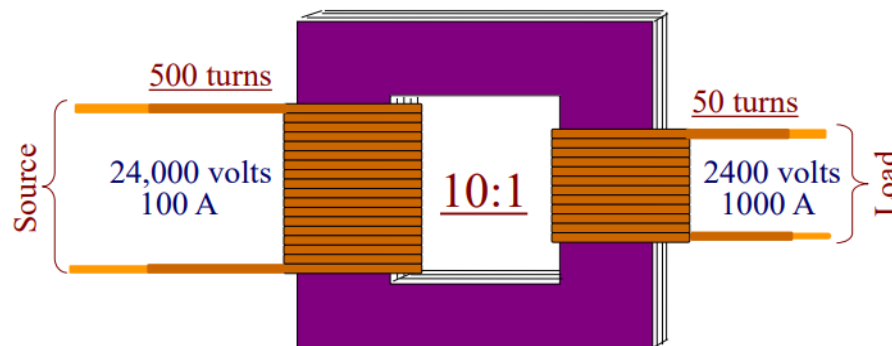


Note that magnitudes of E_2 and E_1 depend upon the number of turns on the secondary and primary respectively. If $N_2 > N_1$, then $E_2 > E_1$ (or $V_2 > V_1$) and we get a step-up transformer. On the other hand, if $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and we get a step-down transformer. If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

The following points may be noted carefully:

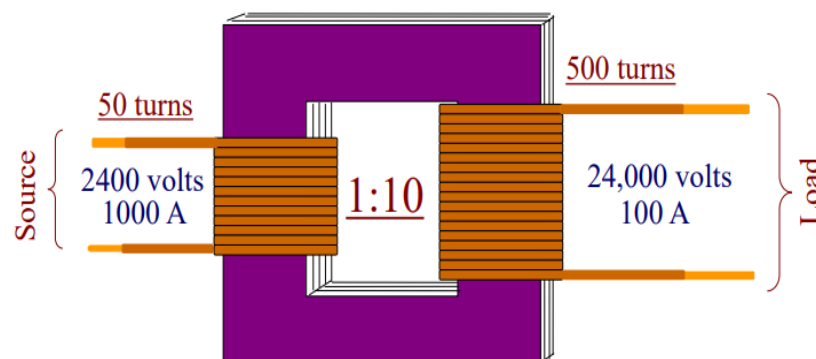
- (i) The transformer action is based on the laws of *electromagnetic induction*.
- (ii) There is no electrical connection between the primary and secondary.
- (iii) There is no change in frequency i.e., output power has the same frequency as the input power

Step-Down Transformer



$$\frac{N_P}{N_S} = \frac{500}{50} = \frac{10}{1} \quad \frac{10}{1} = \frac{E_P}{E_S} \quad \frac{10}{1} = \frac{I_S}{I_P}$$

Step-Up Transformer



$$\frac{N_P}{N_S} = \frac{50}{500} = \frac{1}{10} \quad \frac{1}{10} = \frac{E_P}{E_S} \quad \frac{1}{10} = \frac{I_S}{I_P}$$

➤ Can DC Supply be used for Transformers?

The DC supply cannot be used for the transformers. This is because the transformer works on the principle of *mutual induction*, for which current in one coil must change uniformly. If DC supply is given, the current will not change due to constant supply and transformer will not work.

There can be saturation of the core due to which transformer draws very large

current from the supply when connected to DC.

Thus DC supply should not be connected to the transformers.

Construction Transformer

We usually design a power transformer so that it approaches the characteristics of an ideal transformer. To achieve this, following design features are incorporated:

- (i) The core is made of silicon steel which has low hysteresis loss and high permeability. Further, core is laminated in order to reduce eddy current loss. These features considerably reduce the iron losses and the no-load current.
- (ii) Instead of placing primary on one limb and secondary on the other, it is a usual practice to wind one-half of each winding on one limb. This ensures tight coupling between the two windings. Consequently, leakage flux is considerably reduced.
- (iii) The winding resistances are minimized to reduce Copper loss and resulting rise in temperature and to ensure high efficiency.

Transformers are of two types: (i) core-type transformer (see Fig.3-3) and shell-type transformer (see Fig.3-4).

1. Core-Type Transformer: In a core-type transformer, half of the primary winding and half of the secondary winding are placed round each limb to reduce the leakage flux.

One type consists of a simple rectangular laminated piece of steel with the transformer windings wrapped around two sides of the rectangle. This type of construction is known as core form.

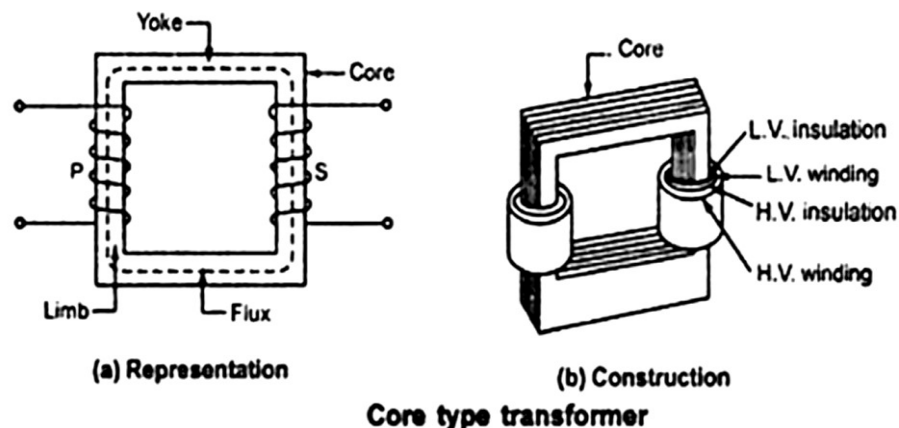


Fig.4

2. **Shell-Type Transformer:** This method of construction involves the use of a double magnetic circuit. Both the windings are placed round the central limb to ensure a low-reluctance flux path.

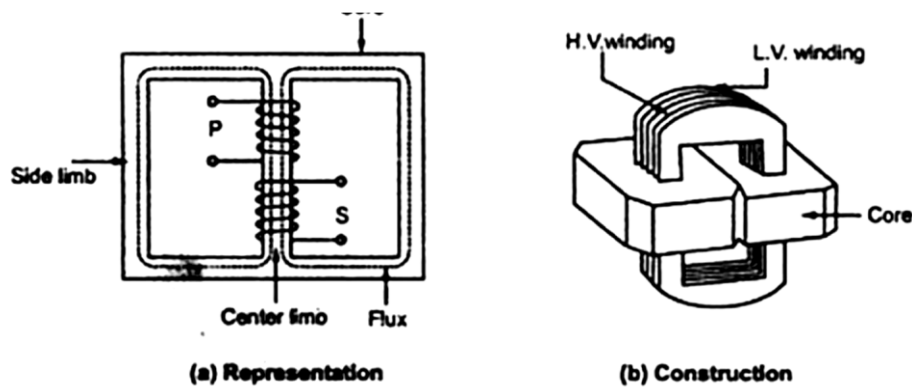
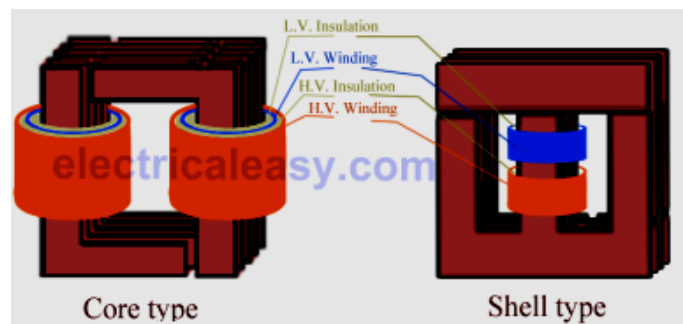


Fig.5

Comparison of Core and Shell Type Transforms

Core Type	Shell Type
The winding encircles the core.	The core encircles most part of the winding
It has single magnetic circuit	It has double magnetic circuit
The core has two limbs	The core has three limbs
The cylindrical coils are used.	The multilayer disc or sandwich type coils are used.
The winding are uniformly distributed on two limbs hence natural cooling is effective	The natural cooling does not exist as the windings are surrounded by the core.
Preferred for low voltage transformers.	Preferred for high voltage transformers.



Primary Winding: The primary winding is the coil of wire connected to the AC power source. It produces the magnetic field that links with the secondary winding.

Secondary Winding: The secondary winding is another coil of wire connected to the load. It receives the induced voltage from the changing magnetic field of the primary winding.

Insulation: Insulation materials are used to separate the windings and prevent electrical contact between them.

Tank and Cooling System: Larger transformers are placed in a tank filled with insulating oil to provide electrical insulation and dissipate heat generated during operation. Cooling systems, such as radiators or oil pumps, help maintain an optimal operating temperature.

Tap Changer (Optional): Some transformers may include a tap changer to vary the turns ratio slightly, allowing for voltage regulation under changing load conditions.

Cooling of Transformers

When transformer supplies a load, two types of losses occur inside the transformer. The iron losses occur in the core while copper losses occur in the windings. The power lost due to these losses appears in the form of heat. This heat increases the temperature of the transformer. *To keep the temperature, rise of the transformer within limits, a suitable coolant and cooling method is necessary.*

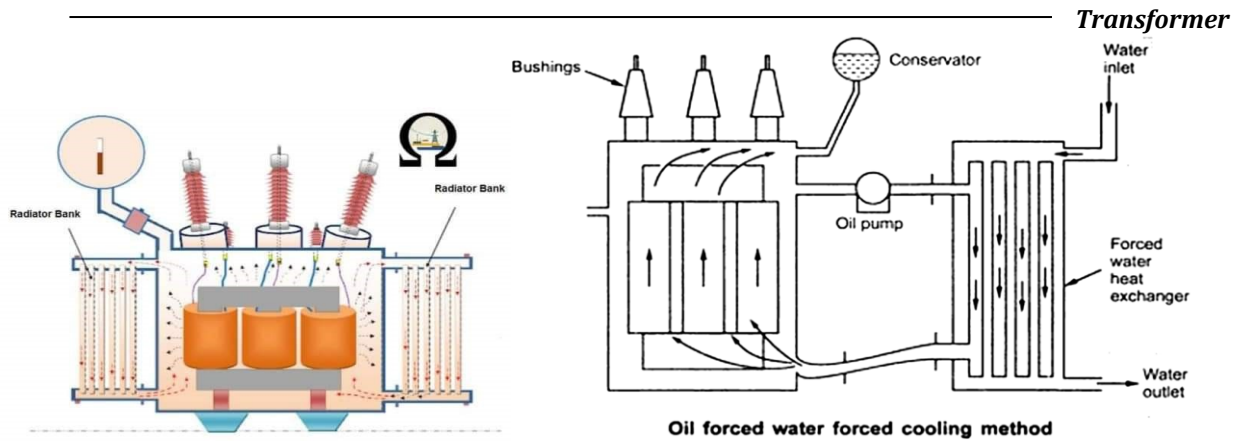
The various cooling methods are designated with depended upon:

A: cooling medium used and

B: type of circulation employed.

The various coolant used such as **Air, Gas, Mineral oil, and water.**

One of cooling method system is shown in figure below which is called *Oil Forced Water Forced cooling system;*



Advantages of transformer :

- A transformer will increase or decrease basically AC voltage, current or independence
- It is efficient for high-frequency range
- The available power cannot change but will slightly too much decrease depending on the efficiency of the transformer
- It has the advantage of preventing condensed flux leakage as well as iron loss
- It offers good mechanical strength
- The transformer is widely used in power transmission

Disadvantages of transformer :

- A transformer will not work with DC voltage under any condition
- The transformer size become un widely
- The physical size of the transformer is directly related to the amount of power to be desired
- It is not good to use outdoors
- It can be noisy

EMF Equation of a Transformer

Consider that an alternating voltage V_1 of frequency f is applied to the primary as shown in Fig.6. The sinusoidal flux Φ produced by the primary can be represented as:

$$\phi = \phi_m \sin \omega t$$

The instantaneous e.m.f. e_1 induced in the primary is

$$\begin{aligned} e_1 &= -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin \omega t) \\ &= -\omega N_1 \phi_m \cos \omega t = -2\pi f N_1 \phi_m \cos \omega t \\ &= 2\pi f N_1 \phi_m \sin(\omega t - 90^\circ) \end{aligned} \quad (i)$$

It is clear from the above equation that maximum value of induced e.m.f. in the primary is

$$E_{m1} = 2\pi f N_1 \phi_m$$

The r.m.s. value E_1 of the primary e.m.f. is

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

or $E_1 = 4.44 f N_1 \phi_m$

Similarly $E_2 = 4.44 f N_2 \phi_m$

In an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$.

Note. It is clear from exp. (i) above that e.m.f. E_1 induced in the primary lags behind the flux ϕ by 90° . Likewise, e.m.f. E_2 induced in the secondary lags behind flux ϕ by 90° .

Voltage Transformation Ratio (K)

From the above equations of induced emf, we have,

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

The constant K is called voltage transformation ratio. Thus, if $K = 5$ (i.e. $N_2/N_1 = 5$), then $E_2 = 5 E_1$.

Ex// A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm^2 . If the primary winding be connected to a 50-Hz supply at 520 V, calculate (i) the peak value of flux density in the core (ii) the voltage induced in the secondary winding.

Sol:

$$a = N_2/N_1 = 1000/400 = 2.5$$

$$(i) E_1 = 4.44 f N_1 B_m A$$

$$520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4})$$

$$\therefore B_m = \mathbf{0.976 \text{ Wb/m}^2}$$

$$(ii) E_2/E_1 = a \therefore E_2 = a E_1 = 2.5 \times 520 = 1300 \text{ V}$$

Example (2):

A 25-kVA transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000-V, 50-Hz supply. Find the full-load primary and secondary currents, the secondary e.m.f. and the maximum flux in the core. Neglect leakage drops and no-load primary current.

$$a = N_2/N_1 = 50/500 = 0.1$$

$$\text{Now, full-load } I_1 = 25,000/3000 = \mathbf{8.33 \text{ A.}}$$

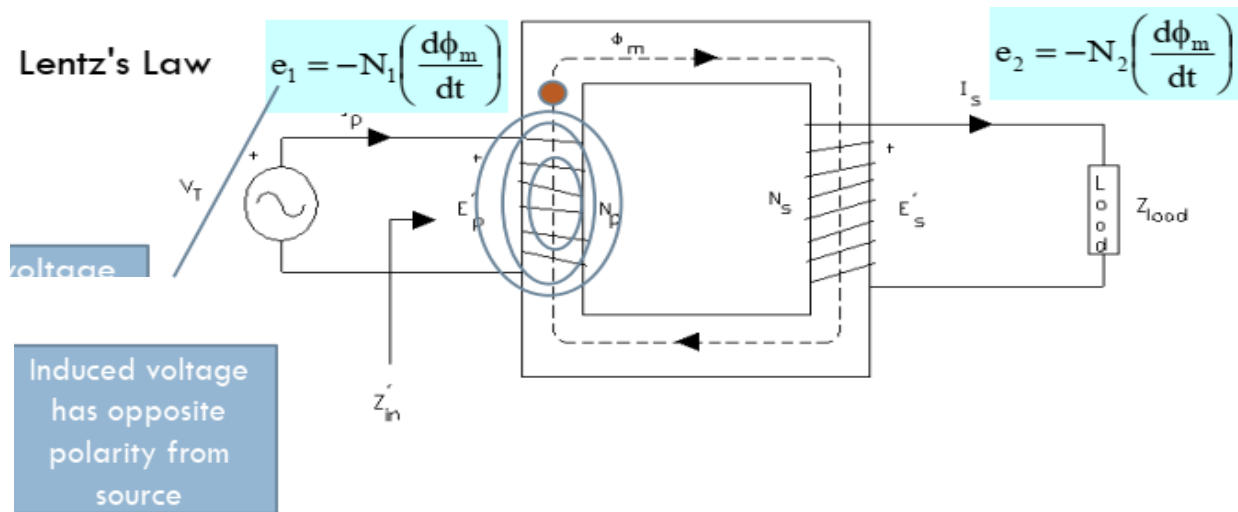
$$\text{F.L. } I_2 = I_1/a = 10 \times 8.33 = \mathbf{83.3 \text{ A}}$$

$$E_2 = aE_1 = 3000 \times 0.1 = \mathbf{300 \text{ V}}$$

$$\text{Also, } E_1 = 4.44 f N_1 \Phi_m; 3000 = 4.44 \times 50 \times 500 \times \Phi_m$$

$$\therefore \Phi_m = \mathbf{27 \text{ mWb}}$$

Concept of Ideal Transformer



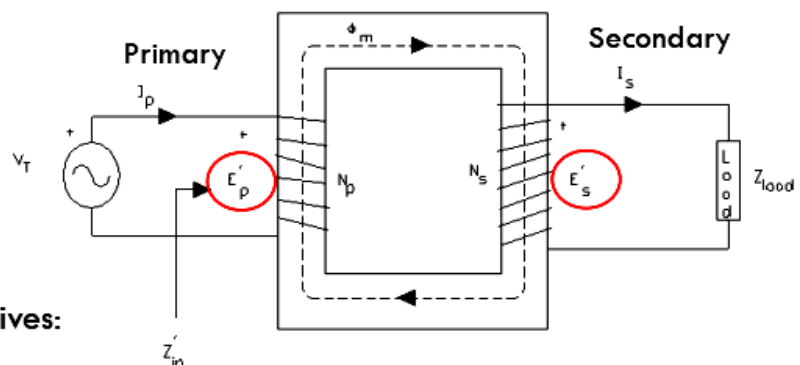
A transformer is said to be ideal if it satisfies following properties:

- It has no losses.
- Its windings have zero resistance.
- Leakage flux is zero i.e. 100 % flux produced by primary links with the secondary.
- Permeability of core is so high that negligible current is required to establish the flux in it.

For sinusoidal sources

$$E'_p = 4.44 \cdot N_p \cdot f \cdot \phi_{\max}$$

$$E'_s = 4.44 \cdot N_s \cdot f \cdot \phi_{\max}$$



Dividing the above equations gives:

$$\frac{E'_p}{E'_s} = \frac{4.44 \cdot N_p \cdot f \cdot \phi_{\max}}{4.44 \cdot N_s \cdot f \cdot \phi_{\max}}$$

$$\frac{E'_p}{E'_s} = \frac{N_p}{N_s}$$

Voltage relationship for Ideal transformer

Where: E'_p = voltage induced in the primary (V)
 E'_s = voltage induced in the secondary (V)
 N_p = turns in the primary coil
 N_s = turns in the secondary coil

Voltage ratio equals the turns ratio

For ideal transformer

$$a = \frac{E'_p}{E'_s} = \frac{N_p}{N_s} = \frac{V_p}{V_s}$$

Where: a = turns ratio

V_p = nameplate rated primary voltage (higher V)

V_s = nameplate rated secondary voltage (lower V)

E'_p = induced primary voltage

E'_s = induced secondary voltage

NOTE:

For an ideal transformer, the primary applied voltage V_1 is same as the primary induced emf E_1 as there are no voltage drops.

For ideal transformer:

- (i) $E_1 = V_1$ and $E_2 = V_2$ as there is no voltage drop in the windings.

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

- (ii) there are no losses. Therefore, volt-amperes input to the primary are equal to the output volt-amperes i.e.

$$V_1 I_1 = V_2 I_2$$

$$\text{or } \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

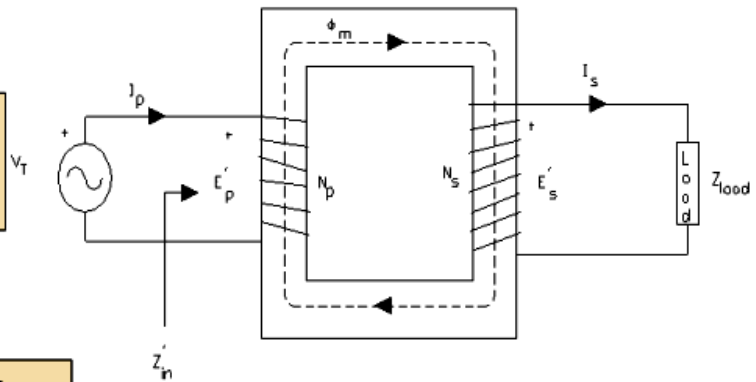
Hence, currents are in the inverse ratio of voltage transformation ratio. This simply means that if we raise the voltage, there is a corresponding decrease of current.

Voltage Ratio

$$a = \frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$E_p = a \cdot E_s$$

The turns ratio is a scalar. Introduces no phase shift



Apparent Power balance

$$E_p \cdot I_p = E_s \cdot I_s$$

$$S_p = S_s$$

No power losses in idea transformer

Current Ratio

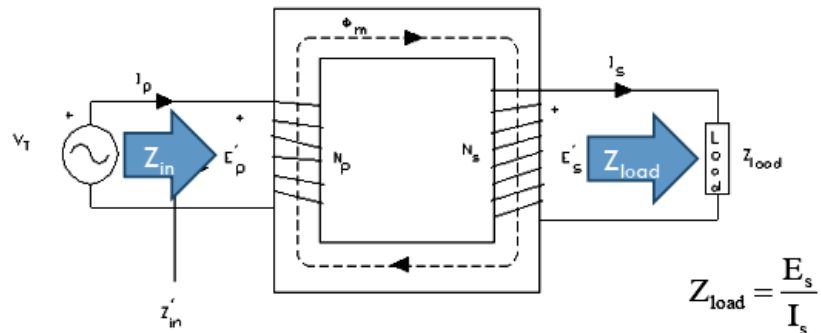
$$\frac{I_p}{I_s} = \frac{1}{a} \quad I_p = \left(\frac{1}{a}\right) \cdot I_s$$

Current ratio is the inverse of the voltage ratio

Ideal Transformer Equations- Impedance Transforms

Impedances Reflected Through Ideal Transformers

Load impedance as seen from primary side of transformer



By Ohm's Law

$$Z_{in} = \frac{E_p}{I_p}$$

$$Z_{load} = \frac{E_s}{I_s}$$

Write E_s and I_s in terms of primary values

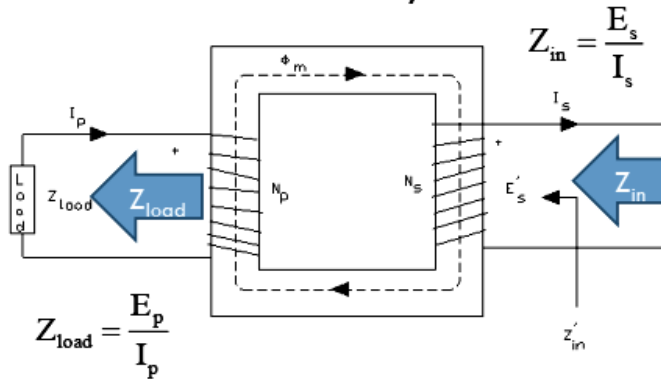
$$E_s = \frac{E_p}{a} \quad I_s = a \cdot I_p$$

Load impedance is increased when viewed from primary side

$$\frac{E_s}{I_s} = \frac{\left(\frac{E_p}{a}\right)}{a \cdot I_p} = \left(\frac{E_p}{a}\right) \left(\frac{1}{a \cdot I_p}\right) = \left(\frac{E_p}{I_p}\right) \left(\frac{1}{a^2}\right)$$

$$Z_{load} = Z_{in} \cdot \left(\frac{1}{a^2}\right) \Rightarrow Z_{load} \cdot a^2 = Z_{in}$$

Derive equation when impedances are connected to the primary side and viewed from the secondary side.



Write primary values in terms of secondary and substitute in the Z_{load} equation.

$$E_p = a \cdot E_s \quad I_p = \frac{I_s}{a}$$

$$Z_{\text{load}} = \frac{E_p}{I_p} = \frac{a \cdot E_s}{\frac{I_s}{a}} = (a \cdot E_s) \left(\frac{a}{I_s} \right) = a^2 \cdot \left(\frac{E_s}{I_s} \right)$$

Generally : Moving impedance from secondary to primary multiply by a^2 . Moving from primary to secondary, divide by a^2 .

$$Z_{\text{load}} = Z_{\text{in}} \cdot a^2 \Rightarrow \frac{Z_{\text{load}}}{a^2} = Z_{\text{in}}$$

$$Z_p = Z_s \cdot a^2 \quad \frac{Z_p}{a^2} = Z_s$$

Lesson 8_ef332b.pptx

H.W: Compare the no-load current in induction motors and transformers.

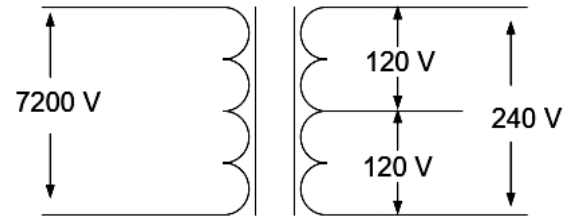
The no-load current in induction motors draws a current of up to 40% of the rated current. This is because the magnetic impedance of the air gap (magnetic medium) is very large, so it requires a large magnetizing current to be magnetized. This current is drawn in the no-load state.

As for the transformer, the no-load current reaches 5% of the rated current, since the magnetic impedance of the core (the magnetic medium) is small, so it does not require a high magnetizing current, so the current drawn in the no-load state is small.



Ex: A 25 kVA, 7200-240/120 center-tap single phase transformer operates at rated voltage. It supplies a single-phase load that has an equivalent impedance of $7.2 \angle +36.90$ ohms. Assume Ideal operation and find:

- turns ratio
- secondary current
- primary current
- load Z as seen from primary side
- PT, ST, QT, and F_p



a) For ideal transformers

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} \quad V_p = 7200 \text{ V} \quad V_s = 240 \text{ V} \quad a = \frac{N_p}{N_s} = \frac{7200 \text{ V}}{240 \text{ V}} = 30$$

b) Secondary current

Use Ohm's law to find I_s

$$\frac{I_p}{I_s} = \frac{1}{a} \Rightarrow I_p = \frac{1}{a} I_s \quad \bar{E}_p = 7200 \angle 0^\circ \text{ V} \quad \bar{E}_s = 240 \angle 0^\circ \text{ V}$$

$$\bar{I}_s = \frac{240 \angle 0^\circ \text{ V}}{7.2 \angle 36.9^\circ \Omega} \quad \bar{I}_s = 33.33 \angle -36.9^\circ \text{ A}$$

c) Find the primary current

$$\bar{I}_p = \frac{1}{a} \bar{I}_s \quad \bar{I}_p = \left(\frac{1}{30} \right) (33.33 \angle -36.9^\circ)$$

$$\bar{I}_p = 1.11 \angle -36.9^\circ \text{ A}$$

d) Find the input impedance as seen from the primary side

$$\bar{Z}_{in} = a^2 Z_{Load}$$

$$\bar{Z}_{in} = (30)^2 (7.2 \angle 36.9^\circ)$$

$$\bar{Z}_{in} = 6480 \angle 36.9^\circ \Omega$$

Example 32.1. The maximum flux density in the core of a 250/3000-volts, 50-Hz single-phase transformer is 1.2 Wb/m^2 . If the e.m.f. per turn is 8 volt, determine

(i) primary and secondary turns (ii) area of the core.

(Electrical Engg.-I, Nagpur Univ. 1991)

Solution. (i)

$$E_1 = N_1 \times \text{e.m.f. induced/turn}$$

$$N_1 = 250/8 = 32; N_2 = 3000/8 = 375$$

(ii) We may use

$$E_2 = -4.44 f N_2 B_m A$$

\therefore

$$3000 = 4.44 \times 50 \times 375 \times 1.2 \times A; A = 0.03 \text{m}^2.$$

EXAMPLE 1.1. A 3300/250 V, 50 Hz, single-phase transformer is built on a core having an effective cross-sectional area of 125 cm^2 and 70 turns on the low-voltage winding. Calculate (a) the value of the maximum flux density, (b) the number of turns on the high voltage winding.

SOLUTION.

$$E_1 = 3300 \text{ V}, E_2 = 250 \text{ V}, f = 50 \text{ Hz}$$

$$A = 125 \text{ cm}^2 = 125 \times 10^{-4} \text{ m}^2$$

$$E_2 = 4.44 \Phi_m f T_2 = 4.44 B_m A f T_2$$

$$B_m = \frac{E_2}{4.44 A f T_2}$$

$$= \frac{250}{4.44 \times 125 \times 10^{-4} \times 50 \times 70} = 1.289 \text{ teslas (T)}$$

$$\frac{E_1}{E_2} = \frac{T_1}{T_2}$$

$$T_1 = \frac{E_1}{E_2} \times T_2 = \frac{3300}{250} \times 70 = 924$$

EXAMPLE 1.2. A transformer with 800 primary turns and 200 secondary turns is supplied from a 100 V a.c. supply. Calculate the secondary voltage and the volts per turn.

SOLUTION. $T_1 = 800$, $T_2 = 200$, $V_1 = 100$ V

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}, \quad V_2 = V_1 \times \frac{T_2}{T_1}$$

$$= 100 \times \frac{200}{800} = 25 \text{ V}$$

$$\text{Volts per turn} = \frac{V_1}{T_1} = \frac{100}{800} = 0.125$$

$$\text{or volts per turn} = \frac{V_2}{T_2} = \frac{25}{200} = 0.125$$

EXAMPLE 1.3. A transformer with an output voltage of 4200 V is supplied at 230 V. If the secondary has 2000 turns, calculate the number of primary turns.

SOLUTION. $V_2 = 4200$ V, $V_1 = 230$ V, $T_2 = 2000$

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

$$T_1 = \frac{T_2 V_1}{V_2}$$

$$= 2000 \times \frac{230}{4200} = 109.52 \text{ turns}$$

Ex: A transformer has 600 turns of the primary winding and 20 turns of the secondary winding. Determine the secondary voltage if the secondary circuit is open and the primary voltage is 140 V.

Given: (N_1) = 600 turns, (N_2) = 20 turns, **Primary** voltage (V_1) = 140 V

Solution:

The voltage on the primary coil = $N_1 V_1$

The voltage on the secondary coil = $N_2 V_2$

The voltage on one turn

$$V_t = \frac{V_2}{N_2} = \frac{V_1}{N_1} \quad k = \frac{V_2}{N_2} = \frac{V_1}{N_1}$$

k is a transformation ratio

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

$$V_2 = \frac{20}{600} \times 140$$

$$V_2 = 4.6 \text{ V}$$

Ex2. A transformer has a primary coil with 1600 loops and a secondary coil with 1000 loops. If the current in the primary coil is 6 Ampere, then what is the current in the secondary coil.

Given: Primary coil (N_1) = 1600 loops, Secondary coil (N_2) = 1000 loops
The current in the primary coil = 4 A

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} \quad \frac{I_2}{4} = \frac{1600}{1000}$$

$$I_2 = 6.4 \text{ A}$$

Current on the secondary coil is 6.4 Ampere

H.W// A two-winding transformer has a primary winding with 208 turns and a secondary winding with 6 turns. The primary winding is connected to a 4160V system.

- What is the secondary voltage at no load?
- What is the current in the primary winding with a 50A load connected to the secondary winding?
- What is the apparent power flowing in the primary and secondary circuits?

First transformer law:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} = \frac{208}{6}$$

$$E_p = 4160 \text{ V}$$

$$E_s = 4160 \text{ V} \times \frac{6}{208} = 120 \text{ V}$$

Second transformer law:

$$\frac{i_p}{i_s} = \frac{N_s}{N_p} = \frac{6}{208}$$

$$i_s = 50 \text{ A}$$

$$i_p = 50 \text{ A} \times \frac{6}{208} = 1.44 \text{ A}$$

$$\begin{aligned} \text{Apparent power in primary circuit} &= E_p \times I_p \\ &= 4160 \text{ V} \times 1.442 \text{ A} = 5999 \text{ VA} \end{aligned}$$

$$\text{Apparent power in secondary circuit} = 120 \text{ V} \times 50 \text{ A} = 6000 \text{ VA}$$

Losses in transformer

A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses.

1. The power consumed is called power loss. It is caused by the following:
 - hysteresis losses
 - eddy current losses
 - copper (I^2R) losses
2. Hysteresis and eddy current losses occur in the transformer's core.
3. Copper losses occur in the windings.
4. All three loss types involve the conversion of electrical energy into heat energy

The efficiency of a transformer

is the ratio of the output power to the input power? But we stated earlier that the power into a transformer is equal to the power out of the transformer, therefore the efficiency equals 100%. This is the ideal case. In reality, the transformer consumes some of the power. Most transformers have an efficiency of between 97% and 99%.

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \times 100$$

- The reactive component of current (I_m) is small in amount and in the same direction of the flux and lag the supply voltage (V_1) by 90°

$$I_m = I_\phi \sin(\phi_o)$$

- The active component of current (I_c) which is in the same direction of the supply voltage (V_1)

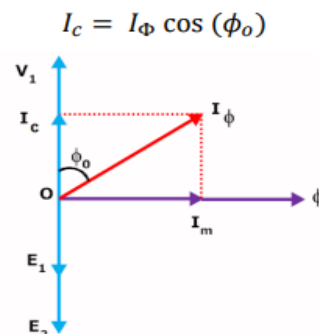


Fig. 18 Phasor diagram at no load

Example:

(a) A 2,200/200-V transformer draws a no-load primary current of 0.6 A and absorbs 400 watts. Find the magnetising and iron loss currents. (neglect winding resistances and leakage reactances)

Iron-loss current $I_c = 400/2200 = \mathbf{0.182\ A}$

As we know, $I_\phi = \sqrt{I_c^2 + I_m^2}$ OR $I_m = \sqrt{I_\phi^2 - I_c^2}$

$$I_m = \sqrt{0.6^2 - 0.182^2} = \mathbf{0.572\ A}$$

(b) A 2,200/250-V transformer takes 0.5 A at a p.f. of 0.3 on open circuit. Find magnetising and working components of no-load primary current. (neglect winding resistances and leakage reactances)

$$\phi_o = \cos^{-1}0.3 = 72.542$$

$$I_m = I_\phi \sin(\phi_o) = 0.5 \times \sin(72.542) = \mathbf{0.477\ A}$$

$$I_c = I_\phi \cos(\phi_o) = 0.5 \times 0.3 = \mathbf{0.15\ A}$$

4.4 Phasor Diagrams of Practical Transformer:

We shall consider two cases:

- (i) when the winding resistance and leakage flux are neglected,
- (ii) when the winding resistance and leakage flux are considered.

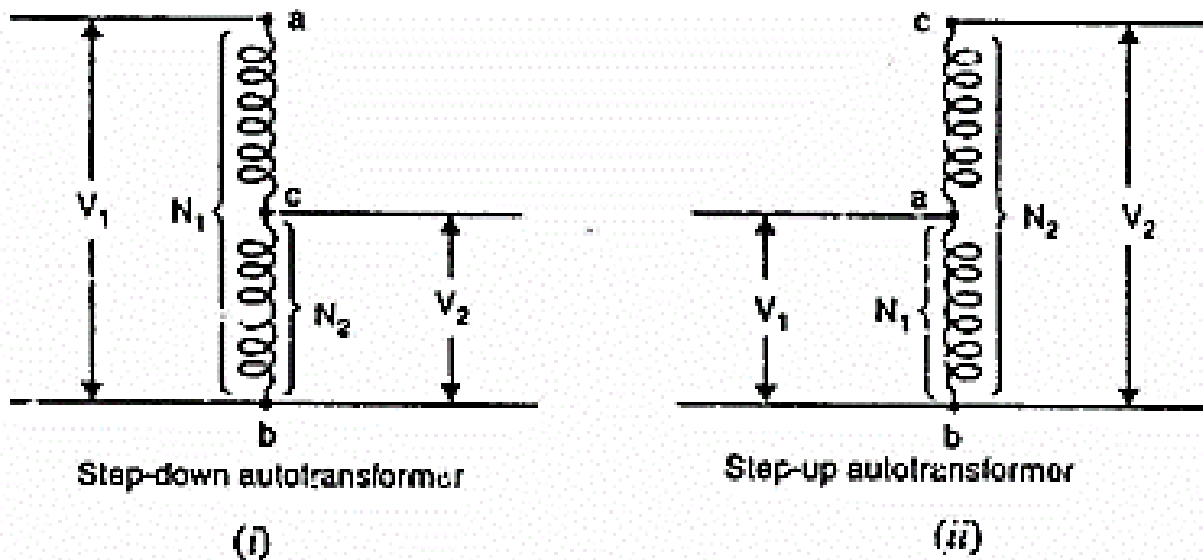
when the winding resistance and leakage flux are neglected

In case of transformer at no load, the phasor diagram is shown in Fig. 18:

- The flux (Φ) is considered as a reference on horizontal axis, and the induced voltage of the primary (E_1) and secondary (E_2) are lagging this flux by 90°

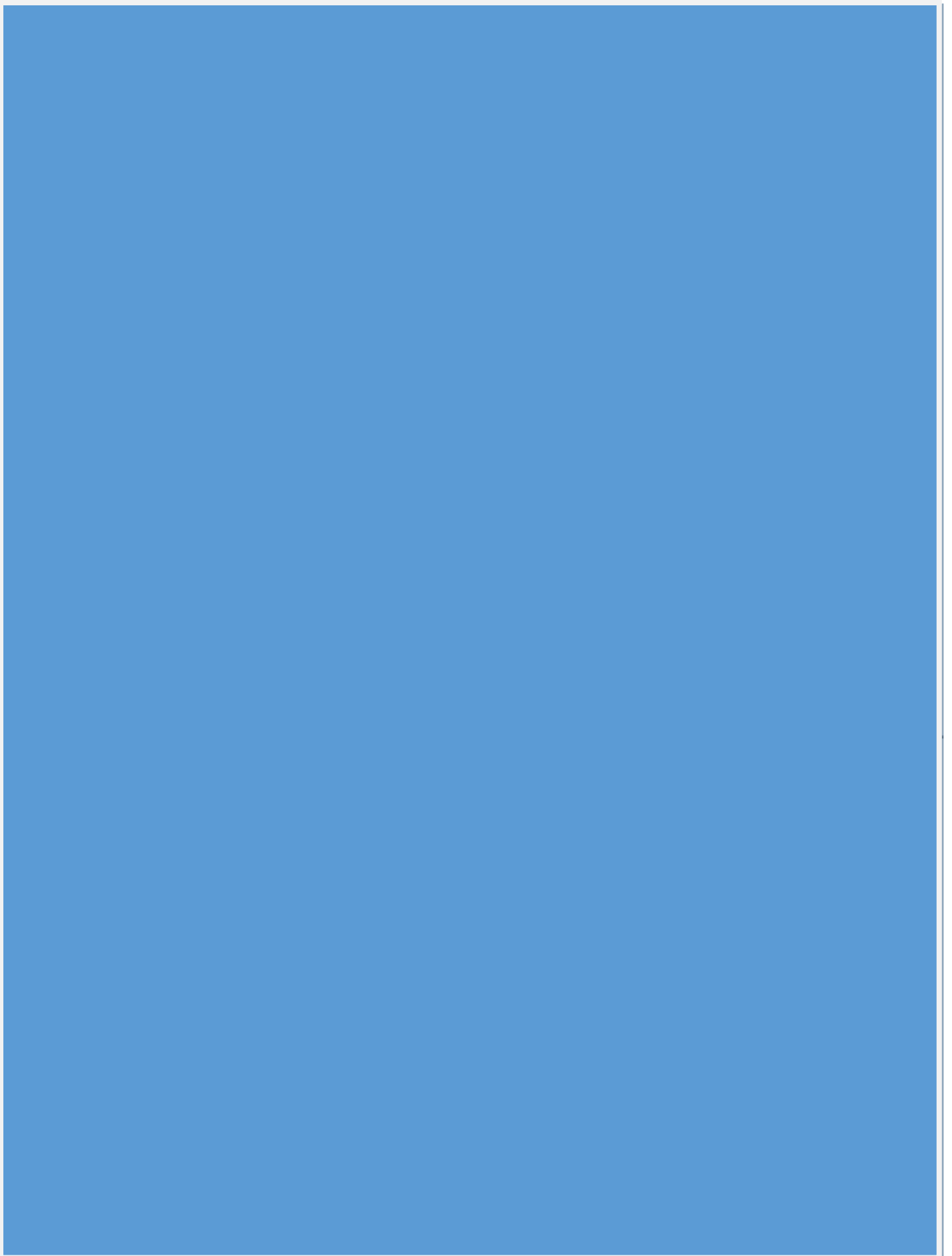
Autotransformer

An autotransformer has a single winding on an iron core and a part of winding is common to both the primary and secondary circuits. Fig.1 (i) shows the connections of a step-down autotransformer whereas Fig. 1 (ii) shows the connections of a step-up autotransformer. In either case, the winding ab having N_1 turns is the primary winding and winding bc having N_2 turns is the secondary winding. Note that the primary and secondary windings are connected electrically as well as magnetically. Therefore, power from the primary is transferred to the secondary conductively as well as inductively (transformer action). The voltage transformation ratio K of an ideal autotransformer.



Advantages of an autotransformer:

1. Copper required is very less.
2. The efficiency is higher compared to two winding transformers.
3. The size and hence cost is less compared to two winding transformers.
4. The resistance and leakage reactance are less compared to two winding transformers.
5. The copper losses I^2R , are less.
6. Due to less resistance and leakage reactance, the voltage regulation is superior than the two winding transformers.
7. VA rating is more compared to two winding version.
8. A smooth and continuous variation of voltage is possible.



Experiment (1)

Speed Control of Separately Excited DC Motor

Objective:

To study the methods of controlling the speed of separately excited DC motor.

Theory: We know that back e.m.f (E_b) is produced by the generator action of the motor.

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

Let V_t be the applied voltage and I_a and R_a is the armature circuit current and resistance respectively. Then

$$E_b = V_t - I_a R_a, \quad E_b = \frac{NPZ\phi}{60 A} = V_t - I_a R_a, \quad N = \frac{(V_t - I_a R_a) * 60 A}{PZ\phi}$$

$$N \propto \frac{(V_t - I_a R_a)}{\phi} \quad \text{Since } P, Z \text{ \& } A \text{ are constants for a particular motor}$$

$N \propto \frac{V_t}{\phi}$ Since $I_a R_a$ drop is very small as compared to the applied voltage V_t From this formula it follows that the speed of a separately excited D.C. motor can be regulated by

1- Armature Control:

This method implies changing the voltage applied to the armature (V_t) of the motor without changing the voltage applied to its field. Therefore, the motor must be separately excited to use armature voltage control.

$$N \propto V_t, \text{ if applied voltage } \phi \text{ is constant}$$

2- Field Control:

$$N \propto \frac{1}{\phi}, \text{ if applied voltage } V_t \text{ is constant}$$

The speed is inversely proportional to flux / per pole if the applied voltage is constant. Then the speed can be decrease by increase the flux and vice versa. The flux of DC motor can be changed by changing the field current (I_f), with help of external field resistance (R_{fx}).

$$\phi \propto I_f, \quad \frac{1}{\phi}, \text{ if applied voltage } V_t \text{ is constant}$$

Procedure:

1. Connect the circuit as shown in Fig.

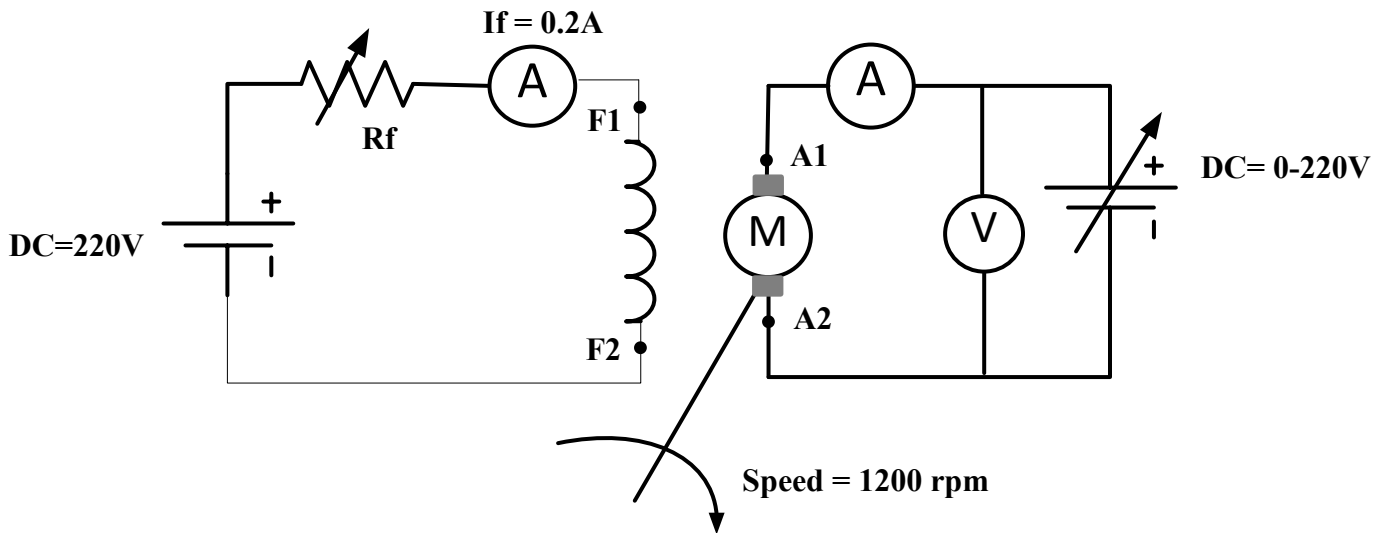


Fig. 1: Circuit diagram of speed control of separately excited DC motor

- 2- Switch on the constant DC power supply after checking connection by concerned teacher.
- 3- Fix the field current (I_f) by external field resistor (R_{fx}) at rated value ($I_f = 0.2$).
- 4- Switch on the variable DC power supply and change the V_t at steps as shown in table (1) and record the speed readings.

Table (1): Speed control by varying V_t

V_t (V)	0	30	50	70	100
N (rpm)					

- 1- Fix the armature voltage at the rated voltage ($V_t = 100V$).
- 2- Change the field current (I_f) (increase the field current (I_f) in steps is in table (2) and record the speed readings.

Table (2): Speed control by varying I_f

I_f (A)	0.05	0.1	0.2	0.25	0.3
N (rpm)					

- 3- Reduce the V_t slowly, and then Switch off the supply and remove connections.

Report:

- 1- Plot the relationship between (N and V_t) with constant I_f , then discuss the plot.
- 2- Plot the relationship between (N and I_f) with constant V_t , then discuss the plot.
- 3- Calculate the back e.m.f of motor at each value of V_t in table (1). ($R_a = 23.5 \Omega$)
- 4- Describe the behavior of motor at (rated V_t and $I_f = 0$).
- 5- How to control the speed of a separately excited DC motor?
- 6- What is the effect on motor speed if the field current is increased in a separately excited DC motor?

Experiment No.2

Separately Excited DC Generator

Object:-

*This experiment learns the students how to connect separately excited DC generator.

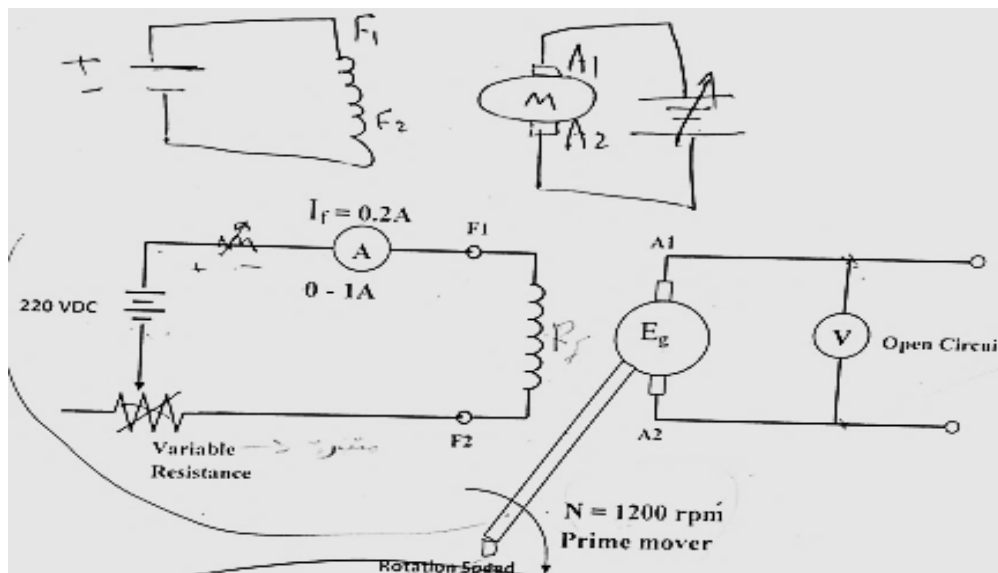
Theory:-

There are two ways to supply the exciting coil or magnet coil by direct current , one is known as separately excited generator. In this way the magnetic field or exciting coil or system field are energized by direct current from an independent supply or individual supply or source i.e the field coil are connected to direct voltage or current from external DC source. like battery which gives direct current or from any external source . The current passes through the magnet coil flux on the pole. These flux will pass through air gap to armature. when the armature rotates in side these magnet field the armature conductors will cut the magnet field so an emf induces in these conductors .

Procedure:

- 1-Connect the circuit as shown below.
- 2-Set the field current of prime mover at 0.2A & its speed at 1200 rpm.
- 3-Vary the field current of separately excited dc generator by varying the variable resistance in steps.
- 4-Record the reading of generated or induced emf across the armature generator as shown in table

I_f (A)	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
E_g (V)									



Discussion:-

- 1-Plot induced emf E_g against field current (I_f).
- 2-Discuss the shape of the (E_g/I_f) curve.
- 3-Discuss the system field in details.
- 4-What are the function of (1) yoke (2) pole & pole shoes (3) magnetic field & air duct in armature core.

Experiment (3)

Speed Control of Shunt DC Motor

Objective: To study the methods of controlling the speed of shunt DC motor.

Theory: We know that back e.m.f (E_b) is produced by the generator action of the motor.

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

Let V_t be the applied voltage and I_a and R_a is the armature circuit current and resistance respectively. Then

$$E_b = V_t - I_a R_a, \quad E_b = \frac{NPZ\phi}{60 A} = V_t - I_a R_a, \quad N = \frac{(V_t - I_a R_a) * 60 A}{PZ\phi}$$

$$N \propto \frac{(V_t - I_a R_a)}{\phi} \quad \text{Since } P, Z \text{ \& } A \text{ are constants for a particular motor}$$

$$N \propto \frac{V_t}{\phi} \quad \text{Since } I_a R_a \text{ drop is very small as compared to the applied voltage } V_t$$

From this formula it follows that the speed of a shunt D.C. motor can be regulated by:

1. Armature Control:

This method implies changing the voltage applied to the armature (V_t) of the motor without changing the voltage applied to its field. Thus, the armature terminal voltage is adjusted by the external armature resistance (R_{ax}). Because voltage source cannot be varied (should be constant, if it varied will cause I_f to be varied also).

$$N \propto V_t, \text{ if applied voltage } \phi \text{ is constant}$$

2. Field Control:

$$N \propto \frac{1}{\phi}, \text{ if applied voltage } V_t \text{ is constant}$$

The speed is inversely proportional to flux / per pole if the applied voltage is constant. Then the speed can be decrease by increase the flux and vice versa. The flux of DC motor can be changed by changing the field current (I_f), with help of external field resistance (R_{fx}). $\phi \propto I_f, \frac{1}{I_f}$, if applied voltage V_t is constant

Procedure:

1- Connect the circuit as shown in Fig.1.

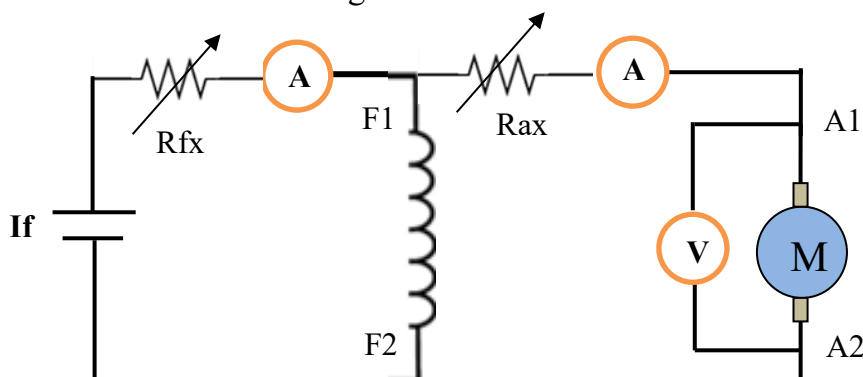


Fig. 1: Circuit diagram of speed control of shunt DC motor

- 2- Switch on the supply after checking connection by concerned teacher.
- 3- Fix the field current (I_f) by aid of external field resistor (R_{fx}) at rated value ($I_f = 0.2$).
- 4- Change the armature terminal voltage by changing the value of external armature resistance (R_{ax}) at steps as shown in table (1) and record the speed readings.

Table (1): Speed control by varying V_t

V_t (V)	0	30	50	70	100
N (rpm)					

- 5- Fix the armature voltage at the rated voltage ($V_t = 100V$).
- 6- Change the field current (I_f) by changing the value of external armature resistance (R_{fx}) (increase I_f) in steps is in table (2) and record the speed readings.

Table (2): Speed control by varying I_f

I_f (A)	0.05	0.1	0.2	0.25	0.3
N (rpm)					

- 7-
- 8- Reduce the V_t slowly, and then Switch off the supply and remove connections.

Report:

- 1- Plot the relationship between (N and V_t) with constant I_f , then discuss the plot.
- 2- Plot the relationship between (N and I_f) with constant V_t , then discuss the plot.
- 3- Calculate the back e.m.f of motor at each value of V_t in table (1). ($R_a = 24 \Omega$)
- 4- Why does a parallel motor have relatively stable speed when the load changes?
- 5- What is the relationship between motor speed and magnetic flux intensity

Experiment No. 4**Self Excited DC Generator****Object:-**

*This experiment learns the students how to connect self excited generator.

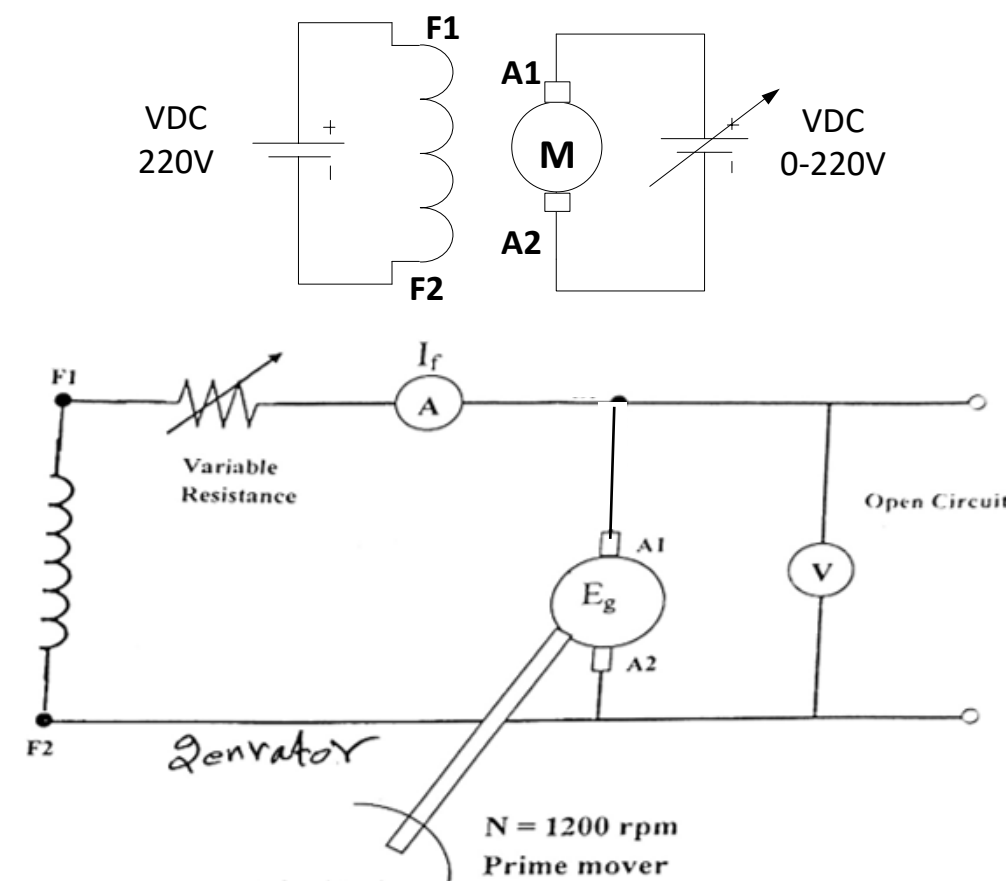
Theory:-

In this type of generator (self excited generator) the field magnets are energized by the current produced by the armature generator themselves, i.e. the magnet field winding is connected directly to the armature terminal. Due to residual magnetisms, there is always present some flux in the pole. When the armature is rotated, some emf & some induced current is produced which is partly or fully passes through the field coils there by strengthening the residual pole flux. There are three types of connections for self excited generator:

- 1-shunt generator. —
- 2-series generator. —
- 3-compound wound generator. —

Procedure:-

- 1-Connect the circuit as shown below.
- 2-Set the field current of prime mover at 0.2A & its speed at 1200 rpm.
- 3-Vary the variable resistance in order to vary the field current in step.
- 4-Record the reading of voltmeter as shown in table.



Discussion:-

- 1-Plot (E_g) against field current (I_f).
- 2-Discuss the shape of the (E_g / I_f) curve.
- 3-Discuss the armature system in details.
- 4-What are the function of following items (1) Armature core (2) Armature winding (3) commutator (4) Brushes & bearings.
- 5-If there is no building voltage in generator, what do?
- 6-Is the series generator is self excited or separately excited & why?

Handwritten notes: 1, 2, 3, 4, 5, 6

Experiment (4)

Compound DC Generator

Object:-

* The main idea of this experiment to learn the student how connected the different types of compound generator.

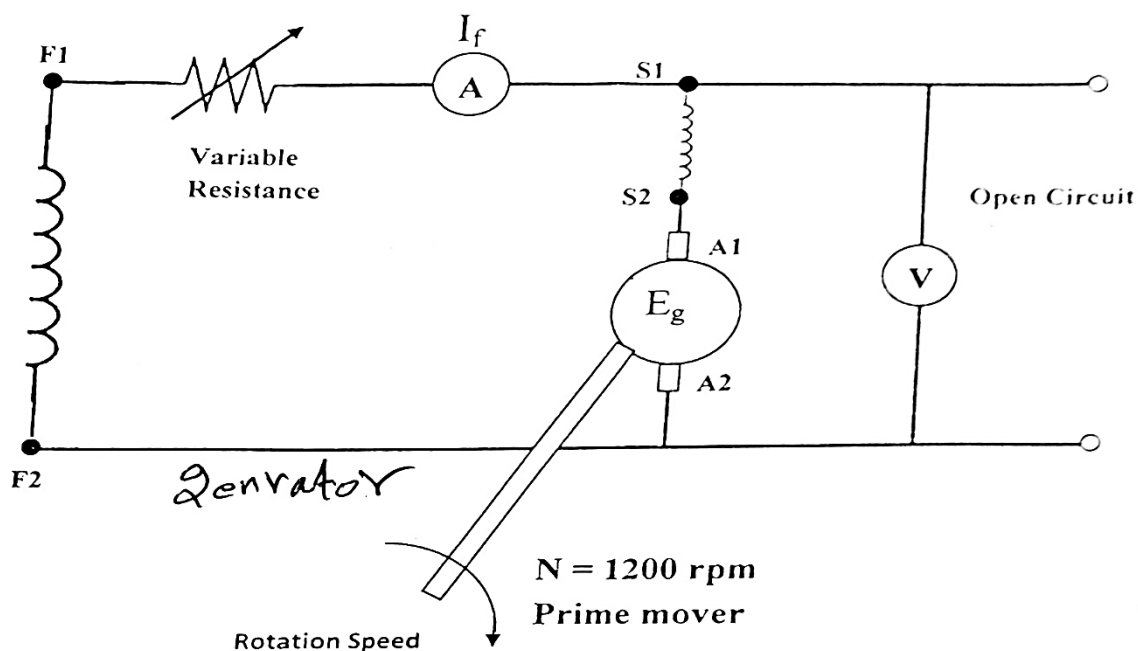
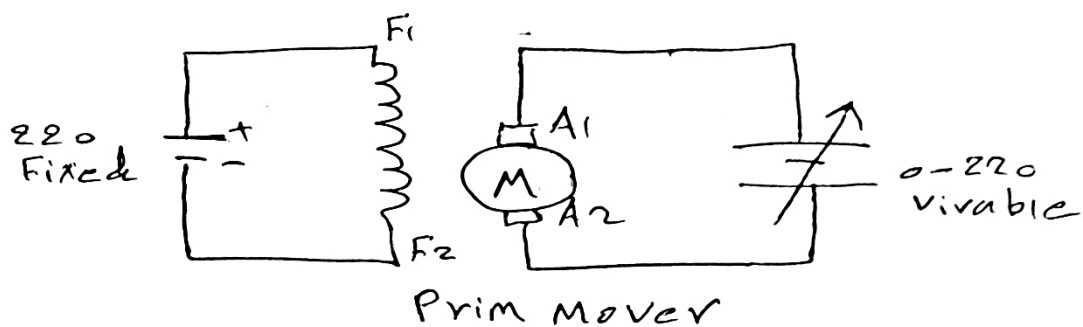
Theory:-

Compound generator is one type of self excited DC generator .it is a combination of a few series winding field & a few shunt windings field.it can be connected as short shunt compound generator or long shunt compound generator. the shunt field winding strengthen the series field winding.

Procedure:-

- 1-Connect the circuit as shown below.
- 2-Set the field current of prime mover to 0.2A and its speed to 1200 rpm.
- 3-Vary the variable resistance in order to vary the field current in steps and record the reading of voltmeter as shown in table

$I_f(A)$	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
$E_g(V)$	13	50	87	112	134	150	162	173	184



Discussion:-

- 1- Plot the relation between (E_g/I_f) curve.
- 2- Discuss the shape of the (E_g/I_f) curve.
- 3- Explain the two types of compound generator (1) cumulative compound (2) differential compound generator.
- 4- What are the differences between the cumulative and differential compound generator.

Experiment (4)

Characteristics Study of Capacitor-Start Induction Motor

Objective: To study the operation of capacitor-start IM under different load condition and finding the efficiency.

Theory: In a capacitor-start motor a capacitor is included in series with the auxiliary winding as shown in Fig. 1. The auxiliary winding and the capacitor are disconnected at about 75% of the synchronous speed. Therefore, at the rated speed the capacitor start motor operates only on the main winding like a split-phase motor.

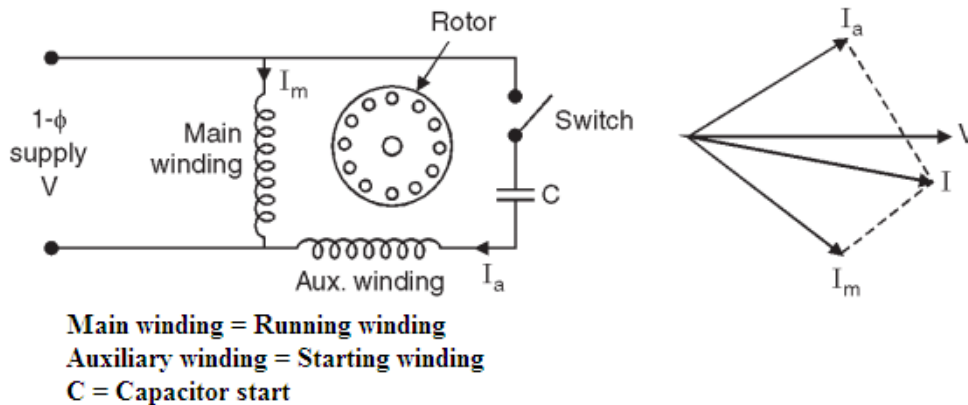


Fig. 1: Capacitor-start motor

The need for an external capacitor makes the capacitor start motor somewhat more expensive than a split phase motor. However, a capacitor start motor is used when the starting torque requirements are 4 to 5 times the rated torque as shown in Fig. 2.

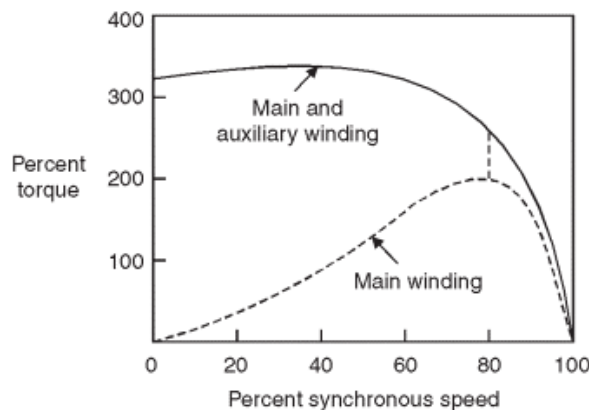


Fig. 2: Torque-speed characteristic of a capacitor start motor

This motor is used in applications, such as compressor, conveyor, machine tool drive, refrigeration and air-conditioning equipment, etc.

Proceduer:

1. Connect the circuit shown in the Fig. 3 below.

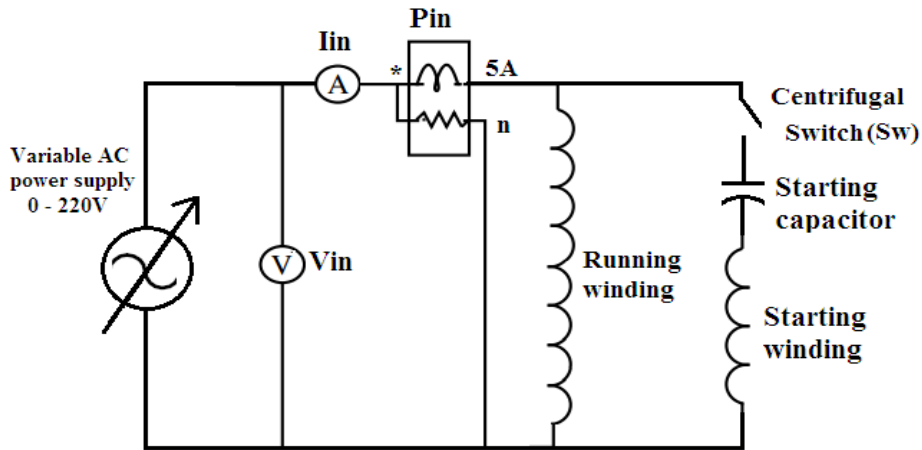


Fig. 3: Laboratory connection of capacitor-start motor

2. Switch on the supply after checking connection by concerned teacher.
3. Increase the supply input voltage slowly until 200V.
4. Increase the force (S_1, S_2) that applied to the pulley of the motor slowly (in various steps)

Calculations:

$$T_s = F * R \text{ (N.m)}$$

T_s : shaft torque of the motor in (N.m)

$$F = (S_1 - S_2) \text{ Kg.} * 9.8 \text{ Force in (Newten = N)}$$

R : radius of the pulley in (meter = m)

$$\omega = \frac{2\pi N}{60} \text{ (rad/s)}$$

Where N : Speed of motor in (r.p.m)

$$P_{out} = T_s * \omega \text{ (Watt) Output power of motor}$$

$P_{in} = V_{in} * I_{in} * \cos\theta \text{ (Watt)}$ Input power of motor, this value can be taken directly from the wattmeter.

$$\eta\% = \frac{P_{out}}{P_{in}} * 100 \text{ Efficiency of motor}$$

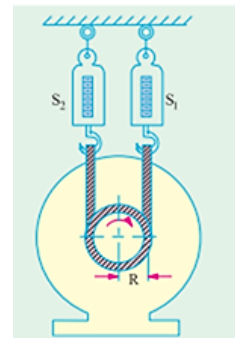


Table (1): reading of capacitor start IM characteristics study test

V_{in} (V)	I_{in} (A)	P_{in} (watt)	Wight		F (N)	T_s (N.m)	N (rpm)	ω (rad/s)	P_{out} (watt)	$\eta\%$
			S1	S2						
150										
150										
150										
150										

Report:

1. Complete the calculations of efficiency of capacitor start IM in table (1).
2. Plot the relationship between the efficiency and the output power of the motor.
3. What is the application of capacitor start induction motor?
4. Why use a capacitor start motor?

Experiment (5)

Stator Resistance Test of Three-phase Induction Motor (DC Test of 3-phase IM)

Objective:

To measure the value of the stator resistance of 3-phase IM.

Theory:

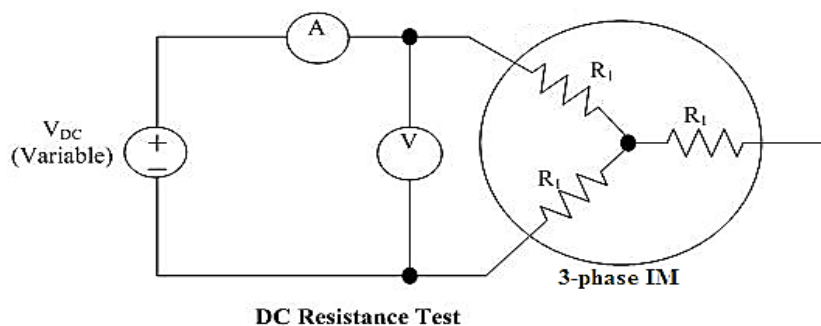
Basically, a DC voltage is applied to the stator windings of a 3-phase IM. Because the current is DC, there is no induced voltage in the rotor circuit and no resulting rotor current. Also, the reactance of the motor is zero at direct current. Therefore, the only quantity limiting current now in the motor is the stator resistance, and that resistance can be determined. The basic circuit for the DC test is shown in the figure. This figure shows a DC power supply connected to two of the three terminals of a Y -connected 3-phase IM.

The measured value of resistance of 3-phase IM should be multiplied by a factor (Skin effect) ranging from (1.05-1.25) in order to convert its value from DC value to AC value. The skin effect factor depends on the temperature of motor before test (t_s) and the temperature of motor at the moment of DC test (t_t).

$$\text{Skin effect} = \frac{t_s + k}{t_t + k} \quad : \quad k = 234.5 \text{ for copper}$$

Procedure:

1. Connect the circuit shown in the Figure below.



2. Switch on the DC supply after checking connection by concerned teacher.
3. Increase the supply input voltage slowly from 5V to 40V with step equal to 5V.
4. Record the readings of the measurements in table (1).

Table (1): reading of DC test of 3-phase IM

V_{dc} (V)	I_{dc} (A)
5	
10	
15	
20	
25	
30	
35	
40	

Calculations:

After applying DC voltage to the terminals of the stator winding and taking the reading of the voltage and the current, the relationship between them should be plotted, then the DC resistance can be determined as follows:

$$R_{dc} = \frac{\Delta V_{dc}}{\Delta I_{dc}} = \frac{V_2 - V_1}{I_2 - I_1}$$

$$R_{1dc} = \frac{R_{dc}}{2} \quad \text{per phase for } \text{Y connection}$$

$$R_{1dc} = \frac{R_{dc} * 3}{2} \quad \text{per phase for } \Delta \text{ connection}$$

Skin effect = 1.01 or 1.15

$$R_1 = R_{1dc} * \text{Skin effect}$$

R_1 : AC value of the stator resistance of three phase induction motor

Report:

1. Calculate the stator resistance (R_1) according the above equations.
2. Is Induction motor a self-starter? Why?
3. What is DC frequency?
4. What is the resistance test for a motor?
5. Define the (Skin effect) and what is depend?

Experiment (6)

No load Test of Three-phase Induction Motor

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.

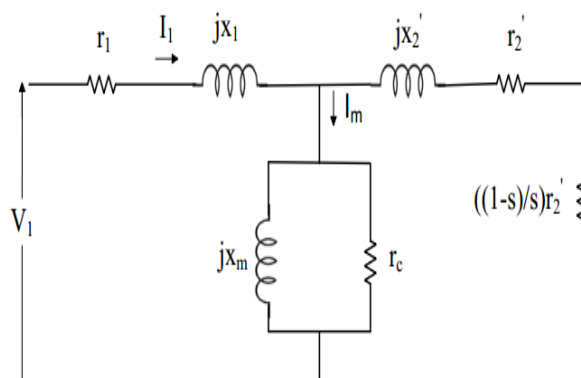


Fig. 1. Per phase equivalent circuit of 3-phase induction motor

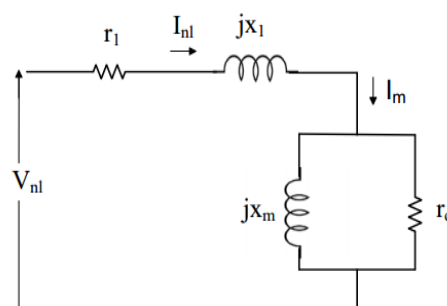


Fig. 2. Approximate Equivalent Circuit for No-Load Test

Calculation:

$$W_T = W_1 + W_2$$

$$W_{ph} = W_T/3$$

$$W_{ph} = I_{ph} * V_{ph} * \cos \theta$$

$$\cos \theta = \frac{W_{ph}}{I_{ph} * V_{ph}} = \text{the power factor at no load}$$

$$\text{core loss current } (I_c) = I_{ph} * \cos \theta$$

$$\text{magnetization current } (I_m) = I_{ph} * \sin \theta$$

$$\text{core loss resistor } (R_c) = \frac{V_{ph}}{I_c}$$

$$\text{magnetization reactance } (X_m) = \frac{V_{ph}}{I_m}$$

Procedure:

1. Connect the circuit as shown in the connection diagram in Figure 3.

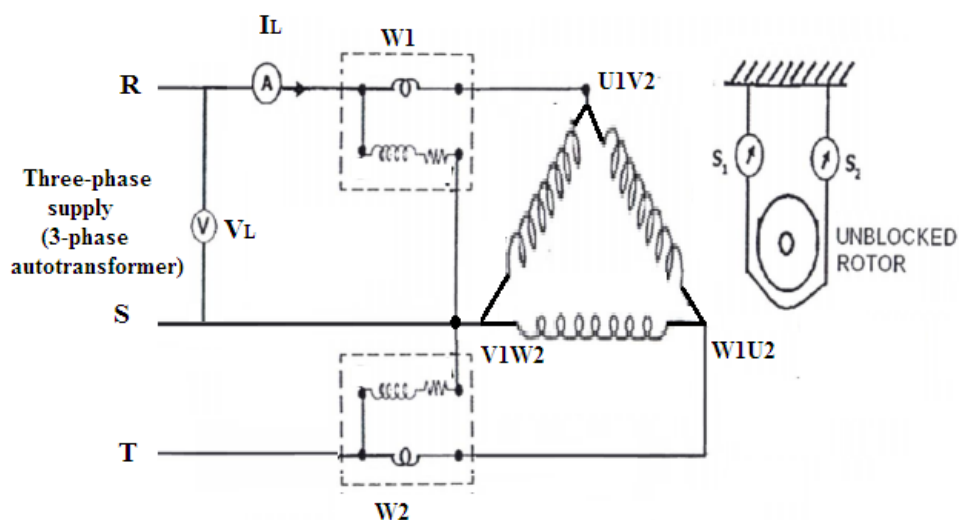


Fig. 3: Schematic diagram for No-load test on three phase induction motor

2. Start the motor by ensuring the shaft is at no load condition.
3. For starting, either use autotransformer or starter to reach rated voltage.
4. Note the readings of voltmeter, ammeter and wattmeter by carefully.
5. Reduce the voltage using autotransformer to zero and turn the main switch off.

Discussion:

1. Calculate the machine parameters that is can be obtained from No-Load test.
2. What is the power factor of the machine? Comment on its value.
4. Even though there is no-load, why wattmeter reading is not zero?
5. Comment on the slip of the machine when operated at rated voltage.
6. Can a three-phase induction motor be started from a single-phase supply?
7. What is the nameplate reading on the machine? What inferences can be drawn from it?
8. What are the different losses that are present in an induction machine?
9. Which loss in the machine is significant in no load test and why?
10. What is the real and reactive power consumed in this test?

Experiment (7)

Blocked Rotor Test of Three-phase Induction Motor

Theory:

For this test, the motor shaft is clamped so that it cannot turn. The motor terminals are connected to a 3-phase supply. The rotor becomes the secondary of a transformer operating at the supply frequency. So, the blocked rotor test is similar to the short circuit test on a transformer. It is performed 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 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. (1).

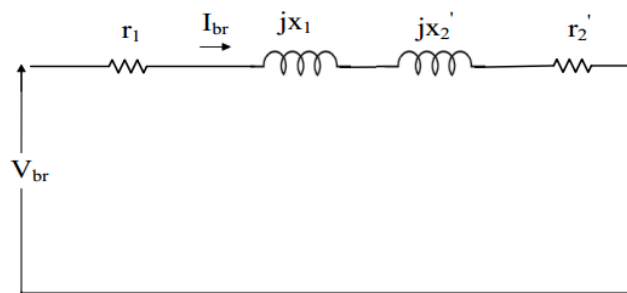


Fig. 1: Equivalent circuit for blocked rotor test

The slip for the blocked rotor test is unity since the rotor is stationary. The resulting speed-dependent equivalent resistance $r_2' \{(1/s)-1\}$ 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.

Calculation:

$$Z_e = \frac{V \text{ per phase}}{I \text{ per phase}} = \frac{V_L/\sqrt{3}}{I_L} \quad I_L = I_{ph} \text{ for star connection}$$

$$R_e = \frac{W}{I_L^2}$$

$$R_e = R_1 + R_2'$$

$$R_1 = \text{stator resistance from dc test}$$

$$X_e = \sqrt{Z_e^2 - R_e^2}$$

$$X_e = X_1 + X_2'$$

It is rather difficult to isolate the leakage reactance (X_1 & X_2'). Thus, for all practical purposes assumed to be equal.

$$X_1 = X_2' = X_e/2$$

Procedure:

1. Connect the circuit as shown in the connection diagram in Figure 2.

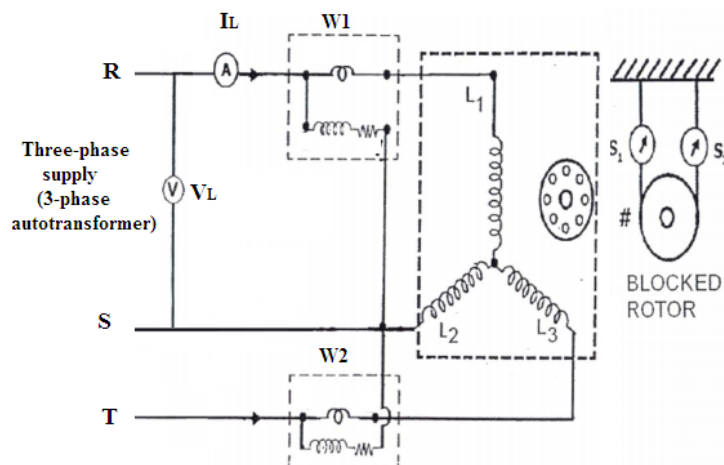


Fig. 2: Schematic diagram for Blocked rotor test on 3-Phase induction motor

2. Before starting, ensure that the shaft is blocked completely from rotating.
3. Using the 3- ϕ autotransformer, increase the voltage to the machine such that it draws rated current.
4. Note the readings of voltmeter, ammeter and wattmeter by carefully.
5. Take the readings quickly so that the machine does not heat up due to full load copper losses taking place at this condition.
6. Reduce the voltage using autotransformer to zero and turn the main switch off.

Discussion:

1. Calculate the R'_2 ; X_1 ; X'_2 .
2. When $r_{2/s}$ is split into a series connection of $r_{2'}$ and $r_{2'} \{(1/s)-1\}$ in the rotor equivalent circuit of an induction machine, what do the power absorbed by the individual resistors physically represent?
3. How does the equivalent circuit of an induction motor simplify to under blocked rotor conditions? Justify.
4. Which loss in the machine is significant in blocked rotor test and why?
5. What is the purpose of locked rotor test in induction motor?
6. Why block rotor test of an induction motor is carried out?

Experiment (8)

Load Test of Three-phase Induction Motor

Aim:

- (a) Perform load test on 3-phase induction motor.
- (b) Compute Torque, Output power, Input power, Efficiency, Input power factor and Slip for every load setting and to determine how speed, efficiency, power factor, stator current torque, and slip of an induction motor vary with load.
- (c) Plot the following performance curves: (i) Efficiency Vs. Output power, (ii) Torque Vs. Output power, (iii) Line current Vs. Output power, (iv) Power factor Vs. Output, (v) Slip Vs. Output power, and (vi) Torque Vs. Speed

Theory:

The load test on induction motor is performed to compute its complete performance i.e. torque, slip, efficiency, power factor etc. During this test, the motor is operated at rated voltage and frequency and normally loaded mechanically by brake and pulley arrangement from the observed data, the performance can be calculated, following the steps given below.

- Slip (S):

The speed of rotor (N_r) droops slightly as the load on the motor is increased. The synchronous speed (N_s) of the rotating magnetic field is calculated, based on the number of poles, P and the supply frequency (f).

$$N_s = 120f/p \quad \text{in r.p.m}$$

$$S = (N_s - N_r)/N_s$$

Normally, the range of slip at full load is from 2 to 5 percent.

- Torque:

Mechanical loading is the most common type of method employed in laboratories, A brake drum is coupled to the shaft of the motor and the load is applied by tightening the belt, provided on the brake drum. The net force exerted at the brake drum in kg is obtained from the readings S_1 and S_2 of the spring balances. Thus as the speed of motor does not vary appreciably with load torque will increase with increasing load.

$$T_s = F * R \quad (N.m)$$

T_s : shaft torque of the motor in (N.m)

$$\text{Net force exerted (F)} = (S_1 - S_2) \text{ Kg.} * 9.8 \quad \text{in (Newten = N)}$$

R : radius of the pulley in (meter = m)

- Output power (P_{out}):

The output power in watts developed by the motor is given by:

Output power = Torque x Speed

$$P_{out} = T_s * \omega \quad (\text{Watt})$$

- Speed:

When the induction motor is on NO-LOAD speed is slightly below the synchronous speed. The current due to induced emf in the rotor winding is responsible for production of torque required at NO-LOAD.

As the load is increased the rotor speed is slightly reduced. The emf induced in the rotor causes the current increased to produce higher torque, until the torque developed is equal to torque required by load on motor.

$$\omega = \frac{2\pi N}{60} \text{ (rad/s)}$$

Where N : Speed of motor in (r.p.m)

- Input power (P_{in}):

Input power is measured by the two wattmeter (W1 and W2), properly connected in the circuit:

$$P_{in} = (W1 + W2) \text{ watts}$$

- Efficiency:

Percentage efficiency of the motor, $\eta\% = \frac{P_{out}}{P_{in}} * 100$

Full load efficiency of 3 phase induction motor lies in the range of 72 % (for small motors) to 82 % (for very large motors).

Summary of Calculations:

$$T_s = F * R \text{ (N.m)}$$

T_s : shaft torque of the motor in (N.m)

$$F = (S_1 - S_2) \text{ Kg.} * 9.8 \text{ Force in (Newten = N)}$$

R : radius of the pulley in (meter = m)

$$\omega = \frac{2\pi N}{60} \text{ (rad/s)}$$

Where N : Speed of motor in (r.p.m)

$$P_{out} = T_s * \omega \text{ (Watt) Output power of motor}$$

$$P_{in} = \sqrt{3} * V_{in} * I_{in} * \cos\theta \text{ (Watt) Input power of motor, this value can be taken directly from the wattmeter.}$$

$$\eta\% = \frac{P_{out}}{P_{in}} * 100 \text{ Efficiency of motor}$$

Procedure:

1- Connect the circuit as per fig. 2.

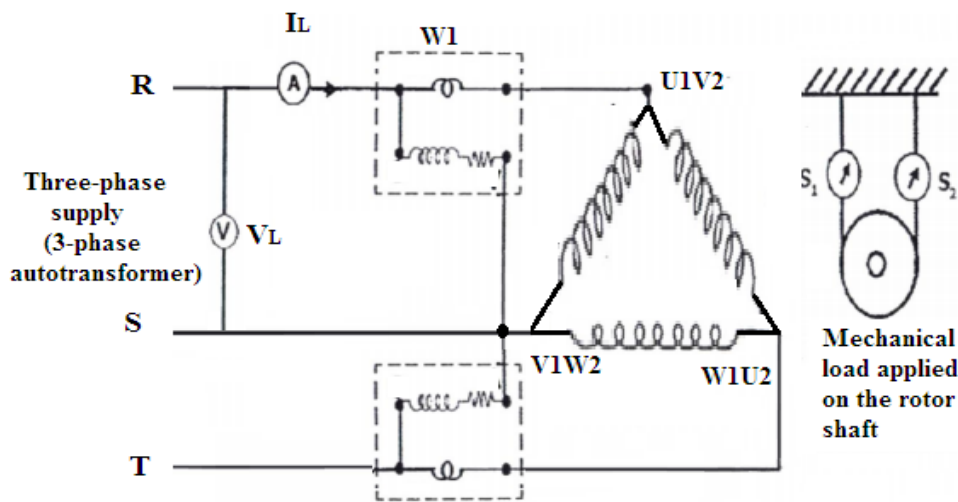


Fig. 2: Schematic diagram for load test on Three Phase Induction Motor

2- Ensure that the motor is unloaded and the variance of autotransformer is set at zero output voltage.

- 3- Switch-on 3 phase AC mains and start the motor at reduced applied voltage.
- 4- Increase the applied voltage, till its rated value.
- 5- Take-down the readings of all the meters and the speed under no load running in table (1).
- 6- Increase the load on the motor gradually by turning of the hand wheels, thus tighten the belt.
- 7- Record the readings of all the meters and the speed at every setting of the load in table (1).
- 8- Observation may be continued up to the full load current rating of the motor.

Table (1): Reading of the load test of three-phase IM

V_{in} (V)	I_{in} (A)	P_{in} (watt)	Wight		F (N)	T_s (N.m)	N (rpm)	ω (rad/s)	S	P_{out} (watt)	$\eta\%$
			S1	S2							
220											
220											
220											
220											

- 9- Reduce the load on the motor and finally unload it completely.
- 10- Switch-off the supply to stop the motor.
- 11- Measure the radius of the pulley (R) in (meter)

Report:

1. Complete the calculations of efficiency of the motor in table (1).

Experiment (1)

Open Circuit Test (O.C. T.) of Single-Phase Transformer (No Load Test)

Objective:

The main purpose of this test is to find the iron core losses (P_0) and no load current (I_0) which are useful in calculating core loss resistance (R_c) and magnetizing reactance (X_m) of the transformer (equivalent circuit parameters of the core).

Theory:

The equivalent circuit of the transformer is shown in figures (1 - 2).

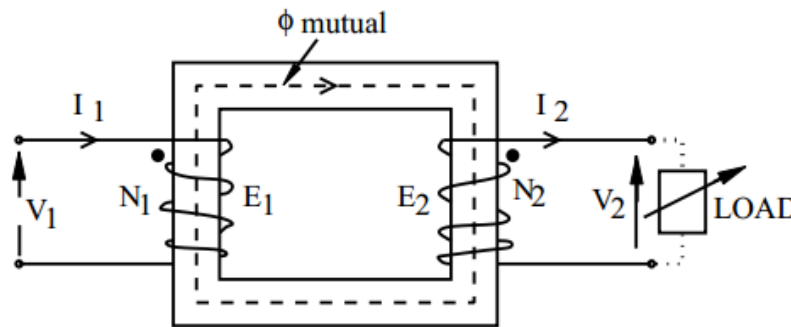


Fig.1: Elementary transformer

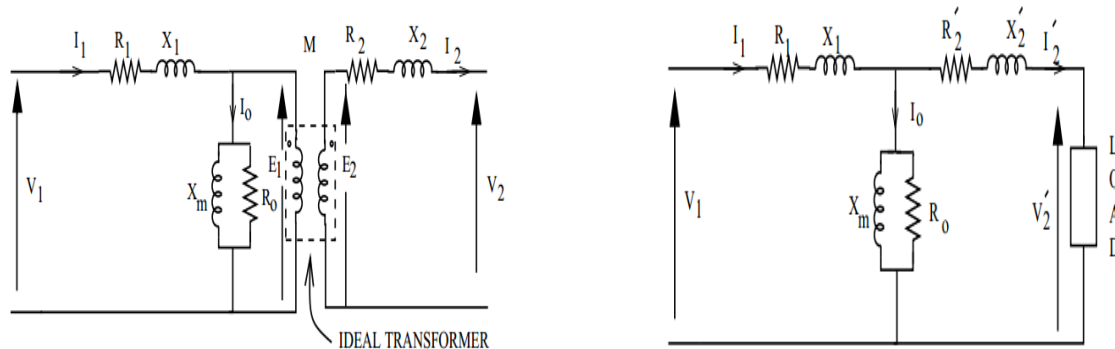


Fig.2: Development of transformer equivalent circuit

As secondary is open (no load), $I_2 = 0$, hence secondary copper losses (in R_2 and X_2) are zero. And the no load current I_0 which equal to I_1 ($I_1 = I_0$) is very low ($I_0 < 6\%$ of load current), hence copper losses on primary (R_1 and X_1) are also very low. Thus the total copper losses (primary and secondary) in this test are negligibly small, hence neglected. Therefore the wattmeter reading (P_0) in this test gives core losses (in R_c & X_m) which remain constant for all the loads (i.e. I_0 will only flow through core circuit, for this reason, it is possible to calculate the core circuit parameter (R_c and X_m)) as shown in figure 3.

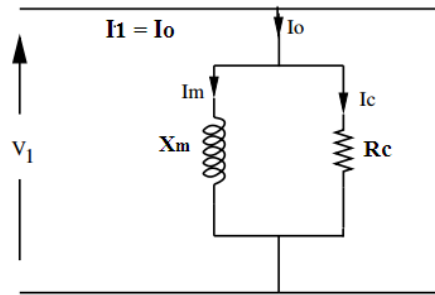


Fig. 3: Equivalent Circuit on No-Load

The no load current I_o has two components as shown in phasor diagram as shown in figure below: these component are: *magnitizing current* (I_m), and *iron losses current* (I_c).

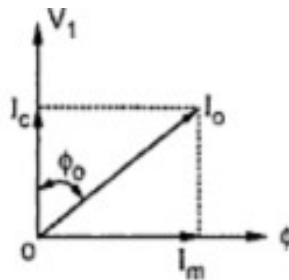


Fig. 4: phasor diagram

Power input can be written as:

$$P_o = I_o V_1 \cos \theta_o$$

Then : $\cos \theta_o = \frac{P_o}{I_o V_1} = \text{the power factor at no load}$

$$I_c = I_o \cos \theta_o$$

$$I_m = I_o \sin \theta_o$$

Once I_c and I_m are known we can determine core circuit parameters as:

$$R_c = \frac{V_1}{I_c} \quad \& \quad X_m = \frac{V_1}{I_m}$$

Procedure:

- 6- Connect the circuit shown in the Fig. 5; the primary winding is connected to AC supply through ammeter and wattmeter, keeping secondary open. Usually, low voltage side is used as primary and high voltage side as secondary to conduct O.C. test.

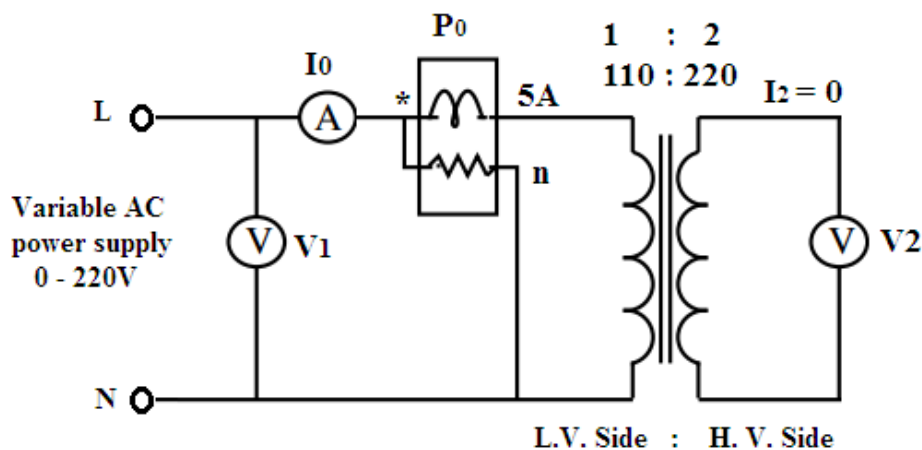


Fig. 5: Circuit diagram of O.C. test

- 7- Switch on the supply after checking connection by concerned teacher.
- 8- The primary is excited by (80 - 90 - 100 - 110V (rated voltage)), which is adjusted precisely.
- 9- When primary voltage is adjusted to its rated value with the help of variac (auto-transformer), readings of ammeter and wattmeter are to be recorded (Take the readings of all meters at each voltage step; record it in table (1) below).

Table (1): Open circuit test readings

(V) V_1	(W) P_o	(A) I_o	(V) V_2	$\cos \theta_o$
80				
90				
100				
110				

- 10- Reduce the voltage slowly, and then Switch off the supply and remove connections.

Report:

- 1. Calculate the value of equivalent circuit parameters of core (R_c , X_m) at each value of applied voltage (80 – 90 – 100 – 110V) according the above equations depending on the table (1).
- 2. What are the approximations are made in this experiment?
- 3. Why the transformer core made from lamination plates?
- 4. Why core losses remain almost constant at any load?

Experiment (2)

Short Circuit Test (S.C.T.) of Single-Phase Transformer

Objective:

The main purpose of this test is to find:

- Full load copper loss, this loss is used in calculating the efficiency of the transformer.
- Winding parameters (R_{e1} & X_{e1} or R_{e2} & X_{e2}).

Theory:

In this test usually LV side is shorted with the help of ammeter and meters are connected on HV side. A variable low voltage is applied (usually 5 to 10% of normal primary voltage) to the HV winding with the help of an auto-transformer. This voltage is varied till the full load currents flowing both in the HV and LV side.

The wattmeter indicates the full load copper losses and iron losses. As the voltage applied is low which a small fraction of the rated voltage and iron losses are function of applied voltage, hence iron losses are negligibly small. Now the current flowing through the windings are rated current hence the total copper loss is full load copper loss. Hence the wattmeter reading represent the full load copper losses (I^2R) for the whole transformer. The equivalent circuit of the transformer under short circuit conditions is shown in fig. 1.

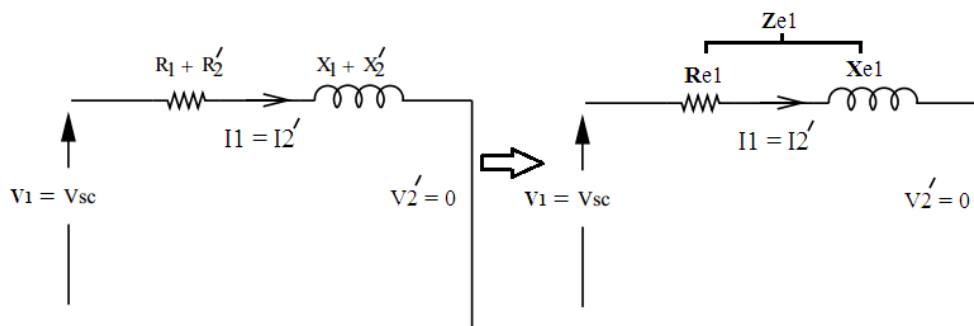


Fig. (1): Approximate circuit of transformer on short circuit

If V_{sc} is the voltage required to circulate rated load currents, then

$$Z_{e1} = \frac{V_{sc}}{I_{sc}}$$

Also

$$P_{sc} = I_{sc}^2 * R_{e1} = \text{Full load copper loss} \longrightarrow R_{e1} = \frac{P_{sc}}{I_{sc}^2}$$

$$X_{e1} = \sqrt{(Z_{e1})^2 - (R_{e1})^2}$$

Thus we get the equivalent circuit parameters Z_{e1} , R_{e1} and X_{e1} . Knowing the transformation ratio K , the equivalent circuit parameters referred to secondary also can be obtained.

Procedure:

1) Connect the circuit as shown in fig. (2).

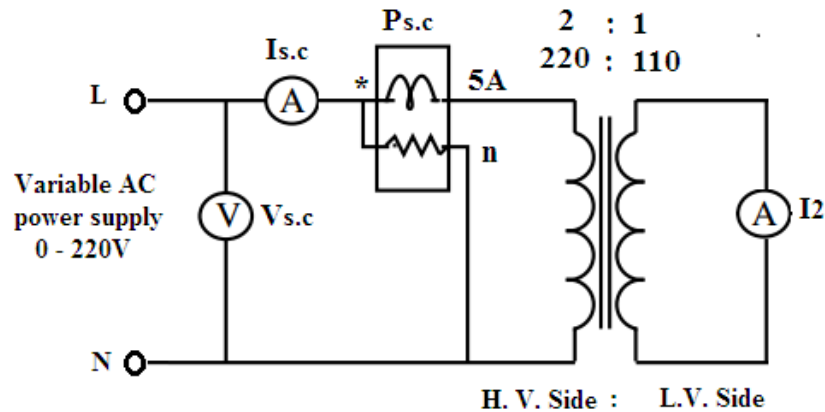


Fig. 2: Circuit diagram of short circuit test

- 2) Switch on the supply after checking connection by concerned teacher.
- 3) Increase the input voltage very carefully and slowly so that the current in secondary winding reaches rated value (from 2A to 5A rated value).
- 4) Record the readings of meters in table (1).

Table (1): Short circuit test readings

(V) V_{sc}	(A) I_{sc}	(W) P_{sc}	(A) I_2
			2
			3
			4

5) Reduce the voltage slowly, and then switch off the supply and remove connections.

Report:

1. Draw the copper losses (P_{sc}) against the input current (I_{sc}).
2. Calculate the rated value of Z_{e1} , R_{e1} , and X_{e1} .
3. What are the approximations are made in this experiment?
4. Why S.C. test is generally performed with L.V. side short circuited?
5. Why the wattmeter readings are considered the copper losses?
6. Discuss all your results clearly and briefly.